Lecture 22 — GPU Programming / OpenCL

Patrick Lam
p.lam@ece.uwaterloo.ca

Department of Electrical and Computer Engineering
University of Waterloo

December 2, 2017

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.

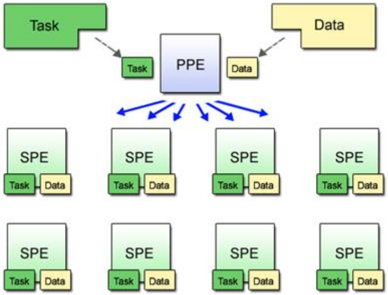
Other Heterogeneous Programming Examples

- 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)

CUDA Overview

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

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

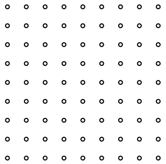
- May be faster than OpenCL on NVIDIA hardware.
- API allows you to use (most) C++ features in CUDA;
  OpenCL has more restrictions.

GPU Programming Model

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*

Work-Items: Three more details

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.

OpenCL's Additions to C in Kernels

In kernels, you can also use:

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

Branches in kernels

```
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.

Loops in kernels

```
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.

Synchronization

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/opencl/`

More specifically:

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

Let's just dive into an example.

First, reminders

- 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);
```

Explanation (1)

Include the OpenCL header.

Request a platform (also known as a host).

A platform contains *compute devices*:

- GPUs or CPUs.

Simple Example (2)

```
// 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);
```

Explanation (2)

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.

Simple Example (3)

```
// 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);
```

Explanation (3)

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).

Simple Example (4)

```
// 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);
```

Explanation (4)

Set kernel arguments to `buffer`.

We launch the kernel, enqueuing 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.

Simple Example (5)

```
    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

C++ Bindings

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

- C++ likes to use the RAII 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.

Vector Addition Kernel

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 Addition (1)

```
// 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;
    }
```

Vector Addition (2)

```
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]);
```

Explanation (2)

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`.

Vector Addition (3)

```
// 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");
```

Vector Addition (4)

```
// 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*

Vector Addition (6)

```
// 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).

Other Improvements

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.

OpenCL Programming Summary

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)

Overall summary

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!