Introduction to OpenCL™ Programming

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Chapter 1

Course Overview

1.1 Objectives

This training session introduces participants to the fundamentals of the OpenCL™ (Open Computing Language) programming language. Areas covered include the following:

• Introduction to parallel computing with heterogeneous systems.
• Introduction to the OpenCL programming framework.
• Setting up the OpenCL development environment.
• Understand and using the OpenCL API.
• Optimizing an OpenCL application.

1.2 Audience

This course is intended for programmers. It assumes prior experience in the C programming language.

1.3 References

• The OpenCL Specification v1.0 (http://www.khronos.org/registry/cl/specs/opencl-1.0.48.pdf)
• OpenCL 1.0 Reference Page (http://www.khronos.org/opencl/sdk/1.0/docs/man/xhtml/)
• ATI Stream Software Development Kit (SDK) (http://developer.amd.com/stream)
• AMD Developer Forums - OpenCL (http://developer.amd.com/opencl)
• ATI Stream Profiler Knowledge Base (http://developer.amd.com/support/KnowledgeBase?Category=2&SubCategory=54)
• GNU GDB Documentation (http://www.gnu.org/software/gdb/documentation)
• OpenCL Zone (http://developer.amd.com/openclzone)
• Image Convolution Tutorial (http://developer.amd.com/gpu/ATIStreamSDK/ImageConvolutionOpenCL/Pages/ImageConvolutionUsingOpenCL.aspx)

Note: The information contained in this guide is current at the time of publication, and may not apply to future technologies, products, or designs.
Chapter 2

Introduction

This chapter provides a brief overview and history of GPU compute.

2.1 What is GPU Compute?

GPU compute is the use of Graphics Processing Units (GPUs) for general purpose computation instead of traditional graphics rendering. GPUs are high performance multi-core processors that can be used to accelerate a wide variety of applications using parallel computing. The highly programmable nature of GPUs makes them useful as high-speed coprocessors that perform beyond their intended graphics capabilities.

2.2 A Brief History of GPU Compute

The birth of the GPU compute revolution occurred in November 2006, when AMD introduced its Close to Metal (CTM) low-level hardware programming interface that allowed developers to take advantage of the native instruction set and memory of modern GPUs for general-purpose computation. CTM provided developers with the low-level, deterministic, and repeatable access to hardware necessary to develop essential tools such as compilers, debuggers, math libraries, and application platforms. With the introduction of CTM, a new class of applications was realized. For example, a GPU-accelerated client for Folding@Home was created that was capable of achieving a 20- to 30-fold speed increase over its predecessor (for more on this story, see http://folding.stanford.edu/English/FAQ-ATI#ntoc5.)

AMD’s continuing commitment to provide a fully-featured software development environment that exposes the power of AMD GPUs resulted in the introduction of the ATI Stream SDK v1 in December 2007. The ATI Stream SDK v1 added a new high-level language, called ATI Brook+. CTM evolved into ATI CAL (Compute Abstraction Layer), the supporting API layer for Brook+. The introduction of the ATI Stream SDK v1 meant that AMD was able to provide both high-level and low-level tools for general-purpose access to AMD GPU hardware.
A drawback to using the ATI Stream SDK v1 was that applications created with the SDK ran only on AMD GPU hardware. To achieve greater adoption for general-purpose computing, an open standard was needed.

In June 2008, AMD, along with various industry players in GPU compute and other accelerator technologies, formed the OpenCL working group under The Khronos Group. Khronos, already known for leadership in other open specifications such as OpenGL®, was a logical choice to drive the OpenCL specification. Five months later, the group completed the technical specification for OpenCL 1.0 and released it to the public. Immediately after that release, AMD announced its intent to adopt the OpenCL programming standard and integrate a compliant compiler and runtime into its free ATI Stream SDK v2. In December 2009, AMD released the ATI Stream SDK v2.0 with OpenCL 1.0 support.

2.3 Heterogeneous Computing

Heterogeneous computing involves the use of a various types of computational units. A computation unit can be a general-purpose processing unit (such as a CPU), a graphics processing unit (such as a GPU), or a special-purpose processing unit (such as digital signal processor, or DSP).

In the past, most computer applications were able to scale with advances in CPU technologies. With modern computer applications requiring interactions with various systems (such as audio/video systems, networked applications, etc.) even the advances in CPU technology proved insufficient to cope with this need. To achieve greater performance gains, specialized hardware was required, making the system heterogeneous. The addition of various types of computation units in these heterogeneous systems allows application designers to select the most suitable one on which to perform tasks.
Chapter  3

Introduction to OpenCL

This chapter introduces OpenCL and describes the anatomy and architecture of the OpenCL API.

3.1 What is OpenCL?

The Open Computing Language (OpenCL) is an open and royalty-free parallel computing API designed to enable GPUs and other coprocessors to work in tandem with the CPU, providing additional raw computing power. As a standard, OpenCL 1.0 was released on December 8, 2008, by The Khronos Group, an independent standards consortium.

Developers have long sought to divide computing problems into a mix of concurrent subsets, making it feasible for a GPU to be used as a math coprocessor working with the CPU to better handle general problems. The potential of this heterogeneous computing model was encumbered by the fact that programmers could only choose proprietary programming languages, limiting their ability to write vendor-neutral, cross-platform applications. Proprietary implementations such as NVIDIA's CUDA limited the hardware choices of developers wishing to run their application on another system without having to retool it.

3.1.1 Benefits of OpenCL

A primary benefit of OpenCL is substantial acceleration in parallel processing. OpenCL takes all computational resources, such as multi-core CPUs and GPUs, as peer computational units and correspondingly allocates different levels of memory, taking advantage of the resources available in the system. OpenCL also complements the existing OpenGL® visualization API by sharing data structures and memory locations without any copy or conversion overhead.

A second benefit of OpenCL is cross-vendor software portability. This low-level layer draws an explicit line between hardware and the upper software layer. All the hardware implementation specifics, such as drivers and runtime, are invisible to the upper-level software programmers through the use of high-level abstractions, allowing the developer to take advantage of the best hardware without having to reshuffle the upper software infrastructure. The change from proprietary programming to open standard also contributes to the acceleration of general computation in a cross-vendor fashion.
3.2 Anatomy of OpenCL

The OpenCL development framework is made up of three main parts:

- Language specification
- Platform layer API
- Runtime API

3.2.1 Language Specification

The language specification describes the syntax and programming interface for writing kernel programs that run on the supported accelerator (GPU, multi-core CPU, or DSP). Kernels can be precompiled or the developer can allow the OpenCL runtime to compile the kernel program at runtime.

The OpenCL programming language is based on the ISO C99 specification with added extensions and restrictions. Additions include vector types and vector operations, optimized image access, and address space qualifiers. Restrictions include the absence of support for function pointers, bit-fields, and recursion. The C language was selected as the first base for the OpenCL language due to its prevalence in the developer community. To ensure consistent results across different platforms, OpenCL C also provides a well-defined IEEE 754 numerical accuracy for all floating point operations and a rich set of built-in functions. For complete language details on the language, see the OpenCL specification.

3.2.2 Platform API

The platform-layer API gives the developer access to software application routines that can query the system for the existence of OpenCL-supported devices. This layer also lets the developer use the concepts of device context and work-queues to select and initialize OpenCL devices, submit work to the devices, and enable data transfer to and from the devices.

3.2.3 Runtime API

The OpenCL framework uses contexts to manage one or more OpenCL devices. The runtime API uses contexts for managing objects such as command queues, memory objects, and kernel objects, as well as for executing kernels on one or more devices specified in the context.

3.3 OpenCL Architecture
3.3.1 The Platform Model

The OpenCL platform model is defined as a host connected to one or more OpenCL devices. Figure 3–1 OpenCL Platform Model shows the platform model comprising one host plus multiple compute devices, each having multiple compute units, each of which have multiple processing elements.

A host is any computer with a CPU running a standard operating system. OpenCL devices can be a GPU, DSP, or a multi-core CPU. An OpenCL device consists of a collection of one or more compute units (cores). A compute unit is further composed of one or more processing elements. Processing elements execute instructions as SIMD (Single Instruction, Multiple Data) or SPMD (Single Program, Multiple Data). SPMD instructions are typically executed on general purpose devices such as CPUs, while SIMD instructions require a vector processor such as a GPU or vector units in a CPU.

Figure 3–1 OpenCL Platform Model
The following depiction of the ATI Radeon™ HD 5870 GPU architecture illustrates a compute device construct. The ATI Radeon HD 5870 GPU is made up of 20 SIMD units, which translates to 20 compute units in OpenCL:

Each SIMD unit contains 16 stream cores, and each stream core houses five processing elements. Thus, each compute unit in the ATI Radeon HD 5870 has 80 (16 × 5) processing elements.
3.3.2 The Execution Model

The OpenCL execution model comprises two components: kernels and host programs. Kernels are the basic unit of executable code that runs on one or more OpenCL devices. Kernels are similar to a C function that can be data- or task-parallel. The host program executes on the host system, defines devices context, and queues kernel execution instances using command queues. Kernels are queued in-order, but can be executed in-order or out-of-order.

3.3.2.1 Kernels

OpenCL exploits parallel computation on compute devices by defining the problem into an N-dimensional index space. When a kernel is queued for execution by the host program, an index space is defined. Each independent element of execution in this index space is called a work-item. Each work-item executes the same kernel function but on different data. When a kernel command is placed into the command queue, an index space must be defined to let the device keep track of the total number of work-items that require execution. The N-dimensional index space can be $N=1$, $2$, or $3$. Processing a linear array of data would be considered $N=1$; processing an image would be $N=2$, and processing a 3D volume would be $N=3$.

Processing a 1024x1024 image would be handled this way: The global index space comprises a 2-dimensional space of 1024 by 1024 consisting of 1 kernel execution (or work-item) per pixel with a total of 1,048,576 total executions. Within this index space, each work-item is assigned a unique global ID. The work-item for pixel $x=30$, $y=22$ would have global ID of $(30,22)$.

OpenCL also allows grouping of work-items together into work-groups, as shown in the following figure. The size of each work-group is defined by its own local index space. All work-items in the same work-group are executed together on the same device.
device. The reason for executing on one device is to allow work-items to share local memory and synchronization. Global work-items are independent and cannot by synchronized. Synchronization is only allowed between the work-items in a work-group.

Figure 3–3  Grouping Work-items Into Work-groups

The following example shows a two-dimensional image with a global size of 1024 (32x32). The index space is divided into 16 work-groups. The highlighted work-group has an ID of (5,1) and a local size of 64 (8x8). The highlighted work-item in the work-group has a local ID of (4,2), but can also be addressed by its global ID of (28,10).

Figure 3–4  Work-group Example

dimension: 2
global size: 32x32=1024
num of groups: 16
The following example illustrates how a kernel in OpenCL is implemented. In this example, each element is squared in a linear array. Normally, a scalar function would be required with a simple for loop iterating through the elements in the array and then squaring it. The data-parallel approach is to read an element from the array in parallel, perform the operation in parallel, and write it to the output. Note that the code segment on the right does not have a for loop: It simply reads the index value for the particular kernel instance, performs the operation, and writes the output.

Table 3–1  Simple Example of Scalar Versus Parallel Implementation

<table>
<thead>
<tr>
<th>Scalar C Function</th>
<th>Data-Parallel Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>void square(int n, const float *a, float *result)</td>
<td>kernel void dp_square (global const float *a, global float *result)</td>
</tr>
<tr>
<td></td>
<td>{</td>
</tr>
<tr>
<td></td>
<td>int id= get_global_id(0);</td>
</tr>
<tr>
<td></td>
<td>result[id] = a[id]*a[id];</td>
</tr>
<tr>
<td></td>
<td>}</td>
</tr>
<tr>
<td></td>
<td>// dp_square execute over &quot;n&quot; work-items</td>
</tr>
</tbody>
</table>

The OpenCL execution model supports two categories of kernels: OpenCL kernels and native kernels.

OpenCL kernels are written in the OpenCL C language and compiled with the OpenCL compiler. All devices that are OpenCL-compliant support execution of OpenCL kernels.

Native kernels are extension kernels that could be special functions defined in application code or exported from a library designed for a particular accelerator. The OpenCL API includes functions to query capabilities of devices to determine if native kernels are supported.

If native kernels are used, developers should be aware that the code may not work on other OpenCL devices.

3.3.2.2 Host Program

The host program is responsible for setting up and managing the execution of kernels on the OpenCL device through the use of context. Using the OpenCL API, the host can create and manipulate the context by including the following resources:

- **Devices** — A set of OpenCL devices use by the host to execute kernels.
- **Program Objects** — The program source or program object that implements a kernel or collection of kernels.
- **Kernels** — The specific OpenCL functions that execute on the OpenCL device.
- **Memory Objects** — A set of memory buffers or memory maps common to the host and OpenCL devices.
After the context is created, command queues are created to manage execution of the kernels on the OpenCL devices that were associated with the context. Command queues accept three types of commands:

- **Kernel execution commands** run the kernel command on the OpenCL devices.
- **Memory commands** transfer memory objects between the memory space of the host and the memory space of the OpenCL devices.
- **Synchronization commands** define the order in which commands are executed.

Commands are placed into the command queue in-order and execute either in-order or out-of-order. In in-order mode, the commands are executed serially as they are placed onto the queue. In out-of-order mode, the order the commands execute is based on the synchronization constraints placed on the command.

### 3.3.3 The Memory Model

Since common memory address space is unavailable on the host and the OpenCL devices, the OpenCL memory model defines four regions of memory accessible to work-items when executing a kernel. The following figure shows the regions of memory accessible by the host and the compute device:
Global memory is a memory region in which all work-items and work-groups have read and write access on both the compute device and the host. This region of memory can be allocated only by the host during runtime.

Constant memory is a region of global memory that stays constant throughout the execution of the kernel. Work-items have only read access to this region. The host is permitted both read and write access.

Local memory is a region of memory used for data-sharing by work-items in a work-group. All work-items in the same work-group have both read and write access.

Private memory is a region that is accessible to only one work-item.

In most cases, host memory and compute device memory are independent of one another. Thus, memory management must be explicit to allow the sharing of data between the host and the compute device. This means that data must be explicitly moved from host memory to global memory to local memory and back. This process works by enqueuing read/write commands in the command queue. The commands placed into the queue can either be blocking or non-blocking. Blocking means that the host memory command waits until the memory transaction is complete before continuing. Non-blocking means the host simply puts the command in the queue and continues, not waiting until the memory transaction is complete.
Chapter 4

Getting Started with OpenCL

This chapter discusses how to set up the OpenCL development environment in the Microsoft® Windows® and Linux® platforms.

4.1 The Software Development Environment and Tools

4.1.1 Requirements

The ATI Stream Software Development Kit (SDK) v2 is required to create OpenCL applications on the AMD platform. The SDK for Windows or Linux may be downloaded free from the ATI Stream SDK v2 Product Page (http://developer.amd.com/stream).
At the time of publication of this guide, the following operating system, compilers, CPUs, GPUs, and drivers were supported by the ATI Stream SDK v2. For the latest list of supported configurations, check the ATI Stream SDK v2 Product Page.

