

# Lecture 22 — GPU Programming / OpenCL

Patrick Lam

`patrick.lam@uwaterloo.ca`

Department of Electrical and Computer Engineering  
University of Waterloo

April 4, 2019

# Part I

## OpenCL concepts

OpenCL: coding on a heterogeneous architecture.

- No longer just programming the CPU; will also leverage the GPU.

OpenCL = Open Computing Language.  
Usable on both NVIDIA and AMD GPUs.

Another term you may see vendors using:

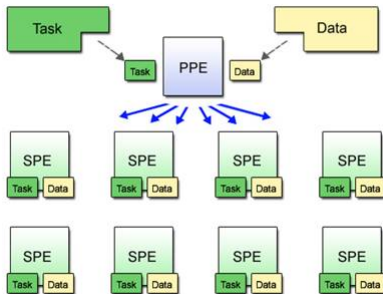
- **S**ingle **I**nstruction, **M**ultiple **T**hreads.
- Runs on a vector of data.
- Similar to SIMD instructions (e.g. SSE).  
However, the vector is spread out over the GPU.

- PlayStation 3 Cell
- CUDA

[PS4: back to a regular CPU/GPU system,  
albeit on one chip.]

Cell consists of:

- a PowerPC core; and
- 8 SIMD co-processors.



(from the Linux Cell documentation)

Compute Unified Device Architecture:  
NVIDIA's architecture for processing on GPUs.

“C for CUDA” predates OpenCL,  
NVIDIA supports it first and foremost.

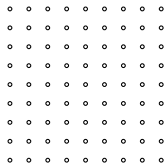
- May be faster than OpenCL on NVIDIA hardware.
- API allows you to use (most) C++ features in CUDA; OpenCL has more restrictions.

The abstract model is simple:

- Write the code for the parallel computation (*kernel*) separately from main code.
- Transfer the data to the GPU co-processor (or execute it on the CPU).
- Wait ...
- Transfer the results back.



- Key idea: evaluate a function (or *kernel*) over a set of points (data).



Another example of data parallelism.

- Another name for the set of points: *index space*.
- Each point corresponds to a **work-item**.

Note: OpenCL also supports *task parallelism* (using different kernels), but documentation is sparse.

**Work-item:** the fundamental unit of work in OpenCL.  
Stored in an  $n$ -dimensional grid (ND-Range); 2D above.

OpenCL spawns a bunch of threads to handle work-items.  
When executing, the range is divided into **work-groups**, which execute on the same compute unit.

The set of compute units (or cores) is called something different depending on the manufacturer.

- NVIDIA - *warp*
- AMD/ATI - *wavefront*

One thread per work item, each with a different thread ID.

You can say how to divide the ND-Range into work-groups, or the system can do it for you.

Scheduler assigns work-items to warps/wavefronts until no more left.

There are many different types of memory available to you:

- private memory: available to a single work-item;
- local memory (aka “shared memory”): shared between work-items belonging to the same work-group; like a user-managed cache;
- global memory: shared between all work-items as well as the host;
- constant memory: resides on the GPU and cached. Does not change.

There is also host memory (normal memory); usually contains app data.

Here's some traditional code to evaluate  $C_i = A_i B_i$ :

---

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

---

And as a kernel:

---

```
kernel void opencl_mul(global const float *a,  
                     global const float *b,  
                     global float *c) {  
    int id = get_global_id(0); // dimension 0  
    c[id] = a[id] * b[id];  
}
```

---

# Restrictions when writing kernels in OpenCL

It's mostly C, but:

- No function pointers.
- No bit-fields.
- No variable-length arrays.
- No recursion.
- No standard headers.

In kernels, you can also use:

- Work-items.
- Work-groups.
- Vectors.
- Synchronization.
- Declarations of memory type.
- Kernel-specific library.

```
kernel void contains_branch(global float *a,  
                             global float *b) {  
    int id = get_global_id(0);  
    if (cond) {  
        x[id] += 5.0;  
    } else {  
        y[id] += 5.0;  
    }  
}
```

The hardware will execute *all* branches that any thread in a warp executes—can be slow!

In other words: an `if` statement will cause each thread to execute both branches; we keep only the result of the taken branch.



```
kernel void contains_loop(global float *a,  
                           global float *b) {  
    int id = get_global_id(0);  
  
    for (i = 0; i < id; i++) {  
        b[i] += a[i];  
    }  
}
```

A loop will cause the workgroup to wait for the maximum number of iterations of the loop in any work-item.

Note: when you set up work-groups, best to arrange for all work-items in a workgroup to execute the same branches & loops.

Different workgroups execute independently.

You can only put barriers and memory fences between work-items in the same workgroup.

OpenCL supports:

- Memory fences (load and store).
- Barriers.
- `volatile` (beware!)

## Part II

# Programming with OpenCL

Today, we'll see how to program with OpenCL.

- We're using OpenCL 1.1.
- There is a lot of initialization and querying.
- When you compile your program, include `-lOpenCL`.

You can find the official documentation here:

<http://www.khronos.org/opencv/>

More specifically:

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

Let's just dive into an example.