### 4.1.1.1 Supported Operating Systems

<table>
<thead>
<tr>
<th>Platform</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>• Windows® XP SP3 (32-bit), SP2 (64-bit)</td>
</tr>
<tr>
<td></td>
<td>• Windows Vista® SP1 (32-bit)</td>
</tr>
<tr>
<td></td>
<td>• Windows® 7 (32/64-bit)</td>
</tr>
<tr>
<td>Linux</td>
<td>• openSUSE™ 11.1 (32/64-bit)</td>
</tr>
<tr>
<td></td>
<td>• Ubuntu® 9.10 (32/64-bit)</td>
</tr>
<tr>
<td></td>
<td>• Red Hat® Enterprise Linux 5.3 (32/64-bit)</td>
</tr>
</tbody>
</table>

### 4.1.1.2 Supported Compilers

<table>
<thead>
<tr>
<th>Platform</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Windows</td>
<td>• Microsoft Visual Studio 2008 Professional Edition</td>
</tr>
<tr>
<td>Linux</td>
<td>• GNU Compiler Collection (GCC) 4.5 or later</td>
</tr>
<tr>
<td></td>
<td>• Intel® C Compiler (ICC) 11.x</td>
</tr>
</tbody>
</table>
4.1.1.3 Supported GPUs and Drivers

Table 4–1 GPUs

<table>
<thead>
<tr>
<th>GPU Type</th>
<th>Models</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATI Radeon HD</td>
<td>5970, 5870, 5850, 5770, 5670, 5570, 5450, 4890, 4870 X2, 4870, 4850, 4830, 4770, 4670, 4650, 4550, 4550</td>
</tr>
<tr>
<td>ATI FirePro™</td>
<td>V8800, V8730, V8700, V7800, V7750</td>
</tr>
<tr>
<td></td>
<td>V5800, V5700, V4800, V3800, V3750</td>
</tr>
<tr>
<td>AMD FireStream™</td>
<td>9270, 9250</td>
</tr>
<tr>
<td>ATI Mobility Radeon™ HD</td>
<td>5870, 5850, 5830, 5770, 5730, 5670, 5650, 5470, 5450, 5430, 4870, 4860, 4850, 4830, 4670, 4650, 4500 series, 4300 series</td>
</tr>
<tr>
<td>ATI Mobility FirePro™</td>
<td>M7820, M7740, M5800</td>
</tr>
<tr>
<td>ATI Radeon Embedded</td>
<td>E4690 Discrete GPU</td>
</tr>
</tbody>
</table>

Table 4–2 Drivers (Minimum Version Requirements)

<table>
<thead>
<tr>
<th>GPU Type</th>
<th>Driver Version</th>
</tr>
</thead>
<tbody>
<tr>
<td>ATI Radeon HD</td>
<td>ATI Catalyst™ 10.4</td>
</tr>
<tr>
<td>ATI FirePro</td>
<td>ATI FirePro Unified Driver 8.723</td>
</tr>
<tr>
<td>AMD FireStream</td>
<td>ATI Catalyst 10.4</td>
</tr>
<tr>
<td>ATI Mobility Radeon HD</td>
<td>ATI Catalyst Mobility 10.4</td>
</tr>
<tr>
<td>ATI Mobility FirePro</td>
<td>Contact notebook manufacturer for appropriate driver.</td>
</tr>
<tr>
<td>ATI Radeon Embedded</td>
<td>Contact notebook manufacturer for appropriate driver.</td>
</tr>
</tbody>
</table>

4.1.1.4 Supported Processors

Any X86 CPU with Stream SIMD Extensions (SSE) 3.x or later.

4.1.2 Installing on Windows

Administrative access is required to install the ATI Stream SDK v2 on a Windows system.
To install, run the ATI Stream SDK v2 executable installation program and follow the instructions in the setup Wizard.
Selecting Express Installation (as shown in the following image) installs the ATI Stream SDK v2, sample code, and the ATI Stream Profiler.
During the installation the installer may analyze the system to detect the currently installed graphics hardware and software drivers. If either the graphics hardware or the software drivers do not support OpenCL, a warning popup may appear as shown in the following image.
4.1.3 Installing on Linux

Root permission is required to install the ATI Stream SDK v2 on Linux.

To install the downloaded ATI Stream SDK v2:

1. Untar the SDK to a location of your choice:
   
   ```
   tar -zxvf ati-stream-sdk-vX.XX-lnxYY.tgz
   
   where X.XX is the downloaded SDK version, and YY is either 32 or 64 (representing 32-bit or 64-bit).
   ```

2. Add `ATISTREAMSDKROOT` to your environment variables:
   
   ```
   export ATISTREAMSDKROOT=<location in which the SDK was extracted>
   ```

3. If the sample code was installed, add `ATISTREAMSDKSAMPLESROOT` to your environment variables:
   
   ```
   export ATISTREAMSDKSAMPLESROOT=<location in which the SDK was extracted>
   ```

4. Add the appropriate path to the `LD_LIBRARY_PATH`:
   
   On 32-bit systems:
   
   ```
   export LD_LIBRARY_PATH=$ATISTREAMSDKROOT/lib/x86:$LD_LIBRARY_PATH
   ```

   On 64-bit systems:
   
   ```
   export LD_LIBRARY_PATH=$ATISTREAMSDKROOT/lib/x86_64:$LD_LIBRARY_PATH
   ```

5. Register the OpenCL ICD to allow applications to run:
   
   ```
   sudo -s
   
   mkdir -p /etc/OpenCL/vendors
   
   On all systems:
   
   echo libatiocl32.so > /etc/OpenCL/vendors/atioc132.icd
   
   On 64-bit systems, also perform the following:
   
   echo libatiocl64.so > /etc/OpenCL/vendors/atioc164.icd
   ```
The following image shows the steps for installing the ATI Stream SDK v2 on a 32-bit Linux system:

4.2 "Hello World" in OpenCL

A typical OpenCL application starts by querying the system for the availability of OpenCL devices. When devices have been identified, a context allows the creation of command queues, creation of programs and kernels, management of memory between host and OpenCL devices, and submission of kernels for execution.

The following example code illustrates the fundamentals of all OpenCL applications. It takes an input buffer, squares the values, and stores the results in an output buffer, illustrating the relationship between device, context, program, kernel, command queue, and buffers.
#include <stdio.h>
#include "CL/cl.h"

#define DATA_SIZE 10

const char *KernelSource = 
  "__kernel void hello(__global float *input, __global float *output)\
  {
    size_t id = get_global_id(0);
    output[id] = input[id] * input[id];
  }"

int main(void)
{
    cl_context context;
    cl_context_properties properties[3];
    cl_kernel kernel;
    cl_command_queue command_queue;
    cl_program program;
    cl_int err;
    cl_uint num_of_platforms=0;
    cl_platform_id platform_id;
    cl_device_id device_id;
    cl_uint num_of_devices=0;
    cl_mem input, output;
    size_t global;
	h float inputData[DATA_SIZE]={1, 2, 3, 4, 5, 6, 7, 8, 9, 10};
	h float results[DATA_SIZE]={0};
    int i;

    // retreives a list of platforms available
    if (clGetPlatformIDs(1, &platform_id, &num_of_platforms)!= CL_SUCCESS)
    {
        printf("Unable to get platform_id\n");
        return 1;
    }

    // try to get a supported GPU device
    if (clGetDeviceIDs(platform_id, CL_DEVICE_TYPE_GPU, 1, &device_id, &num_of_devices) != CL_SUCCESS)
    {
        printf("Unable to get device_id\n");
        return 1;
    }

    // context properties list - must be terminated with 0
    properties[0]= CL_CONTEXT_PLATFORM;
    properties[1]= (cl_context_properties) platform_id;
    properties[2]= 0;

    // create a context with the GPU device
    context = clCreateContext(properties,1,&device_id,NULL,NULL,&err);

    // create command queue using the context and device
    command_queue = clCreateCommandQueue(context, device_id, 0, &err);

    // create a program from the kernel source code
4.3 Compiling OpenCL Source

Note: The ATI Stream SDK v2 must be installed to compile an OpenCL program. See 4.1.1 Requirements for detailed ATI Stream SDK v2 installation procedures.
4.3.1 Compiling on Linux

Ensure the required compiler GNU Compiler Collection (GCC) 4.3 or later is correctly installed. To compile the sample "Hello World" program described earlier in this guide, enter the following at the command line:

For a 32-bit system:

```
 gcc -o hello -I$ATISTREAMSDKROOT/include -L$ATISTREAMSDKROOT/lib/x86 hello.c -lOpenCL
```

For a 64-bit system:

```
 gcc -o hello -I$ATISTREAMSDKROOT/include -L$ATISTREAMSDKROOT/lib/x86_64 hello.c -lOpenCL
```

Where `ATISTREAMSDKROOT` environment points to the ATI Stream SDK v2 installation location.

To execute the program, ensure that the `LD_LIBRARY_PATH` environment variable is set to find `libOpenCL.so`, then enter:

```
./hello
```

The following image shows the sample program output:

![Sample Program Output](image)

4.3.2 Compiling on Windows

To compile using Microsoft Visual Studio® 2008 Professional Edition, the include path and library path to the ATI Stream SDK v2 must be configured in the project. Compilation steps are:
1. Open the project properties page in Visual Studio. On the C/C++ ➪ General page add $ATISTREAMSDKROOT\include to the Additional Include Directories list.
2. In the Linker ▶ General page, add $ATISTREAMSDKROOT\lib\x86
($ATISTREAMSDKROOT\lib\x86_64 for 64-bit systems) to the Additional Library
Directories list.
3. In the **Linker ▷ Input page**, add **OpenCL.lib** to the **Additional Dependencies** list.
Chapter 5

OpenCL Programming in Detail

This chapter describes the structure of an OpenCL program and the relationship between devices, context, programs, kernels, memory objects, and command queues.

5.1 Executing an OpenCL Program

The OpenCL framework is divided into a platform layer API and runtime API. The platform API allows applications to query for OpenCL devices and manage them through a context. The runtime API makes use of the context to manage the execution of kernels on OpenCL devices. The basic steps involved in creating any OpenCL program are shown in the following figure.

To execute an OpenCL program:

1. Query the host system for OpenCL devices.
2. Create a context to associate the OpenCL devices.
3. Create programs that will run on one or more associated devices.
4. From the programs, select kernels to execute.
5. Create memory objects on the host or on the device.
6. Copy memory data to the device as needed.
7. Provide arguments for the kernels.
8. Submit the kernels to the command queue for execution.
9. Copy the results from the device to the host.

5.2 Resource Setup

The section describes how to setup OpenCL resources such as querying for platform information, device information, creating context and command queue.

5.2.1 Query for Platform Information and OpenCL Devices

The first step in any OpenCL application is to query for platform information and OpenCL devices. The function `clGetPlatformIDs` can be used to retrieve a list of platforms available, as shown in the following code:

```c
cl_platform_id platforms;
cl_uint num_platforms;

// query for 1 available platform
cl_int err = clGetPlatformIDs(
    1,                        // the number of entries that can added to platforms
    &platforms,              // list of OpenCL found
    &num_platforms);        // the number of OpenCL platforms found
```

`clGetPlatformIDs` return values are:

- **CL_INVALID_VALUE** — Platforms and num_platforms is NULL or the number of entries is 0.
- **CL_SUCCESS** — The function executed successfully.

With the `platform_id` determined, the function `clGetPlatformInfo()` can be used to get specific information about the OpenCL platform, including `platform_profile`, `platform_version`, `platform_name`, `platform_vendor`, and `platform_extensions`.
5.2.2 Query for OpenCL Device

The function `clGetDeviceIDs()` can be used to search for compute devices in the system. The following code queries for a single GPU compute device:

```c
cl_device_id device_id;
cl_uint num_of_devices;
cl_int err;
err = clGetDeviceIDs(
    platform_id,          // the platform_id retrieved from clGetPlatformIDs
    CL_DEVICE_TYPE_GPU,   // the device type to search for
    1,                    // the number of id add to device_id list
    &device_id,           // the list of device ids
    &num_of_devices       // the number of compute devices found
);
```

`clGetDeviceIDs()` return values are:

- **CL_INVALID_PLATFORM** — Platform is not valid.
- **CL_INVALID_DEVICE_TYPE** — The device is not a valid value.
- **CL_INVALID_VALUE** — `num_of_devices` and devices are NULL.
- **CL_DEVICE_NOT_FOUND** — No matching OpenCL of `device_type` was found.
- **CL_SUCCESS** — The function executed successfully.

The example above shows how to query for one GPU device on which the code will be executed. If the host system physically contains two GPUs and it is determined that the program will execute more efficiently on the two GPUs, simply ask for two device IDs instead. We can restrict the query to different device types by passing the appropriate parameter to the `clGetDeviceIDs()` function. The valid values for `device_type` are shown in the table below. For example, to query for CPU devices, pass `CL_DEVICE_TYPE_CPU` as the `device_type` argument.
Table 5–1 List of device types supported by clGetDeviceIDs()

<table>
<thead>
<tr>
<th>Cl_device_type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_DEVICE_TYPE_CPU</td>
<td>An OpenCL device that is host processor. The host processor runs the OpenCL implementation and is a single or multi-core CPU.</td>
</tr>
<tr>
<td>CL_DEVICE_TYPE_GPU</td>
<td>An OpenCL device that is a GPU. The same device that can be also used to accelerate a 3D API such as OpenGL® or DirectX®.</td>
</tr>
<tr>
<td>CL_DEVICE_TYPE_ACCELERATOR</td>
<td>Dedicated OpenCL accelerators (such as IBM CELL Blade). These devices communicate with the host processor using a peripheral interconnect such as PCI or PCIe.</td>
</tr>
<tr>
<td>CL_DEVICE_TYPE_DEFAULT</td>
<td>The default OpenCL device in the system.</td>
</tr>
<tr>
<td>CL_DEVICE_TYPE_ALL</td>
<td>All OpenCL devices available in the system.</td>
</tr>
</tbody>
</table>

Similarly, specific capabilities can be retrieved on the compute device using the device_id returned from the query using the clGetDeviceInfo() function. Refer to the OpenCL Specification for a full list of capabilities that can be retrieved with the clGetDeviceInfo() function. The figure below shows capabilities of the ATI Radeon HD 4770 GPU using clGetDeviceInfo().
Figure 5–2  Device Capabilities of the ATI Radeon HD 4770 GPU

<table>
<thead>
<tr>
<th>Device Type:</th>
<th>CL DEVICE_TYPE_GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Device ID:</td>
<td>4098</td>
</tr>
<tr>
<td>Max compute units:</td>
<td>0</td>
</tr>
<tr>
<td>Max work items dimensions:</td>
<td>3</td>
</tr>
<tr>
<td>Max work items[0]:</td>
<td>256</td>
</tr>
<tr>
<td>Max work items[1]:</td>
<td>256</td>
</tr>
<tr>
<td>Max work items[2]:</td>
<td>256</td>
</tr>
<tr>
<td>Max work group size:</td>
<td>256</td>
</tr>
<tr>
<td>Preferred vector width char:</td>
<td>16</td>
</tr>
<tr>
<td>Preferred vector width short:</td>
<td>8</td>
</tr>
<tr>
<td>Preferred vector width int:</td>
<td>4</td>
</tr>
<tr>
<td>Preferred vector width long:</td>
<td>2</td>
</tr>
<tr>
<td>Preferred vector width float:</td>
<td>4</td>
</tr>
<tr>
<td>Preferred vector width double:</td>
<td>0</td>
</tr>
<tr>
<td>Max clock frequency:</td>
<td>750MHz</td>
</tr>
<tr>
<td>Address bits:</td>
<td>32</td>
</tr>
<tr>
<td>Max memory allocation:</td>
<td>134217728</td>
</tr>
<tr>
<td>Image support:</td>
<td>No</td>
</tr>
<tr>
<td>Max size of kernel argument:</td>
<td>16924</td>
</tr>
<tr>
<td>Alignment (bits) of base address:</td>
<td>4096</td>
</tr>
<tr>
<td>Minimum alignment (bytes) for any datatype:</td>
<td>128</td>
</tr>
<tr>
<td>Single precision floating point capability:</td>
<td>No</td>
</tr>
<tr>
<td>Denorms:</td>
<td>No</td>
</tr>
<tr>
<td>Quiet Nans:</td>
<td>Yes</td>
</tr>
<tr>
<td>Round to nearest even:</td>
<td>Yes</td>
</tr>
<tr>
<td>Round to zero:</td>
<td>No</td>
</tr>
<tr>
<td>Round to plus and infinity:</td>
<td>No</td>
</tr>
<tr>
<td>IEEE754-2008 fused multiply-add:</td>
<td>No</td>
</tr>
<tr>
<td>Cache Type:</td>
<td>None</td>
</tr>
<tr>
<td>Cache line size:</td>
<td>0</td>
</tr>
<tr>
<td>Cache size:</td>
<td>0</td>
</tr>
<tr>
<td>Global memory size:</td>
<td>134217728</td>
</tr>
<tr>
<td>Constant buffer size:</td>
<td>65536</td>
</tr>
<tr>
<td>Max number of constant args:</td>
<td>8</td>
</tr>
<tr>
<td>Local memory type:</td>
<td>Global</td>
</tr>
<tr>
<td>Local memory size:</td>
<td>16384</td>
</tr>
<tr>
<td>Profiling timer resolution:</td>
<td>1</td>
</tr>
<tr>
<td>Device endianness:</td>
<td>Little</td>
</tr>
<tr>
<td>Available:</td>
<td>Yes</td>
</tr>
<tr>
<td>Compiler available:</td>
<td>Yes</td>
</tr>
<tr>
<td>Execution capabilities:</td>
<td>Execute OpenCL kernels:</td>
</tr>
<tr>
<td>Execute native function:</td>
<td>No</td>
</tr>
<tr>
<td>Queue properties:</td>
<td>Out-of-Order:</td>
</tr>
<tr>
<td>Profiling:</td>
<td>Yes</td>
</tr>
<tr>
<td>Platform ID:</td>
<td>0x87e00488</td>
</tr>
<tr>
<td>Name:</td>
<td>ATI RV770</td>
</tr>
<tr>
<td>Vendor:</td>
<td>Advanced Micro Devices, Inc.</td>
</tr>
<tr>
<td>Driver version:</td>
<td>CAL 1.4.519</td>
</tr>
<tr>
<td>Profile:</td>
<td>FULL PROFILE</td>
</tr>
<tr>
<td>Version:</td>
<td>OpenCL 1.0 ATI-Stream-v2.0.1</td>
</tr>
<tr>
<td>Extensions:</td>
<td>cl_khr_1cd</td>
</tr>
</tbody>
</table>

Note: In early releases of the ATI Stream SDK v2, the clGetDeviceIDs() function allowed platform_id to be NULL. This is no longer supported.

5.2.3 Creating a Context

Once the compute devices and their corresponding device_id(s) have been identified, the device_id(s) can be associated with a context. The context is used by the OpenCL runtime API to manage command queues, program objects, kernel objects, and the sharing of memory objects for the compute devices associated with the context. clCreateContext() is used to create a context, as shown in the following code:
cl_context context;

// context properties list - must be terminated with 0
properties[0] = CL_CONTEXT_PLATFORM; // specifies the platform to use
properties[1] = (cl_context_properties) platform_id;
properties[2] = 0;

context = clCreateContext(
properties,      // list of context properties
1,               // num of devices in the device_id list
&device_id,      // the device id list
NULL,            // pointer to the error callback function (if required)
NULL,            // the argument data to pass to the callback function
&err             // the return code
);

The context properties list is made up of a property name followed immediately by a
property value. The list must be terminated with a 0 (zero). Supported properties are:

<table>
<thead>
<tr>
<th>cl_context_properties_enum</th>
<th>Property Value</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_CONTEXT_PLATFORM</td>
<td>cl_platform_id</td>
<td>Specifies the platform to use</td>
</tr>
</tbody>
</table>

OpenCL allows an optional error callback function to be registered by the application
to report on errors that occur within the context during runtime. OpenCL may call the
error callback function asynchronously. It is, therefore, the application's
responsibility to ensure the callback function is thread-safe.

If the context is created successfully, clCreateContext() returns a non-zero context
with an error return code value of CL_SUCCESS. Otherwise, a NULL value is returned
and one of the following error codes:

- **CL_INVALID_PLATFORM** — The property list is NULL or the platform value is
  not valid.
- **CL_INVALID_VALUE** — Either:
  - The property name in the properties list is not valid.
  - The number of devices is 0.
  - The device_id list is null.
  - The device in the device_id list is invalid or not associated with the
    platform.
- **CL_DEVICE_NOT_AVAILABLE** — The device in the device_id list is currently
  unavailable.
- **CL_OUT_OF_HOST_MEMORY** — The host is unable to allocate OpenCL
  resources.
5.2.4 Creating the Command Queue

When the context is established, command queues can be created that allow commands to be sent to the compute devices associated with the context. Commands are placed into the command queue in order. `clCreateCommandQueue()` is used to create a command queue, as shown in the following code:

```c
cl_command_queue command_queue;

command_queue = clCreateCommandQueue(
    context,   // a valid context
    device_id, // a valid device associated with the context
    0,         // properties for the queue - not used here
    &err       // the return code
);
```

The context that is passed in must be a valid OpenCL context. If the context has multiple compute devices associated with it, you must choose which device to use by specifying the `device_id`. Thus, if the context contains a CPU and a GPU device type, two separate command queues must be created and work sent to the separate queues.

The third parameter, the command queue properties list, is a bit-field:

<table>
<thead>
<tr>
<th>Command Queue Properties</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_QUEUE_OUT_OF_ORDER_EXEC_MODE_ENABLE</td>
<td>If set, commands in the command queue are executed out of order. Otherwise, commands are executed in order.</td>
</tr>
<tr>
<td>CL_QUEUE_PROFILING_ENABLE</td>
<td>If set, profiling of commands in the command queue is enabled. Otherwise, profiling is disabled.</td>
</tr>
</tbody>
</table>

If the command queue is successfully created, `clCreateCommandQueue()` returns a non-zero command queue with an error return code value of `CL_SUCCESS`. Otherwise, a NULL value is returned with one of the following error codes:

- **CL_INVALID_CONTEXT** — The context is not valid.
- **CL_INVALID_DEVICE** — Either the device is not valid or it is not associated with the context.
- **CL_INVALID_VALUE** — The properties list is not valid.
- **CL_INVALID_QUEUE_PROPERTIES** — The device does not support the properties specified in the properties list.
- **CL_OUT_OF_HOST_MEMORY** — The host is unable to allocate OpenCL resources.

5.3 Kernel Programming and Compiling

The previous section described the steps in setting up the resources before any work can be performed on compute devices. In this section, OpenCL program and kernel
5.3.1 Creating the Program Object

An OpenCL program is made up of a collection of kernel functions. Kernel functions are written using the OpenCL C language and is compiled by the OpenCL runtime for execution on a particular compute device. The kernel function in a program is identified by the qualifier `__kernel` in the program source. The program source may also contain helper functions and data constants used by the `__kernel` functions.

A program object in OpenCL encapsulates the program sources or a binary file, the latest successfully-built program executable, the list of devices for which the executable is built, along with any build options and a build log. The program object can be created either online or offline. To create a program object online (or from source code) the `clCreateProgramWithSource()` function is used as shown in the following example:

```c
const char *ProgramSource =
  "__kernel void hello(__global float *input, __global float *output)\n"\n  "{\n  \n  size_t id = get_global_id(0);\n  \n  output[id] = input[id] * input[id];\n}\n";

cl_program program;
program = clCreateProgramWithSource(
        context,           // a valid context
        1,                   // the number strings in the next parameter
        (const char **) &ProgramSource, // the array of strings
        NULL,               // the length of each string or can be NULL terminated
        &err               // the error return code
    );
```

In the example, the program source is included as an array of strings. If the program source is in a separate file, you must read the source file into a string and pass it to the `clCreateProgramWithSource()` function. If multiple source files are to be read, an array of NULL-terminated strings are used and the `clCreateProgramWithSource()` function is informed about how many strings are in the array. In the list above, the `ProgramSource` array contains only one NULL-terminated string.

If the program object is successfully created, `clCreateProgramWithSource()` returns a non-zero program object with an error return code value of `CL_SUCCESS`. Otherwise, a NULL value is returned with one of the following error return code values:

- `CL_INVALID_CONTEXT` — The context is not valid.
- `CL_INVALID_VALUE` — The string count is 0 (zero) or the string array contains a NULL string.
- `CL_OUT_OF_HOST_MEMORY` — The host is unable to allocate OpenCL resources.

At this point a program object is ready for compilation and linking before it can be executed on the compute device. With the program object created, the function
clGetProgramInfo() is used to query specific info regarding the program object. One of the parameters that can be extracted is the program binary reference. Using this reference brings a significant reduction in initialization time in subsequent executions because the program need not be recreated.

The function clCreateProgramWithBinary() can be used to create a program object by referencing the program binary. For more information on clGetProgramInfo() and clCreateProgramWithBinary(), see the OpenCL language specification.

5.3.2 Building Program Executables

After the program object is created (either from source using clCreateProgramWithSource() or binary using clCreateProgramWithBinary()), the next step is to compile and link the program object. The program executable can be built for one or more devices that are encapsulated by the program object. The function clBuildProgram() is used to build the executable:

```c
err = clBuildProgram(
    program, // a valid program object
    0,       // number of devices in the device list
    NULL,    // device list - NULL means for all devices
    NULL,    // a string of build options
    NULL,    // callback function when executable has been built
    NULL     // data arguments for the callback function
);
```

The clBuildProgram() function modifies the program object to include the executable, the build log, and build options. The build option string allows the passing of any additional options to the compiler such as preprocessor options, optimization options, math intrinsic options, and other miscellaneous compiler options. The following example defines GPU_DUAL_ENABLED and disables all optimizations:

```c
char * buildoptions = "-DGPU_DUAL_ENABLED -cl-opt-disable ";
```

For a complete list of supported options, see the Build Options section of the OpenCL language specification.

clBuildProgram() returns CL_SUCCESS if the compilation is successful. Otherwise, the following are common error codes that may be returned by clBuildProgram():

- **CL_INVALID_VALUE** — The number of devices is greater than zero, but the device list is empty.
- **CL_INVALID_VALUE** — The callback function is NULL, but the data argument list is not NULL.
- **CL_INVALID_DEVICE** — The device list does not match the devices associated in the program object.
- **CL_INVALID_BUILD_OPTIONS** — The build options string contains invalid options.
- **CL_OUT_OF_HOST_MEMORY** — The host is unable to allocate OpenCL resources.
For a complete list of return codes for `clBuildProgram()`, see the OpenCL specification.

When compiling source code for any language, compilation errors can occur. In OpenCL, the program object contains the build log. To access the build log, the OpenCL API provides the `clGetBuildProgramInfo()` function to retrieve the latest compilation results embedded in the program object:

```c
if (clBuildProgram(program, 0, NULL, buildoptions, NULL, NULL) != CL_SUCCESS) {
    printf("Error building program\n");
    char buffer[4096];
    size_t length;
    clGetProgramBuildInfo(
        program,              // valid program object
        device_id,            // valid device_id that executable was built
        CL_PROGRAM_BUILD_LOG, // indicate to retrieve build log
        sizeof(buffer),       // size of the buffer to write log to
        buffer,               // the actual buffer to write log to
        &length               // the actual size in bytes of data copied to buffer
    );
    printf("%s\n",buffer);
    exit(1);
}
```

Figure 5–3  Sample Build Log Output

5.3.3 Creating Kernel Objects

The kernel object is created after the executable has been successfully built in the program object. As mentioned earlier, kernel functions are declared with the qualifier `__kernel` in the program object. A kernel object is an encapsulation of the specify `__kernel` function along with the arguments that are associated with the `__kernel`
function when executed. The kernel object is eventually sent to the command queue for execution. The function `clCreateKernel()` is used to create kernel objects:

```c
cl_kernel kernel;
kernal = clCreateKernel(
    program, // a valid program object that has been successfully built
    "hello",  // the name of the kernel declared with __kernel
    &err    // error return code
);
```

If the kernel object is created successfully, `clCreateKernel()` returns a non-zero kernel object with an error return code value of CL_SUCCESS. Otherwise, a NULL value is returned and the error return code will have one of the following values set:

- **CL_INVALID_PROGRAM** — The program is not a valid program object.
- **CL_INVALID_PROGRAM_EXECUTABLE** — The program does not contain a successfully built executable.
- **CL_INVALID_KERNEL_NAME** — The kernel name is not found in the program object.
- **CL_INVALID_VALUE** — The kernel name is NULL.
- **CL_OUT_OF_HOST_MEMORY** — The host is unable to allocate OpenCL resources.

Before the kernel object is submitted to the command queue for execution, input or output buffers must be provided for any arguments required by the `__kernel` function. If the arguments use memory objects such as a buffer or image, the memory objects must be created first and the data must be explicitly copied into the memory object. See 5.5 Memory Objects for instructions on creating memory object data.

### 5.3.4 Setting Kernel Arguments

When the required memory objects have been successfully created, kernel arguments can be set using the `clSetKernelArg()` function:

```c
err = clSetKernelArg(
    kernel,          // valid kernel object
    0,               // the specific argument index of a kernel
    sizeof(cl_mem),  // the size of the argument data
    &input_data      // a pointer of data used as the argument
);
```

The argument index refers to the specific argument position of the `__kernel` definition that must be set. The position can be 0 (zero) or greater. The following example shows the declaration of the `__kernel` function:

```c
__kernel void hello(__global float *input,
                    __global float *output)
```
In this example, the input argument is index 0, and the output argument is index 1. The last two arguments of `clSetKernelArg()` specify the size of the argument data and the pointer to the actual data.

**Note:** If a `__kernel` function argument is declared to be a pointer of a built-in or user defined type with the `__global` or `__constant` qualifier, a buffer memory object must be used. If the argument is an `image2d_t` or `image3d_t`, the memory object specified as the argument in `clSetKernelArg` must be a 2D image or 3D image object, respectively. Refer to the OpenCL Specification for more information on `clSetKernelArg()`.

If the function is executed successfully, `clSetKernelArg()` returns CL_SUCCESS. Otherwise, the follow are some common error codes returned by `clSetKernelArg()`:

- **CL_INVALID_KERNEL** — The kernel is not a valid kernel object.
- **CL_INVALID_ARG_INDEX** — The index value is not a valid argument index.
- **CL_INVALID_MEMORY_OBJECT** — The argument is declared as a memory object, but the argument value is not a valid memory object.
- **CL_INVALID_ARG_SIZE** — The argument size does not match the size of the data type of the declared argument.

OpenCL provides the helper function `clGetKernelInfo()` to allow the application to query specific information about a kernel object:

```c
cl_int clGetKernelInfo (  
    cl_kernel kernel,            // valid kernel object  
    cl_kernel_info param_name,   // the information to query (see below)  
    size_t param_value_size,     // size of the mem buffer to hold the result  
    void *param_value,           // pointer to mem where result of query is returned  
    size_t *param_value_size_ret // actual size of data copied to param_value
)
```

The supported kernel information that can be queried is shown in the following table:

<table>
<thead>
<tr>
<th>cl_kernel_info</th>
<th>Return Type</th>
<th>Data Returned to param_value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_KERNEL_FUNCTION_NAME</td>
<td>char[]</td>
<td>Name of the kernel function</td>
</tr>
<tr>
<td>CL_KERNEL_NUM_ARGS</td>
<td>cl_uint</td>
<td>Number of arguments in the kernel function</td>
</tr>
<tr>
<td>CL_KERNEL_REFERENCE_COUNT</td>
<td>cl_uint</td>
<td>Number of kernel reference count</td>
</tr>
<tr>
<td>CL_KERNEL_CONTEXT</td>
<td>cl_context</td>
<td>The context associated with the kernel</td>
</tr>
<tr>
<td>CL_KERNEL_PROGRAM</td>
<td>cl_program</td>
<td>The program object associated with the kernel</td>
</tr>
</tbody>
</table>
5.4 Program Execution

5.4.1 Determining the Problem Space

As mentioned in 3.3.2 The Execution Model, each kernel execution in OpenCL is called a work-item. OpenCL exploits parallel computation of the compute devices by having instances of the kernel execute on different portions of the N-dimensional problem space. In addition, each work-item is executed only with its assigned data. Thus, it is important to specify to OpenCL how many work-items are needed to process all data.

Before the work-items total can be determined, the N-dimension to be used to represent the data must be determined. For example, a linear array of data would be a one-dimensional problem space, while an image would be a two-dimensional problem space, and spatial data, such as a 3D object, would be a three-dimensional problem space.

When the dimension space is determined, the total work-items (also called the global work size) can be calculated. For a one-dimensional data set, the global work size is simply the size of the data. For two-dimensional data—such as an image—the global
work size is calculated by the data's width*height pixel count. For a three-dimensional object with positional data, the global data size is \( x \times y \times z \).

OpenCL allows work-items to be combined into work-groups, and all work-items within a work-group are executed on the same compute unit on the same compute device. When a work-group size is specified, OpenCL divides the global work size among the compute units on the device. In addition, work-items within a work-group execute synchronously and are able to share memory. The total number of work-items in a work-group is known as the local work size. Group sizes cannot be assigned arbitrarily; the provided OpenCL function `clGetKernelWorkGroupInfo()` must be used to query the group size info of a device. For more information on `clGetKernelWorkGroupInfo()`, consult the OpenCL specification.

When the work-items for each dimension and the group size (local work size) is determined, the kernel can be sent to the command queue for execution. To enqueue the kernel to execute on a device, use the function `clEnqueueNDRangeKernel()`:

```c
err = clEnqueueNDRangeKernel(
    command_queue, // valid command queue
    kernel,        // valid kernel object
    1,             // the work problem dimensions
    NULL,          // reserved for future revision - must be NULL
    &global,       // work-items for each dimension
    NULL,          // work-group size for each dimension
    0,             // number of event in the event list
    NULL,          // list of events that needs to complete before this executes
    NULL           // event object to return on completion
);
```

The work problem dimensions (the third argument) must be 1, 2, or 3. The fifth argument specifies the work-item size for each dimension. If, for example an image of 512x512 pixels is to be processed, an array must be provided that points to the number of work-item for each dimension:

```c
size_t global[2]={512,512};
```

The sixth argument describes the number of work-items that make up a work-group. If, for example, 64 work-items were grouped into an 8x8 work-group, the work-group size for each dimension would be specified as the following array:

```c
size_t local[2]={8,8};
```

The total work-items in each work group must be less than the maximum work group size retrieved using the function `clGetKernelWorkGroupInfo()`. If data does not need to be shared among work-items, a NULL value may be specified and the global work-items are broken into appropriate work-group instances by the OpenCL runtime.