- All data belongs to an **NDRange**.
- The range can be divided into **work-groups**. (in software)
- The work-groups run on **wavefronts/warps**. (in hardware)
- Each wavefront/warp executes **work-items**.

All branches in a wavefront/warp should execute the same path.

If an iteration of a loop takes  $t$ :  
when one work-item executes 100 iterations,  
the total time to complete the wavefront/warp is  $100t$ .

## Part III

### Simple Example

---

```
// Note by PL: don't use this example as a template;
// it uses the C bindings! Instead, use the C++ bindings.
// source: pages 1–9 through 1–11,
// http://developer.amd.com/wordpress/media/2013/07/
//     AMD_Accelerated_Parallel_Processing_OpenCL_
//     Programming_Guide–rev –2.7.pdf

#include <CL/cl.h>
#include <stdio.h>

#define NWITEMS 512

// A simple memset kernel
const char *source =
    "__kernel void memset( __global uint *dst )           \n"
    "{                                                       \n"
    "    dst[get_global_id(0)] = get_global_id(0);         \n"
    "}"                                                       \n";

int main(int argc, char ** argv)
{
    // 1. Get a platform.
    cl_platform_id platform;
    clGetPlatformIDs(1, &platform, NULL);
```

---

Include the OpenCL header.

Request a platform (also known as a host).

A platform contains *compute devices*:

- GPUs or CPUs.



---

```
// 2. Find a gpu device.
cl_device_id device;
clGetDeviceIDs(platform, CL_DEVICE_TYPE_GPU,
               1,
               &device,
               NULL);

// 3. Create a context and command queue on that device.
cl_context context = clCreateContext(NULL,
                                     1,
                                     &device,
                                     NULL, NULL, NULL);
cl_command_queue queue = clCreateCommandQueue(context,
                                               device,
                                               0, NULL);
```

---

Request a GPU device.

Request a OpenCL context (representing all of OpenCL's state).

Create a command-queue:

get OpenCL to do work by telling it to run a kernel in a queue.

---

```
// 4. Perform runtime source compilation, and obtain
//     kernel entry point.
cl_program program = clCreateProgramWithSource(context,
                                                1,
                                                &source,
                                                NULL,
                                                NULL);

clBuildProgram(program, 1, &device, NULL, NULL, NULL);
cl_kernel kernel = clCreateKernel(program, "memset",
                                   NULL);

// 5. Create a data buffer.
cl_mem buffer = clCreateBuffer(context,
                                CL_MEM_WRITE_ONLY,
                                NWITEMS * sizeof(cl_uint),
                                NULL, NULL);
```

---

We create an OpenCL “program” (runs on the compute unit):

- kernels;
- functions; and
- declarations.

In this case, we create a kernel called `memset` from source. OpenCL may also create programs from binaries (may be in intermediate representation).

Next, we need a *data buffer* (enables inter-device communication).

This program does not have any input, so we don't put anything into the buffer (just declare its size).

---

```
// 6. Launch the kernel. Let OpenCL pick the local work
//     size.
size_t global_work_size = NWITEMS;
clSetKernelArg(kernel, 0, sizeof(buffer), (void*)&buffer);
clEnqueueNDRangeKernel(queue,
                       kernel,
                       1, // dimensions
                       NULL, // initial offsets
                       &global_work_size, // number of
                                   // work-items
                       NULL, // work-items per work-group
                       0, NULL, NULL); // events

clFinish(queue);

// 7. Look at the results via synchronous buffer map.
cl_uint *ptr;
ptr = (cl_uint *)clEnqueueMapBuffer(queue, buffer,
                                   CL_TRUE, CL_MAP_READ,
                                   0, NWITEMS *
                                   sizeof(cl_uint),
                                   0, NULL, NULL, NULL);
```

---

Set kernel arguments to buffer.

We launch the kernel, enqueueing the 1-dimensional index space starting at 0.

We specify that the index space has `NWITEMS` elements;  
and not to subdivide the program into work-groups.

There is also an event interface, which we do not use.

We copy the results back; call is blocking (`CL_TRUE`);  
hence we don't need an explicit `clFinish()` call.

We specify that we want to read the results back into buffer.

---

```
int i;  
for(i=0; i < NWITEMS; i++)  
    printf("%d %d\n", i, ptr[i]);  
return 0;  
}
```

---

- The program simply prints 0 0, 1 1, ..., 511 511.
- Note: I didn't clean up or include error handling for any of the OpenCL functions.

## Part IV

### Another Example



If we use the C++ bindings, we'll get automatic resource release and exceptions.

- C++ likes to use the RAI style (resource allocation is initialization).

Change the header to `CL/cl.hpp` and define `__CL_ENABLE_EXCEPTIONS`.

We'd also like to store our kernel in a file instead of a string.

The C API is not so nice to work with.

Let's write a kernel that adds two vectors and stores the result.  
This kernel will go in the file `vector_add_kernel.cl`.

---

```
__kernel void vector_add(__global const int *A,
                        __global const int *B,
                        __global int *C) {

    // Get the index of the current element to be processed
    int i = get_global_id(0);

    // Do the operation
    C[i] = A[i] + B[i];
}
```

---

Other possible qualifiers: `local`, `constant` and `private`.