The seventh and eighth arguments control the sequence of execution of the kernel command. As mentioned earlier, if the command queue properties are set to allow out-of-order execution during the `clCreateCommandQueue()` process, a list of events must be provided, along with the number of events in the list that need to complete before this particular command can be executed. If the event list is empty, then the number of events must be 0 (zero).
The last argument allows the kernel instance to generate an event on completion. This lets other kernel commands to wait for completion of this command as well as allowing querying of the kernel execution. See 5.6 Synchronization section for more information on this event.

If the function executes successfully, `clEnqueueNDRangeKernel()` returns `CL_SUCCESS`. Otherwise, the following common error codes may be returned:

- **CL_INVALID_PROGRAM_EXECUTABLE** — No executable has been built in the program object for the device associated with the command queue.
- **CL_INVALID_COMMAND_QUEUE** — The command queue is not valid.
- **CL_INVALID_KERNEL** — The kernel object is not valid.
- **CL_INVALID_CONTEXT** — The command queue and kernel are not associated with the same context.
- **CL_INVALID_KERNEL_ARGS** — Kernel arguments have not been set.
- **CL_INVALID_WORK_DIMENSION** — The dimension is not between 1 and 3.
- **CL_INVALID_GLOBAL_WORK_SIZE** — The global work size is NULL or exceeds the range supported by the compute device.
- **CL_INVALID_WORK_GROUP_SIZE** — The local work size is not evenly divisible with the global work size or the value specified exceeds the range supported by the compute device.
- **CL_INVALID_GLOBAL_OFFSET** — The reserved global offset parameter is not set to NULL.
- **CL_INVALID_EVENT_WAIT_LIST** — The events list is empty (NULL) but the number of events arguments is greater than 0; or number of events is 0 but the event list is not NULL; or the events list contains invalid event objects.
- **CL_OUT_OF_HOST_MEMORY** — The host is unable to allocate OpenCL resources.

Refer to the OpenCL Specification for a more comprehensive list of error return codes.

When the kernel command is enqueued for execution, additional kernels can be sent to the command queue, or the results can be copied back from the device to host memory. See 5.5 Memory Objects for a description of how to read data from memory objects.

### 5.4.2 Cleaning Up

When execution is complete, all OpenCL platform and runtime API resources, including memory objects, kernel, program, command queue, etc., should be released:
clReleaseMemObject(input);
ciReleaseMemObject(output);
ciReleaseProgram(program);
ciReleaseKernel(kernel);
ciReleaseCommandQueue(command_queue);
ciReleaseContext(context);

All `clRelease<object>()` functions decrement and return a reference count to the object. If all resources are correctly released, the reference count should be zero. Otherwise, the returned reference counts can be used to track down memory leaks.

## 5.5 Memory Objects

The OpenCL framework provides a way to package data into a memory object. By using a memory object, OpenCL allows easy packaging of all data and easy transfer to the compute device memory so that the kernel function executing on the device has local access to the data.

Using a memory object minimizes memory transfers from the host and device as the kernel processes data. OpenCL memory objects are categorized into two types: buffer objects and image objects. The buffer object is used to store one-dimensional data such as an `int`, `float`, `vector`, or a user-defined structure. The image object is used to store two- or three-dimensional data such as textures or images.

### 5.5.1 Creating Buffer Objects

To use the `clCreateBuffer()` function to create a buffer object:

```c
cl_mem input;
inpu = clCreateBuffer(
        context,    // a valid context
        CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR, // bit-field flag to specify
        sizeof(float) * DATA_SIZE, // size in bytes of the buffer to allocated
        inputsrc, // pointer to buffer data to be copied from host
        &err     // returned error code
);
```

The bit-field flag is used to specify allocation and define how the memory is used. The following table describes the supported values for the flag.
Table 5–2  Supported Cl_MEM Flags

<table>
<thead>
<tr>
<th>Cl_MEM Flags</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_MEM_READ_WRITE</td>
<td>Kernel can read and write to the memory object.</td>
</tr>
<tr>
<td>CL_MEM_WRITE_ONLY</td>
<td>Kernel can write to memory object. Read from the memory object is undefined.</td>
</tr>
<tr>
<td>CL_MEM_READ_ONLY</td>
<td>Kernel can only read from the memory object. Write from the memory object is undefined.</td>
</tr>
<tr>
<td>CL_MEM_USE_HOST_PTR</td>
<td>Specifies to OpenCL implementation to use memory reference by host_ptr (4th arg) as storage for memory object.</td>
</tr>
<tr>
<td>CL_MEM_COPY_HOST_PTR</td>
<td>Specifies to OpenCL to allocate the memory and copy data pointed by host_ptr (4th arg) to the memory object.</td>
</tr>
<tr>
<td>CL_MEM_ALLOC_HOST_PTR</td>
<td>Specifies to OpenCL to allocate memory from host accessible memory.</td>
</tr>
</tbody>
</table>

If the buffer object is created successfully, clCreateBuffer() returns a non-zero buffer object with an error return code value of CL_SUCCESS. Otherwise, a NULL value is returned with one of the following error codes:

- **CL_INVALID_CONTEXT** — The context is not valid.
- **CL_INVALID_VALUE** — The value in cl_mem_flag is not valid (see table above for supported flags).
- **CL_INVALID_BUFFER_SIZE** — The buffer size is 0 (zero) or exceeds the range supported by the compute devices associated with the context.
- **CL_INVALID_HOST_PTR** — Either: The host_ptr is NULL, but CL_MEM_USE_HOST_PTR, CL_MEM_COPY_HOST_PTR, and CL_MEM_ALLOC_HOST_PTR are set; or host_ptr is not NULL, but the CL_MEM_USE_HOST_PTR, CL_MEM_COPY_HOST_PTR, and CL_MEM_ALLOC_HOST_PTR are not set.
- **CL_INVALID_OBJECT_ALLOCATION_FAILURE** — Unable to allocate memory for the memory object.
- **CL_OUT_OF_HOST_MEMORY** — The host is unable to allocate OpenCL resources.

5.5.2 Reading, Writing, and Copying Buffer Objects

After the buffer memory object is created, commands can be enqueued to write data to a buffer object from host memory or read data from a buffer object to host memory. OpenCL provides the clEnqueueWriteBuffer() and clEnqueueReadBuffer() functions for these purposes.
err = clEnqueueReadBuffer(
    command_queue,  // valid command queue
    output,         // memory buffer to read from
    CL_TRUE,        // indicate blocking read
    0,              // the offset in the buffer object to read from
    sizeof(float) * DATA_SIZE, // size in bytes of data being read
    results,        // pointer to buffer in host mem to store read data
    0,              // number of event in the event list
    NULL,           // list of events that needs to complete before this executes
    NULL            // event object to return on completion
);

clEnqueueReadBuffer() enqueues a command to read data from a buffer object into host memory. This function is typically used to read the results from the kernel execution back to the host program. The CL_TRUE parameter indicates that the read command is blocked until the buffer data is completely copied into host memory. If the blocking parameter is set to CL_FALSE, the read command is returned as soon as it's enqueued. Another way to determine when the read command has finished copying data to the host memory is to use an event object that is returned by the read command and can be used to check on the execution status.

err = clEnqueueWriteBuffer(
    command_queue,  // valid command queue
    input,          // memory buffer object to write to
    CL_TRUE,        // indicate blocking write
    0,              // the offset in the buffer object to write to
    sizeof(float) * DATA_SIZE, // size in bytes of data to write
    host_ptr,       // pointer to buffer in host mem to read data from
    0,              // number of event in the event list
    NULL,           // list of events that needs to complete before this executes
    NULL            // event object to return on completion
);

clEnqueueWriteBuffer() enqueues a command to write data from host memory to a buffer object. This function is typically used to provide data for the kernel for processing. Similar to clEnqueueReadBuffer(), the block flag can be set to CL_TRUE or CL_FALSE to indicate blocking or non-blocking for the write command.

If the functions execute successfully, clEnqueueReadBuffer() and clEnqueueWriteBuffer() return CL_SUCCESS. Otherwise, one of the following common error codes may be returned:

- **CL_INVALID_COMMAND_QUEUE** — The command queue is not valid
- **CL_INVALID_CONTEXT** — The command queue buffer object is not associated with the same context.
- **CL_INVALID_VALUE** — The region being read/write specified by the offset is out of bounds or the host pointer is NULL.
- **CL_INVALID_EVENT_WAIT_LIST** — Either: The events list is empty (NULL), but the number of events argument is greater than 0; or number of events is 0, but the event list is not NULL; or the events list contains invalid event objects.
- **CL_OUT_OF_HOST_MEMORY** — The host is unable to allocate OpenCL resources.
The function `clEnqueueCopyBuffer()` can be used to copy data from one memory buffer object to another. For more information on the `clEnqueueCopyBuffer()` function, see the OpenCL specification.

### 5.5.3 Retaining and Releasing Buffer Objects

Whenever a memory buffer object is created the reference counter for that object is set to 1. The reference counter is used to track how many objects have references to a particular buffer object. At any time, other object can retain a reference to the buffer object by calling `clRetainMemObject()`. This increases the buffer object's reference count by 1. When the memory buffer object is no longer needed, the `clReleaseMemObj()` function can be used to decrement the reference counter by 1. When the reference counter becomes zero, the memory object is freed.

`clRetainMemObject()` and `clReleaseMemObj()` return CL_SUCCESS if the function executes successfully. Otherwise, CL_INVALID_MEM_OBJECT is returned if the buffer object is not a valid memory object.

### 5.5.4 Creating Image Objects

OpenCL has built-in support for representing image data in a wide range of formats. This is useful when creating kernel functions that must perform processing on image data. The function `clCreateImage2D()` is used to create a two-dimensional image object.

```c
image2d = clCreateImage2D(
    context,      // valid context
    flags,        // bit-field flag to specify usage of memory
    image_format, // ptr to struct that specifies image format properties
    width,        // width of the image in pixels
    height,       // height of the image in pixels
    row_pitch,    // scan line row pitch in bytes
    host_ptr,     // pointer to image data to be copied from host
    &err          // error return code
);```

Options such as read-only, write-only, read-write, etc., that are used by `clCreateBuffer()` can also be used by `clCreateImage2D()`. For details, see Table 5-2 Supported CL_MEM Flags.

The row-pitch is the number of bytes necessary to represent one line of the image. Row-pitch is calculated as width × size of each element in bytes. If the row-pitch is set to 0, the OpenCL implementation will perform the row-pitch calculation.

The image format is a structure that describes the properties such as number of channels and channel ordering in the image:
typedef struct _cl_image_format {
    cl_channel_order image_channel_order;
    cl_channel_type  image_channel_data_type;
} cl_image_format;

Supported channel data order settings are listed in the following table.

Table 5–3 Supported Channel Data Order

<table>
<thead>
<tr>
<th>channel data order</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_R or CL_A</td>
<td></td>
</tr>
<tr>
<td>CL_INTENSITY</td>
<td>Supported only if channel data type = CL_UNORM_INT8, CL_UNORM_INT16,</td>
</tr>
<tr>
<td></td>
<td>CL_SNORM_INT8, CL_SNORM_INT16, CL_HALF_FLOAT, or CL_FLOAT.</td>
</tr>
<tr>
<td>CL_LUMINANCE</td>
<td>Supported only if channel data type = CL_UNORM_INT8, CL_UNORM_INT16,</td>
</tr>
<tr>
<td></td>
<td>CL_SNORM_INT8, CL_SNORM_INT16, CL_HALF_FLOAT, or CL_FLOAT.</td>
</tr>
<tr>
<td>CL_RG or CL_RA</td>
<td></td>
</tr>
<tr>
<td>CL_RGB</td>
<td>Supported only if channel data type = CL_UNORM_SHORT_565, CL_UNORM_SHORT_555, or</td>
</tr>
<tr>
<td></td>
<td>CL_UNORM_INT_101010</td>
</tr>
<tr>
<td>CL_RGBA</td>
<td></td>
</tr>
<tr>
<td>CL_ARGB or CL_BGRA</td>
<td>Supported if channel data type = CL_UNORM_INT8, CL_SNORM_INT8,</td>
</tr>
<tr>
<td></td>
<td>CL_SIGNED_INT8, or CL_UNSIGNED_INT8</td>
</tr>
</tbody>
</table>

The channel data type specifies the size of the channel data type, as listed in the following table:

Table 5–4 Supported Channel Data Types

<table>
<thead>
<tr>
<th>channel data type</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_SNORM_INT8</td>
<td>Each channel is a signed normalized 8-bit integer.</td>
</tr>
<tr>
<td>CL_SNORM_INT16</td>
<td>Each channel is a signed normalized 16-bit integer.</td>
</tr>
<tr>
<td>CL_UNORM_INT8</td>
<td>Each channel is a unsigned normalized 8-bit integer.</td>
</tr>
<tr>
<td>CL_UNORM_INT16</td>
<td>Each channel is a unsigned normalized 16-bit integer.</td>
</tr>
<tr>
<td>CL_UNORM_SHORT_565</td>
<td>3-channel RGB image packed into a single unsigned short of 5-6-5. Bits 15:11=R, 10:5=G, 4:0=B. The channel order must be set to CL_RGB.</td>
</tr>
<tr>
<td>CL_UNORM_SHORT_555</td>
<td>3-channel RGB image packed into a single unsigned short of 5-5-5. Bits 14:10=R, 9:5=G, 4:0=B. The channel order must be set to CL_RGB. The channel order must be set to CL_RGB.</td>
</tr>
<tr>
<td>CL_UNORM_INT_101010</td>
<td>5-channel RGB image packed into a single unsigned int of 10-10-10. Bits 31:30=undefined, 29:20=R, 19:10=G, 9:0=B. The channel order must be set to CL_RGB.</td>
</tr>
<tr>
<td>CL_SIGNED_INT8</td>
<td>Each channel is signed unnormalized 8-bit integer.</td>
</tr>
<tr>
<td>CL_SIGNED_INT16</td>
<td>Each channel is signed unnormalized 16-bit integer.</td>
</tr>
<tr>
<td>CL_SIGNED_INT32</td>
<td>Each channel is signed unnormalized 32-bit integer.</td>
</tr>
<tr>
<td>CL_UNSIGNED_INT8</td>
<td>Each channel is unsigned unnormalized 8-bit integer.</td>
</tr>
<tr>
<td>channel_data_type</td>
<td>Description</td>
</tr>
<tr>
<td>----------------------------</td>
<td>-------------------------------------------------------</td>
</tr>
<tr>
<td>CL_UNSIGNED_INT16</td>
<td>Each channel is unsigned unnormalized 16-bit integer</td>
</tr>
<tr>
<td>CL_UNSIGNED_INT32</td>
<td>Each channel is unsigned unnormalized 32-bit integer</td>
</tr>
<tr>
<td>CL_HALF_FLOAT</td>
<td>Each channel is a 16-bit half-float</td>
</tr>
<tr>
<td>CL_FLOAT</td>
<td>Each channel is a single precision float</td>
</tr>
</tbody>
</table>

Example: For a floating point data channel with RGBA channel-ordering the `image_format` struct would be set as follows:

```c
CL_image_format image_format;
image_format.image_channel_data_type = CL_FLOAT;
image_format.image_channel_order = CL_RGBA;
```

Similar to 2D images, a 3D image object is created using the `clCreateImage3D()` function. For a 3D object, the depth of the object must be provided in addition to the width and height. The slice_pitch size must also be provided in addition to row_pitch size (slice_pitch is the size of each 2D slice in the 3D image, in bytes). See the OpenCL Specification for more details on creating a 3D image object.

As with buffer objects, OpenCL also provides functions to enqueue commands to write 2D or 3D image data to host memory or read back 2D or 3D image objects to host memory.

```c
err = clEnqueueReadImage (  
    command_queue, // valid command queue  
    image,         // valid image object to read from  
    blocking_read, // blocking flag, CL_TRUE or CL_FALSE  
    origin_offset, // (x,y,z) offset in pixels to read from z=0 for 2D image  
    region,        // (width,height,depth) in pixels to read from, depth=1 for 2D image  
    row_pitch,     // length of each row in bytes  
    slice_pitch,   // size of each 2D slice in the 3D image in bytes, 0 for 2D image  
    &event         // event object to return on completion
);
```

```c
err = clEnqueueWriteImage (  
    command_queue, // valid command queue  
    image,         // valid image object to write to  
    blocking_read, // blocking flag, CL_TRUE or CL_FALSE  
    origin_offset, // (x,y,z) offset in pixels to write to z=0 for 2D image  
    region,        // (width,height,depth) in pixels to write to, depth=1 for 2D image  
    row_pitch,     // length of each row in bytes  
    slice_pitch,   // size of each 2D slice in the 3D image in bytes, 0 for 2D image  
    host_ptr,      // host memory pointer to store read data from  
    &event         // event object to return on completion
);
```
If the function executes successfully, \texttt{clEnqueueReadImage()} and \texttt{clEnqueueWriteImage()} return \texttt{CL_SUCCESS}. Otherwise, one of the following common error codes may be returned:

- \texttt{CL_INVALID_COMMAND_QUEUE} — The command queue is not valid.
- \texttt{CL_INVALID_CONTEXT} — The command queue and image object are not associated with the same context.
- \texttt{CL_INVALID_MEM_OBJECT} — The image object is not valid.
- \texttt{CL_INVALID_VALUE} — The region being read/write specified by the \texttt{origin_offset} and region is out of bounds or the host pointer is NULL.
- \texttt{CL_INVALID_VALUE} — The image object is 2D and \texttt{origin_offset[2]} (y component) is not set to 0, or \texttt{region[2]} (depth component) is not set to 1.
- \texttt{CL_INVALID_EVENT_WAIT_LIST} — Either: The events list is empty (NULL), but the number of events argument is greater than 0; or number of events is 0, but the event list is not NULL; or the events list contains invalid event objects.
- \texttt{CL_INVALID_OPERATION} — The associated device does not support images.
- \texttt{CL_OUT_OF_HOST_MEMORY} — The host is unable to allocate OpenCL resources.

For a complete list of error codes, see the OpenCL specification.

### 5.5.5 Retaining and Releasing Image Objects

Image objects should be freed when no longer required by the application. They are retained and released using the same \texttt{clRetainMemObj()} and \texttt{clReleaseMemObj()} functions used by buffer objects. For details, see 5.5.3 Retaining and Releasing Buffer Objects.

### 5.6 Synchronization

When a kernel is queued, it may not execute immediately. Execution can be forced by using a blocking call. The \texttt{clEnqueueRead*()} and \texttt{clEnqueueWrite*()} functions contain a blocking flag that, when set to \texttt{CL_TRUE}, forces the function to block until read/write commands have completed. Using a blocking command forces the OpenCL runtime to flush all the commands in the queue by executing all kernels.

The recommended way to track the execution status of kernels in the command queue is to use events. Events allow the host application to work without blocking OpenCL calls. The host application can send tasks to the command queue and return later to check if the execution is done by querying the event status.

The queue can execute commands in-order or out-of-order, depending on how the command is created. An in-order queue behaves as expected as long the commands are enqueued from a single thread. If there are multiple devices—for example, a GPU and a CPU, each of which have their own queue—commands must be synchronized between the two queues using specific functions such as \texttt{clEnqueue*}. All \texttt{clEnqueue*} functions take three arguments: The number of events to wait on, a list of
events to wait on, and an event that the command creates that can be used by other commands to perform synchronization:

```c
clEnqueue(..., num_events, events_wait_list, event_return)
```

The following image illustrates a scenario with one OpenCL device and one command queue.

Figure 5–5  Kernel Execution with One Device and One Queue

Kernel 2 waits until
Kernel 1 is finished

When two kernels must be executed, with the second kernel using the results of the first, the first kernel command enters the queue but may not execute immediately. Since the enqueue function is an asynchronous call and returns when it is called, the second kernel command is enqueued when the function returns. Thus, as a single in-order command queue, the second kernel command will not execute until the first command has finish executing.

The same result can be achieved when using multiple OpenCL devices, each having its own queue, and kernel execution must be synchronized between the two devices. If kernel 1 is running on a GPU, kernel 2 is running on a CPU, and the second kernel must use the results of the first, the second kernel will execute only after the first is finished—but again, only if events are used.
The following figure illustrates what can happen in the same two-devices, two-queue scenario, but without using events to synchronize execution. In this illustration, the first kernel is enqueued into the GPU queue but is not executed immediately. When it is executed, the OpenCL runtime may also detect that the CPU is free, and begin executing the second kernel before results from the first kernel are returned.

Figure 5–6 Two Devices with Two Queues, Unsynchronized
In the same two-devices, two-queue scenario, this time using events to synchronize execution, overlapping execution is avoided, as illustrated in the following figure:

Figure 5–7  Two Devices with Two Queues Synchronized Using Events

In addition to using events in the `clEnqueue` functions to manage how kernels are executed, host application events can also be managed, allowing the application to better manage resources for maximum optimization.

The function `clWaitForEvents(num_events, event_list)` causes the host application to block and wait until all commands identified by the event list are complete (that is, when the execution status of each command is CL_COMPLETE). The OpenCL runtime, rather than the host application, can also perform the block by using the `clEnqueueWaitForEvents(command_queue, num_events, event_list)` function to introduce a wait command into the queue to wait for specific events to complete before any future commands in the queue are executed.

An event marker can also be inserted into the command queue. This allows tracking of how quickly commands are moving through the queue. The function `clEnqueueMarker(command_queue, *event_return)` returns an event which can be used to queue a wait on the specified event.

Another useful synchronization function is `clGetEventInfo()`:

```c
clGetEventInfo(
    event,      // the event object to query
    param_name, // the cl_event_info
    param_size, // the size of the returned info
    param_value, // the value of the returned info
    actual_param_size_ret // actual size of info returned
)`
This function allows the querying of an event object to determine what command the event is associated with and the execution status of the command (whether it's running or completed). The list of supported param_name types and the information returned by `clGetEventInfo()` is described in the following table.

Table 5–5  Supported List param_name and Return Values for clGetEventInfo()

<table>
<thead>
<tr>
<th>cl_event_info</th>
<th>Return Type</th>
<th>Info returned in parm_value</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_EVENT_COMMAND_QUEUE</td>
<td>cl_command_queue</td>
<td>Return the command queue associated with the event</td>
</tr>
<tr>
<td>CL_EVENT_COMMAND_TYPE</td>
<td>cl_command_type</td>
<td>Command type is one of the following:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_NDRange_KERNEL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_TASK</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_Native_KERNEL</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_READ_BUFFER</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_WRITE_BUFFER</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_COPY_BUFFER</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_READ_IMAGE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_WRITE_IMAGE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_COPY_IMAGE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_COPY_BUFFER_TO_IMAGE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_COPY_IMAGE_TO_BUFFER</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_MAP_BUFFER</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_MAP_IMAGE</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_UNMAP_MEM_OBJECT</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_MARKER</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_ACQUIRE_GL_OBJECTS</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMMAND_RELEASE_GL_OBJECTS</td>
</tr>
<tr>
<td>CL_EVENT_COMMAND_EXECUTION_STATUS</td>
<td>cl_int</td>
<td>Execution status is one of the following:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_QUEUED — command has been enqueued into the command queue</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_SUBMITTED — enqueued command has been submitted to the OpenCL device</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_RUNNING — the command is currently executing by the device</td>
</tr>
<tr>
<td></td>
<td></td>
<td>CL_COMPLETE — the command has completed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Error code — negative integer value indicating command was terminated abnormally.</td>
</tr>
<tr>
<td>CL_EVENT_REFERENCE_COUNT</td>
<td>cl_unit</td>
<td>Returns the reference counter of the event object.</td>
</tr>
</tbody>
</table>

The following code shows how to get the execution status of an event object:
cl_int status;
size_t return_size;
err = clGetEventInfo(
    event,
    CL_EVENT_COMMAND_EXECUTION_STATUS,
    sizeof(cl_int),
    &status,
    &return_size
);

If the function is executed successfully, clGetEventInfo() returns CL_SUCCESS. Otherwise, one of the following values are returned:

- CL_INVALID_EVENT — The event object is invalid.
- CL_INVALID_VALUE — The param_name is not valid, or the param_size is less than the size of the return type.
Chapter 6

The OpenCL C Language

The OpenCL C programming language is based on the ISO C99 specification with some modifications and restrictions. This chapter highlights important aspects of the OpenCL C language that are used to create kernels for execution on OpenCL devices. For complete details on the language, see the OpenCL specification.

6.1 Restrictions

Key restrictions in the OpenCL C language are:

- Function pointers are not supported.
- Bit-fields are not supported.
- Variable length arrays are not supported.
- Recursion is not supported.
- No C99 standard headers such as ctypes.h, errno.h, stdlib.h, etc. can be included.

6.2 Data Types

OpenCL C language has many built-in scalar types that should be familiar to C programmers. A set of vector data types and vector operations were also added for easier manipulation of data sets such as matrices. The OpenCL implement ensures that data is portable, so when data must be moved from one device to another—such as from a GPU to a CPU, OpenCL ensures that the data always endianness safe and properly aligned. This section describes the various data types supported by OpenCL C.

6.2.1 Scalar Data Types

The table below shows the common built-in scalar data types supported by OpenCL C as well as the matching types declared in the OpenCL API that can be used in the host application. Refer to the OpenCL specification for complete list of supported scalar data types.
6.2.2 Vector Data Types

One addition to the OpenCL C language is support of various vector data types. The vector data is defined with the type name follow by a value \( n \) that specifies the number of elements in the vector. For example a 4 component floating point vector would be float4. The supported components are: 2, 4, 8, and 16. The table below shows the built-in vector data types supported by OpenCL C as well as the matching types declared in the OpenCL API that can be used in the host application.

<table>
<thead>
<tr>
<th>OpenCL C Type</th>
<th>OpenCL API Type for host app</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>char</td>
<td>cl_char</td>
<td>signed two's complement 8-bit integer</td>
</tr>
<tr>
<td>unsigned char, uchar</td>
<td>cl_uchar</td>
<td>unsigned 8-bit integer</td>
</tr>
<tr>
<td>short</td>
<td>cl_short</td>
<td>signed two's complement 16-bit integer</td>
</tr>
<tr>
<td>unsigned short, ushort</td>
<td>cl_ushort</td>
<td>unsigned 16-bit integer</td>
</tr>
<tr>
<td>int</td>
<td>cl_int</td>
<td>signed two's complement 32-bit integer</td>
</tr>
<tr>
<td>unsigned int, unit</td>
<td>cl_uint</td>
<td>unsigned 32-bit integer</td>
</tr>
<tr>
<td>long</td>
<td>cl_long</td>
<td>signed two's complement 64-bit integer</td>
</tr>
<tr>
<td>unsigned long, ulong</td>
<td>cl_ulong</td>
<td>unsigned 64-bit integer</td>
</tr>
<tr>
<td>float</td>
<td>cl_float</td>
<td>IEEE 754 single precision floating point</td>
</tr>
</tbody>
</table>

Note: Even if the OpenCL device does not support any of all of the above vector data types, the OpenCL compiler will convert the vector types to the appropriate types supported built-in types supported by the OpenCL device.

There are several ways to access the components of a vector data type depending on the how many components are in the vector. Vectors types with 2 components such as char2, unint2, etc. can access the different components using <vector2>.xy.
types with 4 components such as long4, float4, etc. can access components using `<vector4>.xyzw. An example:

```c
float2 pos;
pos.x = 1.0f;
pos.y = 1.0f;
pos.z = 1.0f; // illegal since vector only has 2 components
```

```c
float4 c;
c.x = 1.0f;
c.y = 1.0f;
c.z = 1.0f;
c.w = 1.0f;
```

Vector components can also be accessed using numeric index to address the particular component. Table below shows the numeric indices used for accessing. When using number index to access the components, the indices must be prefixed with by the letter s or S.

<table>
<thead>
<tr>
<th>Vector components</th>
<th>Numeric indices</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 components</td>
<td>0, 1</td>
</tr>
<tr>
<td>4 components</td>
<td>0, 1, 2, 3</td>
</tr>
<tr>
<td>8 components</td>
<td>0, 1, 2, 3, 4, 5, 6, 7</td>
</tr>
<tr>
<td>16 components</td>
<td>0, 1, 2, 3, 4, 5, 6, 7, 8, 9, a, b, c, d, e, f, F</td>
</tr>
</tbody>
</table>

Examples:

```c
float8 f;
f.s0 = 1.0f; // the 1st component in the vector
f.s7 = 1.0f; // the 8th component in the vector
```

```c
float16 x;
f.sa = 1.0f; // or f.sA is the 10th component in the vector
f.sF = 1.0f; // or f.sF is the 16th component in the vector
```

OpenCL also provides quick addressing to a grouping of components in a vector:

<table>
<thead>
<tr>
<th>Vector access suffix</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>.lo</td>
<td>Returns the lower half of a vector</td>
</tr>
<tr>
<td>.hi</td>
<td>Returns the upper half of a vector</td>
</tr>
<tr>
<td>.odd</td>
<td>Returns the odd components of a vector</td>
</tr>
<tr>
<td>.even</td>
<td>Returns the even components of a vector</td>
</tr>
</tbody>
</table>

Examples:
float4 f = (float4) (1.0f, 2.0f, 3.0f, 4.0f);
float2 low, high;
float2 o, e;

low = f.lo; // returns f.xy (1.0f, 2.0f)
high = f.hi; // returns f.zw (3.0f, 4.0f)
o = f.odd; // returns f.yw (2.0f, 4.0f)
e = f.even; // returns f.xz (1.0f, 3.0f)

6.2.3 Vector Operations

In addition to all the typical operator C programmers are used to, such as +, -, *, /, &, |, etc., the OpenCL C language allows the same operators to be perform on vectors. Vector operations are perform on each component in the vector independently. The following examples illustrate this:

Example 1:

int4 vi0, vi1;
int v;
vi1 = vi0 + v;

is equivalent to:

vi1.x = vi0 + v;
vi1.y = vi0 + v;
vi1.z = vi0 + v;
vi1.w = vi0 + v;

Example 2:

float4 u, v, w;
w = u + v
w.odd = v.odd + u.odd;

is equivalent to:

w.x = u.x + v.x;
w.y = u.y + v.y;
w.z = u.z + v.z;
w.w = u.w + v.w;

w.y = v.y + u.y;
w.w = v.w + u.w;

6.3 Type Casting and Conversions

OpenCL C language allows implicit conversion of scalar data types and pointer types as described in the C99 specification. The implicit conversion process converts the value of a type into an equivalent value in the new type. The built-in scalar types
shown in Table 6-1 Supported Scalar Data Types all support implicit conversion. For built-in vector types, implicit conversions are not allowed. Thus, the following is illegal:

```cpp
int4 v4;
float4 f = v4; // not allowed
```

Explicit conversions through casting for built-in data types are also supported. For example, the following will convert the floating point value of $x$ into an integer value:

```cpp
float x;
int i = (int)x;
```

If, however, explicit casting is applied between vector data types such as those used in the following example, an error is generated:

```cpp
int4 i;
float4 f = (float4) i; // not allowed
```

OpenCL provides a set of built-in functions to explicitly convert between the data types. These functions can operate on both scalar and vector data types. The conversion functions take the form:

```cpp
convert_<destination_type>(source_type)
```

Examples:

```cpp
int4 i;
float4 f = convert_float4(i); // converts an int4 vector to float4

float f;
int i = convert_int(f); // converts a float scalar to an integer scalar
```

When converting between vector types, the number of components in each vector must be the same. The following example is illegal.

```cpp
int8 i;
float4 f = convert_float4(i); // illegal
```

Sometimes the conversion may not produce the expected results due to rounding or out-of-range values. OpenCL allows us to specify how out-of-range values and rounding should be treated by using two optional modifiers on the conversion functions.

```cpp
convert_<destination_type><_sat><_roundingMode>(source_type)
```

The saturation (sat) modifier specifies how an out-of-range conversion is handled. When the value to be converted is beyond the range that can be represented by the target type, the values are clamped to the nearest representable value. The sat modifier is only supported when converting to an integer type. Conversion to a floating point type follows IEEE754 rules, and may not use the saturation modifier.
The rounding modifier specifies the rounding mode to use in the conversion. The table below lists the supported rounding modes.