---

```
// Vector add example, C++ bindings (use these!)
// source:
// http://www.thebigblob.com/getting-started-with-opencl-and-gpu-computing/
//
#define __CL_ENABLE_EXCEPTIONS

#include <CL/cl.hpp>

#include <iostream>
#include <fstream>
#include <string>
#include <utility>
#include <vector>

int main() {
    // Create the two input vectors
    const int LIST_SIZE = 1000;
    int *A = new int[LIST_SIZE];
    int *B = new int[LIST_SIZE];
    for(int i = 0; i < LIST_SIZE; i++) {
        A[i] = i;
        B[i] = LIST_SIZE - i;
    }
```

---

---

```
try {  
    // Get available platforms  
    std::vector<cl::Platform> platforms;  
    cl::Platform::get(&platforms);  
  
    // Select the default platform and create a context  
    // using this platform and the GPU  
    cl_context_properties cps[3] = {  
        CL_CONTEXT_PLATFORM,  
        (cl_context_properties)(platforms[0])(),  
        0  
    };  
    cl::Context context(CL_DEVICE_TYPE_GPU, cps);  
  
    // Get a list of devices on this platform  
    std::vector<cl::Device> devices =  
        context.getInfo<CL_CONTEXT_DEVICES>();  
  
    // Create a command queue and use the first device  
    cl::CommandQueue queue = cl::CommandQueue(context,  
        devices[0]);
```

---

You can define `__NO_STD_VECTOR` and use `cl::vector` (same with strings).

You can enable profiling by adding `CL_QUEUE_PROFILING_ENABLE` as 3rd argument to `queue`.

---

```
// Read source file
std::ifstream sourceFile("vector_add_kernel.cl");
std::string sourceCode(
    std::istreambuf_iterator<char>(sourceFile),
    (std::istreambuf_iterator<char>())
);
cl::Program::Sources source(
    1,
    std::make_pair(sourceCode.c_str(),
                    sourceCode.length()+1)
);

// Make program of the source code in the context
cl::Program program = cl::Program(context, source);

// Build program for these specific devices
program.build(devices);

// Make kernel
cl::Kernel kernel(program, "vector_add");
```

---

---

```
// Create memory buffers
cl::Buffer bufferA = cl::Buffer(
    context,
    CL_MEM_READ_ONLY,
    LIST_SIZE * sizeof(int)
);
cl::Buffer bufferB = cl::Buffer(
    context,
    CL_MEM_READ_ONLY,
    LIST_SIZE * sizeof(int)
);
cl::Buffer bufferC = cl::Buffer(
    context,
    CL_MEM_WRITE_ONLY,
    LIST_SIZE * sizeof(int)
);
```

---

---

```
// Copy lists A and B to the memory buffers
queue.enqueueWriteBuffer(
    bufferA,
    CL_TRUE,
    0,
    LIST_SIZE * sizeof(int),
    A
);
queue.enqueueWriteBuffer(
    bufferB,
    CL_TRUE,
    0,
    LIST_SIZE * sizeof(int),
    B
);

// Set arguments to kernel
kernel.setArg(0, bufferA);
kernel.setArg(1, bufferB);
kernel.setArg(2, bufferC);
```

---



enqueue\*Buffer arguments:

- *buffer*
- *cl\_ bool blocking\_write*
- *::size\_t offset*
- *::size\_t size*
- *const void \*ptr*

---

```
// Run the kernel on specific ND range
cl::NDRange global(LIST_SIZE);
cl::NDRange local(1);
queue.enqueueNDRangeKernel(
    kernel ,
    cl::NullRange ,
    global ,
    local
);

// Read buffer C into a local list
int* C = new int[LIST_SIZE];
queue.enqueueReadBuffer(
    bufferC ,
    CL_TRUE ,
    0 ,
    LIST_SIZE * sizeof(int) ,
    C
);
```

---

---

```
        for(int i = 0; i < LIST_SIZE; i++) {
            std::cout << A[i] << " + " << B[i] << " = "
                        << C[i] << std::endl;
        }
    } catch(cl::Error error) {
        std::cout << error.what() << "(" << error.err()
                  << ")" << std::endl;
    }

    return 0;
}
```

---

This program just prints all the additions (equalling 1000).

The host memory is still unreleased.

- With the same number of lines, we could use the C++11 `unique_ptr`, which would free the memory for us.

You can use a vector instead of an array, and use `&v[0]` instead of `<type>*`.

- Valid as long as the vector is not resized.

Went through real OpenCL examples.  
Have the reference card for the API.

Saw a C++ template for setting up OpenCL.

**Aside:** if you're serious about programming in C++, check out **Effective C++** by Scott Meyers (slightly dated with C++11, but it still has some good stuff)

**First Half:** Brief overview of OpenCL and its programming model.

Many concepts are similar to plain parallel programming (more structure).

**Second Half:** Looked at an OpenCL implementation and how to organize it.

Need to write lots of boilerplate!