<table>
<thead>
<tr>
<th>Rounding Modifier</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>_rte</td>
<td>Round to nearest even</td>
</tr>
<tr>
<td>_rtz</td>
<td>Round towards zero</td>
</tr>
<tr>
<td>_rtp</td>
<td>Round towards positive infinity</td>
</tr>
<tr>
<td>_rtn</td>
<td>Round towards negative infinity</td>
</tr>
<tr>
<td>No modifier</td>
<td>Defaults to _rtz for conversions to integer</td>
</tr>
<tr>
<td></td>
<td>Defaults to _rte for conversions to floating point</td>
</tr>
</tbody>
</table>

Explicit conversion examples:

```c
float4 f = (float4)(-1.0f, 252.5f, 254.6f, 1.2E9f);
uchar4 c = convert_uchar4_sat(f);
// c = (0, 253, 255, 255)
// negative value clamped to 0, value > TYPE MAX is set to the type MAX
// -1.0 clamped to 0, 1.2E9f clamped to 255
```

```c
float4 f = (float4)(-1.0f, 252.5f, 254.6f, 1.2E9f);
uchar4 c = convert_uchar4_sat_rte(f);
// c = (0, 252, 255, 255)
// 252.5f round down to near even becomes 252
```

```c
int4 i;
float4 = convert_float4(i);
// convert to floating point using the default rounding mode
```

```c
int4 i;
float4 = convert_float4_rtp(i);
// convert to floating point. Integer values not representable as float
// are rounded up to the next representable float
```

Built-in scalar and vector data types can also be reinterpreted as another data type as long as they are the same size. The function `as_<typen>(value)` reinterprets the bit pattern in the source to another type without any modification. For example, the value `1.0f` is represented as `0x3F800000` in an IEE754 value. The value `1.0f` can be reinterpreted as a `uint` this way:

```c
uint i = as_uint(1.0f);
// i will have value 0x3F800000
```
6.4 Qualifiers

6.4.1 Address Space Qualifiers

3.3.3 The Memory Model briefly described the OpenCL memory model defines four regions of memory for work-items to access when executing a kernel. The different address spaces allow memory to be shared between work-items, or allow us to choose the best memory space for the operations to be performed. The four disjointed address spaces are: __global, __local, __constant, and __private. To allocate memory for a specific region of memory, one of the above qualifiers may be used in the variable declaration.

All functions (including the __kernel function) and their arguments or local variables are in the __private address space. Arguments of a __kernel function declared as a pointer type can point to only one of the following memory spaces: __global, __local, or __constant. Assigning a pointer address to one space to another is not allowed. For example, a pointer to __global can only be assigned to a pointer to __global. Casting of pointers between different address spaces may cause unexpected behavior. A __kernel function with arguments declared as image2d_t or image3d_t can only point to the __global address space.

Examples:

__global float *ptr // the pointer ptr is declared in the __private address space
// space and points to a float that is in the __global address space

int4 x    // declares an int4 vector in the __private address

Global address space
This address space refers to memory objects such as scalars, vectors, buffer objects, or image objects that are allocated in the global memory pool. For a GPU compute device, this is typically the frame buffer memory.

Local address space
This address space is typically used by local variables that are allocated in local memory. Memory in the local address space can be shared by all work-items of a work group. For example, local memory on a GPU compute device could be the local data store for one of the compute units (or core) on the GPU.

Constant address space
This address space describes variables that allocated in global memory pool but can only be accessed as read-only variables. These variables are accessible by the entire global work-items. Variable that need to have a global scope must be declared in the constant address space.

Private address space
This address space describes variables that are passed into all functions (including __kernel functions) or variables declared without a qualifier. A private variable can only be accessed by the work-item in which it was declared.
6.4.2 Image Qualifiers

OpenCL also provides access to qualifiers when passing an image memory object as arguments to __kernel functions. The qualifier __read_only and __write_only can specify whether the image object passed to the kernel is read-only or write-only. Default access is __read_only when no qualifier is explicitly provided. Kernel functions cannot have both read and write access to the same image memory object.

The following kernel declaration declares the argument inputImage as a read-only image object, and outputImage as a write-only image object:

```c
__kernel void myfunc(__read_only image2d_t inputImage,
                    __write_only image2d_t outputImage)
```

6.5 Built-in Functions

The OpenCL C language includes a wide set of built-in functions for many types of operations such as math functions, work-item functions, image access functions. Refer to the OpenCL Specification for details of all the built-in function. This section will describes some of the common functions used to operate on work-items, image objects, and work-items synchronization.

6.5.1 Work-item Functions

Work-item functions can be used to query the information relating to the data that the kernel is asked to process. These functions allow querying of dimension size of the data, the global size for each dimension, the local work size, number of work-groups, as well the unique global and local work-item ID of the kernel that is being executed.

```c
// returns the number of dimensions of the data problem space
uint get_work_dim()

// returns the number total work-items for the specified dimension
size_t get_global_size(dimidx)

// returns the number of local work-items in the work-group specified by dimension
size_t get_local_size(dimidx)

// returns the unique global work-item ID for the specified dimension
size_t get_global_id(dimidx)

// returns the unique local work-item ID in the work-group for the specified dimension
size_t get_local_id(dimidx)

// returns the number of work-groups for the specified dimension
size_t get_num_groups(dimidx)

// returns the unique ID of the work-group being processed by the kernel
size_t get_group_id(dimidx)
```
The following kernel function illustrates how these functions are used:

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

The following figure shows the input and expected output:

<table>
<thead>
<tr>
<th>input</th>
<th>4 5 2 7 1 9 3 1 2 7 8 5 6 1 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>output</td>
<td>16 25 4 49 1 0 81 9 1 4 49 54 25 35 1 36</td>
</tr>
</tbody>
</table>

Since the kernel function is a data parallel function, it is executed for each work-item. When a work-item calls `get_global_id(0)` the request is for the unique global work-item ID used to index the data. The example below, the work-item instance is returned `id=6` when it makes a call to `get_global_id(0)`. The work-item can then use the id to index the data to perform the operation.
If, for example, the kernel function is enqueued by indicating that the input will be divided into groups of eight elements, the results of the various work-item functions will appear as shown in the following image.

![Image Access Functions Diagram]

### 6.5.2 Image Access Functions

When using image memory objects, the data in the image object can only be read and written using the built-in image access functions. A wide range of read and write functions are available, depending on the image channel data type when the image memory object is created. The following is a list of some of the built-in image access functions. Refer to the OpenCL specification for the details of each function.

- `read_imagef()` // for reading image with float-point data channel
- `read_imagei()` // for reading image with integer data channel
- `read_imageui()` // for reading image with unsigned integer data channel
- `write_imagef()` // for writing image with float-point data channel
- `write_imagei()` // for writing image with integer data channel
- `write_imageui()` // for writing image with unsigned integer data channel
- `get_image_width()` // returns width of the 2D or 3D image
- `get_image_height()` // returns height of the 2D or 3D image
- `get_image_depth()` // returns depth of the 3D image

### 6.5.3 Synchronization Functions

The OpenCL C language provides functions to allow synchronization of work-items. The memory model discussion in Chapter 3 Introduction to OpenCL described how synchronization can only occur between work-items in the same work-group. To achieve that, OpenCL implements a barrier memory fence for synchronization.
The function `barrier(mem_fence_flag)` creates a barrier that blocks the current work-item until all other work-items in the same group has executed the barrier before allowing the work-item to proceed beyond the barrier. It is important to note that when using barrier, all work-items in the work-group must execute the barrier function. If the barrier function is called within a conditional statement, it is important to ensure that all work-items in the work-group enter the conditional statement to execute the barrier.

For example, the following function is an illegal use of barrier because the barrier will not be encountered for more than five work-items:

```c
__kernel void read(__global float *input, __global float *output)
{
    size_t id = get_global_id(0);
    if (id < 5)
        barrier(CLK_GLOBAL_MEM_FENCE);
    else
        ...
}
```

The `mem_fence_flag` can be either `CLK_LOCAL_MEM_FENCE`, or `CLK_GLOBAL_MEM_FENCE` is use by the barrier function to either flush any variable in local or global memory or setup a memory fence to ensure that correct ordering of memory operations to either local or global memory.

OpenCL C language implements memory fence functions to provide ordering between memory operations of a work-item. Memory fence can be useful when work-items needs to write data to a buffer and then read back the updated data. Using memory fence ensures that reads or writes before the memory fence have been committed to memory. OpenCL allows explicit setup of memory fence by using one of the following functions.

```c
// ensures all reads and writes before the memory fence have committed to memory
void mem_fence(mem_fence_flag)

// ensures all reads before memory fence have completed
void read_mem_fence(mem_fence_flag)

// ensures all writes before memory fence have completed
void write_mem_fence(mem_fence_flag)
```
Chapter 7

Application Optimization and Porting

This chapter describes OpenCL kernel debugging and provides performance and optimization tips for kernel execution on AMD GPU and CPU devices. Also included are language equivalents for use in porting applications from NVIDIA’s C for CUDA language to OpenCL.

7.1 Debugging OpenCL

The ATI Stream SDK v2 provides debugging features that allow the debugging of OpenCL kernels on Linux using GDB. This section covers only some of the basic GDB commands; for complete GDB documentation, see GDB: The GNU Project Debugger.

7.1.1 Setting Up for Debugging

To enable debugging, an OpenCL program passes the "-g" option to the build clBuildProgram() function:

```c
err = clBuildProgram(program, 1, devices, "-g", NULL, NULL);
```

To avoid changes to the source code, the following environment variable can be used to force debugging when compiling for a CPU device:

```
export CPU_COMPILER_OPTIONS=-g
```

When debugging, the kernel program must be set to execute on a CPU device. It is also important to set the environment variable so the kernel program is executed deterministically:

```
export CPU_MAX_COMPUTE_UNITS=1
```

7.1.2 Setting Breakpoints

If no breakpoint is set during a GDB session, the program does not stop until execution has completed. To set a breakpoint using GDB:
A breakpoint can be set at a particular line in the source code by simply specifying the line number. A break point can also be set at the start of a function by specifying the function_name. To set a break point for a kernel function, use the construct __OpenCL_function_kernel. For example, to set a breakpoint for the following kernel function:

```c
__kernel void square(__global int *input, __global int *output)
```

Use the following code:

```c
b __OpenCL_square_kernel
```

**Note:** The OpenCL kernel symbols are not visible to the debugger until the kernel is loaded, when a question is asked about making the breakpoint pending on future library load:

```
(gdb) b __OpenCL_hello_kernel
Function "__OpenCL_hello_kernel" not defined.
Make breakpoint pending on future shared library load? [y or [n]] y
Breakpoint 1 { __OpenCL_hello_kernel } pending.
```

To check that the symbol is correct, set a breakpoint in the host code at the `clEnqueueNDRangeKernel` function, then list all OpenCL symbols using the GDB command:

```c
info functions __OpenCL
```
A conditional breakpoint can also be set to stop the program at a particular work-item. This is done by setting a conditional breakpoint when `get_global_id == ID`. For example, to set a breakpoint at the kernel function for the work-item with `global id=5`:

```
b __OpenCL_square_kernel if get_global_id(0) == 5
```

### 7.2 Performance Measurement

The OpenCL runtime provides a built-in mechanism for timing the execution of kernels. This allows the developer to evaluate kernel performance for maximum
optimization. Kernel command profiling is done by specifying the CL_QUEUE_PROFILING_ENABLE properties when creating the command queue with clCreateCommandQueue(). The command queue properties can also be set after the queue has been created by using the clSetCommandQueueProperties() function.

When queue profiling is enabled, the OpenCL runtime automatically records timestamp information for every kernel and memory operation submitted to the queue. The profiling function and supported data are as follows:

```c
err = clGetEventProfilingInfo(
    event,               // the event object to get info for
    param_name        // the profiling data to query - see list below
    param_value_size  // the size of memory pointed by param_value
    param_value       // pointer to memory in which the query result is returned
    param_actual_size // actual number of bytes copied to param_value
);
```

Table 7–1  Supported Profiling Data for clGetEventProfilingInfo()

<table>
<thead>
<tr>
<th>Profiling data</th>
<th>Return Type</th>
<th>Information returned</th>
</tr>
</thead>
<tbody>
<tr>
<td>CL_PROFILING_COMMAND_QUEUE</td>
<td>cl_ulong</td>
<td>A 64-bit counter in nanoseconds when the command is enqueued in a command queue.</td>
</tr>
<tr>
<td>CL_PROFILING_COMMAND_SUBMIT</td>
<td>cl_ulong</td>
<td>A 64-bit counter in nanoseconds when the command that has been enqueued is submitted to compute the device for execution</td>
</tr>
<tr>
<td>CL_PROFILING_COMMAND_START</td>
<td>cl_ulong</td>
<td>A 64-bit counter in nanoseconds when the command started execution on the compute device</td>
</tr>
<tr>
<td>CL_PROFILING_COMMAND_END</td>
<td>cl_ulong</td>
<td>A 64-bit counter in nanoseconds when the command has finished execution on the compute device</td>
</tr>
</tbody>
</table>

If the function executes successfully, clGetEventProfilingInfo() returns CL_SUCCESS. Otherwise, one of the following error codes are returned:

- **CL_INVALID_EVENT** — The event object is not valid.
- **CL_PROFILING_INFO_NOT_AVAILABLE** — The command queue does not have the CL_QUEUE_PROFILING_ENABLE properties flag set, or the event associated with the command is not completed.
- **CL_INVALID_VALUE** — The query data param_name is not valid, or the size param_actual_size is greater than param_value_size.

The following sample code determines the execution time for a kernel command:
cl_event myEvent;
cl_ulong startTime, endTime;

clCreateCommandQueue (..., CL_QUEUE_PROFILING_ENABLE, NULL);
clEnqueueNDRangeKernel(..., &myEvent);
clFinish(myCommandQ); // wait for all events to finish

clGetEventProfilingInfo(myEvent, CL_PROFILING_COMMAND_START,
sizeof(cl_ulong), &startTime, NULL);
clGetEventProfilingInfo(myEvent, CL_PROFILING_COMMAND_END,
sizeof(cl_ulong), &endTime, NULL);
cl_ulong elapsedTime = endTime - startTime;

### 7.2.1 Using the ATI Stream Profiler

The ATI Stream Profiler provides a Microsoft® Visual Studio® integrated view of key static kernel characteristics such as work-group dimensions and memory transfer sizes, as well as kernel execution time, dynamic hardware performance counter information (ALU operations, local bank conflicts), and kernel disassembly. The ATI Stream Profiler is installed if the SDK was installed using the express option.

**To confirm that the profiler is installed:**

1. Open a Visual Studio solution file.
2. Select **Help ▶ About Microsoft Visual Studio** from the Visual Studio's main menu bar. Under Installed products, you should find ATI Stream Profiler 1.1. If you don't see it, open a command window using the **Run as Administrator** option and run `C:\Program Files (x86)\Microsoft Visual Studio 9.0\Common7\IDE\devenv.exe /setup` for a 64-bit system or `C:\Program Files\Microsoft Visual Studio 9.0\Common7\IDE\devenv.exe /setup` for a 32-bit system from a command line prompt (with "Run as Administrator" option).

**To use the profiler plugin:**

1. Open an OpenCL solution or project file.
2. Set a startup project by right-clicking on a project and selecting **Setup as StartUp Project**.
3. Compile the project and run it. Verify that it compiles and runs successfully.
4. To start profiling, click on the **Start Profiling** button under the **OpenCL Session List** panel. If you can't find the **OpenCL Session List Panel**, enable it by selecting **View ▶ Other Windows ▶ OpenCL Session List Window** from the Visual Studio's main menu bar. An OpenCL Session panel will be docked to the main document panel. This panel shows the profiling result.
5. Hover the mouse pointer over the profile header in the OpenCL Session panel to get the description of the counters.
6. Click on the kernel name (the first column) to see the ISA and IL code of the kernel. An OpenCL Code Viewer panel will be docked to the main document panel.
Note:

- If you run the kernel in the CPU mode, only the global work size, work group size, local memory, memory transfer size, and kernel time statistics will be available.

- Under the project directory, a new ProfilerOutput directory is created. This directory holds the profiling result of each session in a .csv file.

The following table lists the performance counters available through the ATI Stream Profiler.

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Method</td>
<td>The kernel name or the memory operation name.</td>
</tr>
<tr>
<td>ExecutionOrder</td>
<td>The order of execution for the kernel and memory operations from the program.</td>
</tr>
<tr>
<td>GlobalWorkSize</td>
<td>The global work-item size of the kernel.</td>
</tr>
<tr>
<td>GroupWorkSize</td>
<td>The work-group size of the kernel.</td>
</tr>
<tr>
<td>KernelTime</td>
<td>Time spent executing the kernel in milliseconds (does not include the kernel setup time).</td>
</tr>
<tr>
<td>LocalMem</td>
<td>The amount of local memory in bytes being used by the kernel.</td>
</tr>
<tr>
<td>MemTransferSize</td>
<td>The memory transfer size in bytes.</td>
</tr>
<tr>
<td>ALU</td>
<td>The average ALU instructions executed per thread (affected by flow control).</td>
</tr>
<tr>
<td>Fetch</td>
<td>The average Fetch instructions (from global memory) executed per thread (affected by flow control).</td>
</tr>
<tr>
<td>Write</td>
<td>The average Write instructions (to global memory) executed per thread (affected by flow control).</td>
</tr>
<tr>
<td>WaveFront</td>
<td>Total wavefronts.</td>
</tr>
<tr>
<td>ALUBusy</td>
<td>The percentage of time ALU instructions are processed relative to GPUTime.</td>
</tr>
<tr>
<td>ALUFetchRatio</td>
<td>The ratio of ALU to Fetch instructions.</td>
</tr>
<tr>
<td>ALUPacking</td>
<td>The ALU vector packing efficiency (in percentage). This value indicates how well the Shader Compiler packs the scalar or vector ALU in your kernel to the 5-way VLIW instructions. Values below 70 percent indicate that ALU dependency chains may be preventing full utilization of the processor.</td>
</tr>
<tr>
<td>FetchUnitBusy</td>
<td>The percentage of time the Fetch unit is active relative to GPUTime. This is measured with all extra fetches and any cache or memory effects taken into account.</td>
</tr>
<tr>
<td>FetchUnitStalled</td>
<td>The percentage of time the Fetch unit is stalled relative to GPUTime. Try reducing the number of fetches or reducing the amount per fetch if possible.</td>
</tr>
<tr>
<td>WriteUnitStalled</td>
<td>The percentage of time Write unit is stalled relative to GPUTime.</td>
</tr>
</tbody>
</table>

Additional counters available for the ATI Radeon HD 5000 Series graphics cards:

<table>
<thead>
<tr>
<th>Name</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALUStalledByLDS</td>
<td>The percentage of time ALU is stalled by LDS input queue being full and output queue is not ready relative to GPUBusy. If there are LDS bank conflicts, reduce it. Otherwise, try reducing the number of LDS accesses if possible.</td>
</tr>
<tr>
<td>LDSBankConflict</td>
<td>The percentage of time LDS is stalled by bank conflicts relative to GPUTime.</td>
</tr>
</tbody>
</table>
For additional information regarding the ATI Stream profiler, consult the ATI Stream Profiler Knowledge Base.

7.3 General Optimization Tips

This section offers general tips for optimizing kernel execution on AMD GPUs and CPUs. For more information, such as how the AMD GPU architecture maps to the OpenCL implementation, see the ATI Stream SDK OpenCL Programming Guide.

7.3.1 Use Local Memory

Using local memory is typically an order of magnitude faster than using global memory. AMD GPU includes a fast, high-bandwidth local memory for each work-group. All work-items in the work-group can efficiently share data using the high-bandwidth local memory. Collaborative read/write to the local memory can lead to highly efficient memory accessing. Collaborative write works by having each work-item write a subsection of an array, and as the work-item execute in parallel, the entire array is written. Before reading the values written collaboratively, the kernel must issue a barrier() call to ensure that memory is consistent across all work-items.

The following example calculates the transpose of a matrix using collaborative writes, then reads, from local memory. This implementation is twice as fast as the equivalent implementation that uses only global memory.
void matrixTranspose(__global float * output, 
__global float * input, 
__local float * block, 
const uint width, 
const uint height, 
const uint blockSize)
{
    uint globalIdx = get_global_id(0);
    uint globalIdy = get_global_id(1);
    uint localIdx = get_local_id(0);
    uint localIdy = get_local_id(1);
    /* copy from input to local memory */
    block[localIdy*blockSize + localIdx] = input[globalIdy*width + globalIdx];
    /* wait until the whole block is filled */
    barrier(CLK_LOCAL_MEM_FENCE);
    uint groupIdx = get_group_id(0);
    uint groupIdy = get_group_id(1);
    /* calculate the corresponding target location for transpose 
    by inverting x and y values*/
    uint targetGlobalIdx = groupIdy*blockSize + localIdx;
    uint targetGlobalIdy = groupIdx*blockSize + localIdx;
    /* calculate the corresponding raster indices of source and target */
    uint targetIndex  = targetGlobalIdy*height     + targetGlobalIdx;
    uint sourceIndex  = localIdy       * blockSize + localIdx;
    /* read final data from the local memory */
    output[targetIndex] = block[sourceIndex];
}

7.3.2 Work-group Size

The OpenCL data-parallel model allows you to divide work-items into work-groups. Work-group division can be performed explicitly or implicitly.

- Explicitly: the developer defines the total number of work-items to execute in parallel, as well as the division of work-items into specific work-groups.
- Implicitly: the developer specifies the total number of work-items to execute in parallel, and OpenCL manages the division into work-groups.

Explicit group division generally offers better performance. To maximize efficiency, however, always choose the largest group size supported by the target device.

AMD GPUs are optimized with work-groups sized in multiple of 64. The maximum supported device work-group size can be determined by querying CL_DEVICE_MAX_WORK_GROUP_SIZE with clGetDeviceInfo(). Sometimes, depending on kernel resource usage or instructions used by the kernel, it may not be possible to use the maximum work group size supported by the device and specified by
CL_DEVICE_MAX_WORK_GROUP_SIZE. In this case, clGetKernelWorkGroupInfo() can be used to retrieve information about the kernel object that is specific to a device. The parameter of interest is CL_KERNEL_WORK_GROUP_SIZE, which determines the maximum work-group size that can be used to execute a kernel on a specific device based on the resource requirement of the kernel. Refer to the OpenCL specification for more details on clGetKernelWorkGroupInfo().

7.3.3 Loop Unrolling

OpenCL kernels typically are high instruction-per-clock applications. Thus, the overhead to evaluate control-flow and execute branch instructions can consume a significant part of resource that otherwise can be used for high-throughput compute operations. The ATI Stream SDK v2 OpenCL compiler performs simple loop unrolling optimizations. However, for more complex loop unrolling, it may be beneficial to do this manually. For more on image convolution using OpenCL and how to further optimize the OpenCL kernel by performing loop unrolling, see the Image Convolution tutorial at the ATI Stream SDK v2 product page.

7.3.4 Reduce Data and Instructions

If possible, create a smaller version of the data set for easier debugging and faster turnaround. GPUs do not have automatic caching mechanisms and typically scale well as resources are added. In many cases, therefore, performance optimization for the smaller data implementation also benefits the full-size data set.

The profiler reports statistics on a per-kernel granularity. To further narrow down bottlenecks, it can be useful to remove or comment-out sections of code, then re-collect timing data to determine problem areas.

7.3.5 Use Built-in Vector Types

When possible, use built-in vector types such as float4 and the built-in vector functions (vload, vstore, etc.). These enable the ATI Stream SDK OpenCL implementation to generate efficiently-packed SSE instructions when running on the CPU. Vectorization can benefit both AMD CPUs and GPUs.

7.4 Porting CUDA to OpenCL

The data-parallel programming model in OpenCL shares some functionality with NVIDIA's C for CUDA programming model, making it relatively straightforward to convert programs from CUDA to OpenCL. This section describes terminology equivalents in C for CUDA and OpenCL.
7.4.1 General Terminology

The following table provides general terminology equivalents for describing computations and memory spaces between C for CUDA and OpenCL.

Table 7–2 General Terminology Equivalents

<table>
<thead>
<tr>
<th>C for CUDA Terminology</th>
<th>OpenCL Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thread</td>
<td>Work-item</td>
</tr>
<tr>
<td>Thread block</td>
<td>Work-group</td>
</tr>
<tr>
<td>Global memory</td>
<td>Global memory</td>
</tr>
<tr>
<td>Constant memory</td>
<td>Constant memory</td>
</tr>
<tr>
<td>Shared memory</td>
<td>Local memory</td>
</tr>
<tr>
<td>Local memory</td>
<td>Private memory</td>
</tr>
</tbody>
</table>

7.4.2 Kernel Qualifiers

The following table provides equivalents for qualifiers used when writing kernel functions in both C for CUDA and OpenCL. The most significant difference is the main entry point to the kernel function. C for CUDA uses the __global__ qualifier and local functions (not callable by the host) are prefixed with the __device__ qualifier. In OpenCL, entry functions use the __kernel qualifier, and qualifiers are not required for local (non-entry point) functions.

Table 7–3 Kernel Qualifier Equivalents

<table>
<thead>
<tr>
<th>C for CUDA Terminology</th>
<th>OpenCL Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>global</strong> function</td>
<td>__kernel function</td>
</tr>
<tr>
<td><strong>device</strong> function</td>
<td>function (no qualifier required)</td>
</tr>
<tr>
<td><strong>constant</strong> variable declaration</td>
<td>__constant variable declaration</td>
</tr>
<tr>
<td><strong>device</strong> variable declaration</td>
<td>__global variable declaration</td>
</tr>
<tr>
<td><strong>shared</strong> variable declaration</td>
<td>__local variable declaration</td>
</tr>
</tbody>
</table>

7.4.3 Kernel Indexing

The following table indexing access function equivalents for C for CUDA and OpenCL. CUDA provides indexing via special predefined variables, while OpenCL accomplished the same through function calls. Global indexing in CUDA requires manual computation, while OpenCL provides a global indexing function.
Table 7–4  Indexing Terminology Equivalents Used in Kernel Functions

<table>
<thead>
<tr>
<th>C for CUDA Terminology</th>
<th>OpenCL Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>gridDim</td>
<td>get_num_groups()</td>
</tr>
<tr>
<td>blockDim</td>
<td>get_local_size()</td>
</tr>
<tr>
<td>blockIdx</td>
<td>get_group_id()</td>
</tr>
<tr>
<td>threadIdx</td>
<td>get_local_id()</td>
</tr>
<tr>
<td>Global index calculated by combining blockDim, blockIdx, and threadIdx.</td>
<td>get_global_id()</td>
</tr>
<tr>
<td>Global size calculated by combining blockDim, gridDim.</td>
<td>get_global_size()</td>
</tr>
</tbody>
</table>

7.4.4 Kernel Synchronization

The following table provides equivalents for functions used for synchronization in kernel functions in C for CUDA and OpenCL. `__syncthreads()` and `barrier()` functions are similar in that they provide synchronization for all work-items in a work-group. In OpenCL, work-items are blocked until all work-items in the work-group have called `barrier()`.

`__threadfence()` and `mem_fence()` force various orderings on outstanding memory transactions, which can allow for more sophisticated sharing of data. For example, `mem_fence()` forces all outstanding loads and stores to be completed before execution proceeds, disallowing the compiler, runtime, and hardware from reordering any loads and stores through the `mem_fence()`. This can be used to ensure that all data produced in a work-group is flushed to global memory before signaling another work-group that execution has completed.

Table 7–5  Synchronization Terminology Equivalents Used in Kernel Functions

<table>
<thead>
<tr>
<th>C for CUDA Terminology</th>
<th>OpenCL Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>__syncthreads()</td>
<td>barrier()</td>
</tr>
<tr>
<td>__threadfence()</td>
<td>No direct equivalent.</td>
</tr>
<tr>
<td>__threadfence_block()</td>
<td>`mem_fence(CLK_GLOBAL_MEM_FENCE</td>
</tr>
<tr>
<td>No direct equivalent.</td>
<td><code>read_mem_fence()</code></td>
</tr>
<tr>
<td>No direct equivalent.</td>
<td><code>write_mem_fence()</code></td>
</tr>
</tbody>
</table>

7.4.5 General API Terminology

The following table provides general API terminology equivalents between C for CUDA and OpenCL. Note that in OpenCL, command queues provide task parallelism by allowing the developer to declare dependences between commands executing on a device. CUDA does not have a direct equivalent. The closest approximation would be the CUDA Stream mechanism, which allows kernels and memory transaction to be placed in independent streams. This is different from the command queue, since it does not provide parallelism within the stream, making synchronization between streams difficult.
### General API Terminology Equivalents

<table>
<thead>
<tr>
<th>C for CUDA Terminology</th>
<th>OpenCL Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>CUdevice</td>
<td>cl_device_id</td>
</tr>
<tr>
<td>CUcontext</td>
<td>cl_context</td>
</tr>
<tr>
<td>CUmodule</td>
<td>cl_program</td>
</tr>
<tr>
<td>CUFunction</td>
<td>cl_kernel</td>
</tr>
<tr>
<td>CUdeviceptr</td>
<td>cl_mem</td>
</tr>
</tbody>
</table>

No direct equivalent. Closest approximation would be the CUDA Stream mechanism.

### Important API Calls

The following table provides equivalents for calls used to set up host programs to execute parallel kernels in C for CUDA and OpenCL. A significant difference is that OpenCL is capable of compiling programs off-line or during runtime. CUDA only allows programs to be compiled off-line.

<table>
<thead>
<tr>
<th>C for CUDA Terminology</th>
<th>OpenCL Terminology</th>
</tr>
</thead>
<tbody>
<tr>
<td>cuInit()</td>
<td>No OpenCL initialization required</td>
</tr>
<tr>
<td>cuDeviceGet()</td>
<td>clGetContextInfo()</td>
</tr>
<tr>
<td>cuCtxCreate()</td>
<td>clCreateContextFromType()</td>
</tr>
<tr>
<td>No direct equivalent</td>
<td>clCreateCommandQueue()</td>
</tr>
<tr>
<td>cuModuleLoad()</td>
<td>clCreateProgramWithSource() or clCreateProgramWithBinary()</td>
</tr>
<tr>
<td>Note: Requires pre-compiled binary.</td>
<td></td>
</tr>
<tr>
<td>No direct equivalent</td>
<td>clBuildProgram()</td>
</tr>
<tr>
<td>cuModuleGetFunction()</td>
<td>clCreateKernel()</td>
</tr>
<tr>
<td>cuMemAlloc()</td>
<td>clCreateBuffer()</td>
</tr>
<tr>
<td>cuMemcpyHtoD()</td>
<td>clEnqueueWriteBuffer()</td>
</tr>
<tr>
<td>cuMemcpyDtoH()</td>
<td>clEnqueueReadBuffer()</td>
</tr>
<tr>
<td>cuFuncSetBlockShape()</td>
<td>No direct equivalent; functionality is part of clEnqueueNDRangeKernel()</td>
</tr>
<tr>
<td>cuParamSeti()</td>
<td>clSetKernelArg()</td>
</tr>
<tr>
<td>cuParamSetSize()</td>
<td>No direct equivalent; functionality is part of clSetKernelArg()</td>
</tr>
<tr>
<td>cuLaunchGrid()</td>
<td>clEnqueueNDRangeKernel()</td>
</tr>
<tr>
<td>cuMemFree()</td>
<td>clReleaseMemObj()</td>
</tr>
</tbody>
</table>
7.4.7 Additional Tips

- Pointers in OpenCL kernels must be prefixed with their memory space. For example, a pointer to local memory would be declared as `__local int* p;`. This applies to kernel arguments as well; data passed to a kernel are usually arrays represented by `__global` pointers.

- CUDA encourages the use of scalar code in kernels. While this works in OpenCL as well, but depending on the target architecture it may be more efficient to write programs operating on OpenCL's vector types (such as float4) rather than pure scalar types. This is useful for both AMD CPUs and AMD GPUs, which can operate efficiently on vector types. OpenCL also provides flexible swizzle/broadcast primitives for efficient creation and rearrangement of vector types.

- CUDA does not provide rich facilities for task parallelism, so it may be beneficial to think about how to take advantage of OpenCL's task parallelism when porting.
Chapter 8
Exercises

This chapter offers exercises to help further your understanding of OpenCL programming. Solutions are available in the Appendix.

8.1 Matrix Transposition Exercise

This exercise involves creating an OpenCL application that takes as input a matrix (width \( \times \) height) and determines the transposition of the input matrix.

In the following example, the transposition of matrix A is obtained by swapping the writing of the rows in A with the columns of \( A^T \):

\[
\begin{bmatrix}
1 & 2 & 3 \\
4 & 5 & 6 \\
7 & 8 & 9
\end{bmatrix}^T = \begin{bmatrix}
1 & 4 & 7 \\
2 & 5 & 8 \\
3 & 6 & 9
\end{bmatrix}
\]

\[
\begin{bmatrix}
1 & 2 & 3 \\
4 & 5 & 6
\end{bmatrix}^T = \begin{bmatrix}
1 & 4 \\
2 & 5 \\
3 & 6
\end{bmatrix}
\]

8.1.1 Completing the Code

Given the source skeleton below, complete the necessary OpenCL host portions in the main application as well as the kernel function that perform the matrix transposition using parallelism. The kernel source is to be placed in a file called transposeMatrix_kernel.cl and read into the kernel_source string by the main program.

Skeleton OpenCL host application to find a matrix transposition:
001 // transposeMatrix.c
002 #include <stdio.h>
003 #include <stdlib.h>
004 #include "CL/cl.h"
005
006 #define DATA_SIZE 65536
007 #define ROWS 16
008 #define COLS 16
009
010 int main()
011 {
012    cl_float *inputMatrix;
013    cl_float *results;
014    cl_uint width = COLS;
015    cl_uint height = ROWS;
016
017    // OpenCL host variables go here:
018
019    // variables used to read kernel source file
020    FILE *fp;
021    long filelen;
022    long readlen;
023    char *kernel_src;  // char string to hold kernel source
024
025    // initialize inputMatrix with some data and print it
026    int x,y;
027    int data=0;
028
029    inputMatrix = malloc(sizeof(cl_float)*width*height);
030    results = malloc(sizeof(cl_float)*width*height);
031    printf("Input Matrix\n");
032    for(y=0;y<height;y++)
033    {
034        for(x=0;x<width;x++)
035        {
036            inputMatrix[y*height+x] = data;
037            results[y*height+x]=0;
038            data++;
039        }
040    }
041    printf("%.2f, ",inputMatrix[y*height+x]);
042    printf("\n");
043
044    // read the kernel
045    fp = fopen("transposeMatrix_kernel.cl","r");
046    fseek(fp,0L, SEEK_END);
047    filelen = ftell(fp);
048    rewind(fp);
049    kernel_src = malloc(sizeof(char)*filelen+1));
050    readlen = fread(kernel_src,1,filelen,fp);
051    if(readlen!= filelen)
052    {
053        printf("error reading file\n");
054        exit(1);
055    }
056    // ensure the string is NULL terminated
057    //
Skeleton kernel source for calculating transpose of matrix:

// Kernel source file for calculating the transpose of a matrix
__kernel void matrixTranspose(.....)
{
    // insert kernel source here
}

For the solution to this exercise, see A.1 Matrix Transposition Solution.

8.2 Matrix Multiplication Exercise

This exercise demonstrates how to improve the performance of a kernel by breaking the work into subgroups. Use the kernel implementation below that performance the multiplication of two matrices and create a new kernel function that decomposes the multiplication into small work-groups working in parallel.
The multiplication of two matrices is shown in the following images. The kernel function simply does what is shown in the figure. For every element in matrix C, a work-item calculates the sums of products for the corresponding rows in image A and columns in image B.

For each element in image C, the kernel function must access the input data from the global memory in images A and B. For very large matrices, a large amount of access to global memory is required. Access to global memory is slow, however, and should be minimized where possible. Also note that work-items that are on the same row or column access the same data multiple times. In the previous figure, work-items C(1,0), C(1,2), and C(1,3) all need to access the same column data from B as C(1,1). Thus, the number of access to global memory increases.
The number of global memory accesses can be minimized by changing the kernel function to copy a block of data from A and B into fast local memory that can be shared by all work-items in the group. The following figure shows one possible way to decompose the matrix into local sub-matrices that can be shared by all work-items:

This kernel should copy a portion of A and B into local matrices (grpA and grpB) and then calculate the grpC output by using the local matrices. For very large input matrices, this method of decomposition dramatically minimizes the number of access to global memory, since all work-items within grpC can make use of the local memory matrices of A and B.

For the solution to this exercise, see A.2 Matrix Multiplication Solution.
Appendix A
Exercise Solutions

A.1 Matrix Transposition Solution

Solution to the 8.1 Matrix Transposition Exercise:
```c
#include <stdio.h>  
#include <stdlib.h>  
#include "CL/cl.h"

#define ROWS 16
#define COLS 16

int main()
{
    cl_float *inputMatrix;
    cl_float *results;
    cl_uint width = COLS;
    cl_uint height = ROWS;

    // OpenCL host variables
    cl_uint num_devs_returned;
    cl_context_properties properties[3];
    cl_device_id device_id;
    cl_int err;
    cl_platform_id platform_id;
    cl_uint num_platforms_returned;
    cl_context context;
    cl_command_queue command_queue;
    cl_program program;
    cl_kernel kernel;
    cl_mem input_buffer, output_buffer;
    size_t global[2];

    // variables used to read kernel source file
    FILE *fp;
    long filelen;
    long readlen;
    char *kernel_src;  // char string to hold kernel source

    // initialize inputMatrix with some data and print it
    int x,y;
    int data=0;

    inputMatrix = malloc(sizeof(cl_float)*width*height);
    results = malloc(sizeof(cl_float)*width*height);
    printf("Input Matrix\n");
    for(y=0;y<height;y++)
    {
        for(x=0;x<width;x++)
        {
            inputMatrix[y*height+x]= data;
            results[y*height+x]=0;   
            data++;
            printf("%.2f, ",inputMatrix[y*height+x]);
        }
        printf("\n");
    }

    // read the kernel
    fp = fopen("transposeMatrix_kernel.cl","r");
    fseek(fp,0L, SEEK_END);
    filelen = ftell(fp);
```
rewind(fp);

kernel_src = malloc(sizeof(char)*(filelen+1));
readlen = fread(kernel_src,1,filelen,fp);
if(readlen!= filelen)

    printf("error reading file\n");
    exit(1);

// ensure the string is NULL terminated
kernel_src[filelen+1] = '\0';

// Insert OpenCL host source here ----

// get a platform id
err = clGetPlatformIDs(1,&platform_id,&num_platforms_returned);
if (err != CL_SUCCESS)
    {
        printf("Unable to get Platform ID. Error Code=%d\n",err);
        exit(1);
    }

err = clGetDeviceIDs(platform_id, CL_DEVICE_TYPE_CPU, 1,
                        &device_id, &num_devs_returned);
if (err != CL_SUCCESS)
    {
        printf("Unable to get Device ID. Error Code=%d\n",err);
        exit(1);
    }

// context properties list - must be terminated with 0
properties[0]= CL_CONTEXT_PLATFORM;
properties[1]= (cl_context_properties) platform_id;
properties[2]= 0;

// create context
context = clCreateContext(properties, 1, &device_id, NULL, NULL, &err);
if (err != CL_SUCCESS)
    {
        printf("Unable to create context. Error Code=%d\n",err);
        exit(1);
    }

// create command queue
command_queue = clCreateCommandQueue(context,device_id, 0, &err);
if (err != CL_SUCCESS)
    {
        printf("Unable to create command queue. Error Code=%d\n",err);
        exit(1);
    }

// create program object from source.
// kernel_src contains source read from file earlier
program = clCreateProgramWithSource(context, 1,(const char **) &kernel_src, NULL, &err);
if (err != CL_SUCCESS)
    {
        printf("Unable to create program object. Error Code=%d\n",err);
        exit(1);
    }
err = clBuildProgram(program, 0, NULL, NULL, NULL, NULL);
if (err != CL_SUCCESS)
{
    printf("Build failed. Error Code=%d\n", err);
    size_t len;
    char buffer[2048];
    // get the build log
    clGetProgramBuildInfo(program, device_id, CL_PROGRAM_BUILD_LOG,
                           sizeof(buffer), buffer, &len);
    printf("--- Build Log -- \n%s\n",buffer);
    exit(1);
}

kernel = clCreateKernel(program, "matrixTranspose", &err);
if (err != CL_SUCCESS)
{
    printf("Unable to create kernel object. Error Code=%d\n",err);
    exit(1);
}

// create buffer objects to input and output args of kernel function
input_buffer =
    clCreateBuffer(context, CL_MEM_READ_ONLY|CL_MEM_COPY_HOST_PTR,
                    sizeof(cl_float) * ROWS*COLS, inputMatrix, NULL);
output_buffer = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
                                sizeof(cl_float) * ROWS*COLS, NULL ,NULL);

// set the kernel arguments
if ( clSetKernelArg(kernel, 0, sizeof(cl_mem), &output_buffer) ||
     clSetKernelArg(kernel, 1, sizeof(cl_mem), &input_buffer) ||
     clSetKernelArg(kernel, 2, sizeof(cl_uint), &width) != CL_SUCCESS)
{
    printf("Unable to set kernel arguments. Error Code=%d\n",err);
    exit(1);
}

// set the global work dimension size
global[0]= width;
global[1]= height;

// Enqueue the kernel object with
// Dimension size = 2,
// global worksise = global,
// local worksize = NULL - let OpenCL runtime determine
// No event wait list
err = clEnqueueNDRangeKernel(command_queue, kernel, 2, NULL,
                               NULL, 0, NULL, NULL);
if (err != CL_SUCCESS)
{
    printf("Unable to enqueue kernel command. Error Code=%d\n",err);
    exit(1);
}

// wait for the command to finish
clFinish(command_queue);

// read the output back to host memory
err = clEnqueueReadBuffer(command_queue, output_buffer, CL_TRUE, 0,
A.2 Matrix Multiplication Solution

Solution to the 8.2 Matrix Multiplication Exercise:
001 // ------ multMatrix.c **************
002
003 #include <stdio.h>
004 #include <stdlib.h>
005 #include "CL/cl.h"
006
007 #define ROWS 2048
008 #define COLS 2048
009
010 #define BLOCK_SIZE 8
011 int main()
012 {
013     cl_float *inputMatrix1;
014     cl_float *inputMatrix2;
015     cl_float *results;
016     cl_uint width = COLS;
017     cl_uint height = ROWS;
018
019     // OpenCL host variables
020     cl_uint num_devs Returned;
021     cl_context_properties properties[3];
022     cl_device_id device_id;
023     cl_int err;
024     cl_platform_id platform_id;
025     cl_uint num_platforms Returned;
026     cl_context context;
027     cl_command_queue command_queue;
028     cl_program program;
029     cl_kernel kernel;
030     cl_mem input_buffer1, input_buffer2, output_buffer;
031     size_t global[2];
032     size_t local[2];
033
034     // variables used to read kernel source file
035     FILE *fp;
036     long filelen;
037     long readlen;
038     char *kernel_src; // char string to hold kernel source
039
040     // initialize inputMatrix with some data and print it
041     int x, y;
042     int data = 0;
043
044     inputMatrix1 = malloc(sizeof(cl_float)*width*height);
045     inputMatrix2 = malloc(sizeof(cl_float)*width*height);
046     results = malloc(sizeof(cl_float)*width*height);
047
048     for (y = 0; y < height; y++)
049         {
050             for (x = 0; x < width; x++)
051                 {
052                     inputMatrix1[y*height + x] = data;
053                     inputMatrix2[y*height + x] = data;
054                     results[y*height + x] = 0;
055                     data++;
056                 }
057             data++;
058     }
062     // read the kernel
063     fp = fopen("multMatrix_kernel.cl","r");
064     fseek(fp,0L, SEEK_END);
065     filelen = ftell(fp);
066     rewind(fp);
067
068     kernel_src = malloc(sizeof(char)*(filelen+1));
069     readlen = fread(kernel_src,1,filelen,fp);
070     if(readlen!= filelen)
071     {
072        printf("error reading file\n");
073        exit(1);
074     }
075
076     // ensure the string is NULL terminated
077     kernel_src[filelen+1]="\0";
078
079
080     // OpenCL host source starts here ----
081
082     // get a platform id
083     err = clGetPlatformIDs(1,&platform_id,&num_platforms Returned);
084     if (err != CL_SUCCESS)
085     {
086        printf("Unable to get Platform ID. Error Code=\%d\n",err);
087        exit(1);
088     }
089
090     err = clGetDeviceIDs(platform_id, CL_DEVICE_TYPE_CPU, 1, &device_id, &num_devs_Returned);
091     if (err != CL_SUCCESS)
092     {
093        printf("Unable to get Device ID. Error Code=\%d\n",err);
094        exit(1);
095     }
096
097
098     // context properties list - must be terminated with 0
099     properties[0]= CL_CONTEXT_PLATFORM;
100     properties[1]= (cl_context_properties) platform_id;
101     properties[2]= 0;
102
103     // create context
104     context = clCreateContext(properties, 1, &device_id, NULL, NULL, &err);
105     if (err != CL_SUCCESS)
106     {
107        printf("Unable to create context. Error Code=\%d\n",err);
108        exit(1);
109     }
110
111     // create command queue
112     command_queue = clCreateCommandQueue(context,device_id, 0, &err);
113     if (err != CL_SUCCESS)
114     {
115        printf("Unable to create command queue. Error Code=\%d\n",err);
116        exit(1);
117     }
118
119     // create program object from source. kernel_src contains
120     // source read from file earlier
121     program = clCreateProgramWithSource(context, 1,(const char **) &kernel_src, NULL, &err);
122     if (err != CL_SUCCESS)
123     {
printf("Unable to create program object. Error Code=%d\n",err);
exit(1);
}

err = clBuildProgram(program, 0, NULL, NULL, NULL, NULL);
if (err != CL_SUCCESS)
{
    printf("Build failed. Error Code=%d\n", err);

    size_t len;
    char buffer[4096];
    // get the build log
    clGetProgramBuildInfo(program, device_id, CL_PROGRAM_BUILD_LOG, sizeof(buffer), buffer, &len);
    printf("--- Build Log -- \n %s\n",buffer);
    exit(1);
}

//kernel = clCreateKernel(program, "multMatrix", &err);
kernel = clCreateKernel(program, "multMatrixSimple", &err);
if (err != CL_SUCCESS)
{
    printf("Unable to create kernel object. Error Code=%d\n",err);
    exit(1);
}

// create buffer objects to input and output args of kernel function
input_buffer1 = clCreateBuffer(context, CL_MEM_READ_ONLY|CL_MEM_COPY_HOST_PTR, sizeof(cl_float) * ROWS*COLS, inputMatrix1, NULL);
input_buffer2 = clCreateBuffer(context, CL_MEM_READ_ONLY|CL_MEM_COPY_HOST_PTR, sizeof(cl_float) * ROWS*COLS, inputMatrix2, NULL);
output_buffer = clCreateBuffer(context, CL_MEM_WRITE_ONLY, sizeof(cl_float) * ROWS*COLS, NULL ,NULL);
// set the kernel arguments
if ( clSetKernelArg(kernel, 0, sizeof(cl_mem), &output_buffer) ||
     clSetKernelArg(kernel, 1, sizeof(cl_mem), &input_buffer1) ||
     clSetKernelArg(kernel, 2, sizeof(cl_mem), &input_buffer2) ||
     clSetKernelArg(kernel, 3, sizeof(cl_uint), &width) ||
     clSetKernelArg(kernel, 4, sizeof(cl_uint), &width) != CL_SUCCESS)
{
    printf("Unable to set kernel arguments. Error Code=%d\n",err);
    exit(1);
}

// set the global & local work size
global[0]= width;
global[1]= height;

local[0]=BLOCK_SIZE;
local[1]=BLOCK_SIZE;

// Enqueue the kernel object with
// Dimension size = 2,
// global worksizes = global,
// local worksizes = local
// No event wait list
err = clEnqueueNDRangeKernel(command_queue, kernel, 2, NULL, global,local, 0, NULL, NULL);
if (err != CL_SUCCESS)
{
    printf("Unable to enqueue kernel command. Error Code=%d\n",err);
    exit(1);
}

// wait for the command to finish
clFinish(command_queue);
186 // read the output back to host memory
187 err = clEnqueueReadBuffer(command_queue, output_buffer, CL_TRUE, 0, sizeof(cl_float)*width*height, results, 0, NULL, NULL);
188 if (err != CL_SUCCESS)
189 {
190     printf("Error enqueuing read buffer command. Error Code=%d\n",err);
191     exit(1);
192 }
193
194 // clean up
195 clReleaseMemObject(input_buffer1);
196 clReleaseMemObject(input_buffer2);
197 clReleaseMemObject(output_buffer);
198 clReleaseProgram(program);
199 clReleaseKernel(kernel);
200 clReleaseCommandQueue(command_queue);
201 clReleaseContext(context);
202
203 // ---- End of OpenCL host portion
204
205 // uncomment this block to print out matrix results
206 /*
207     printf("\nMatrix A\n");
208     for(y=0;y<height;y++)
209     {
210        for(x=0;x<width;x++)
211        {
212            printf("%.2f , ",inputMatrix1[y*height+x]);
213        }
214        printf("\n");
215    }
216
217     printf("\nMatrix B\n");
218     for(y=0;y<height;y++)
219     {
220            for(x=0;x<width;x++)
221            {
222                printf("%.2f , ",inputMatrix2[y*height+x]);
223            }
224            printf("\n");
225        }
226
227     // print out the transposed matrix
228     printf("\n Matrix A + Matrix B \n");
229     for(y=0;y<height;y++)
230     {
231            for(x=0;x<width;x++)
232            {
233                printf("%.2f , ",results[y*height+x]);
234            }
235            printf("\n");
236        }
237 */
238 free(kernel_src);
239 free(inputMatrix1);
240 free(inputMatrix2);
241 free(results);
242 return 0;
243 }