Master Educational Program
“Information technology in applications”

Mathematical computations with GPUs

Introduction to OpenCL

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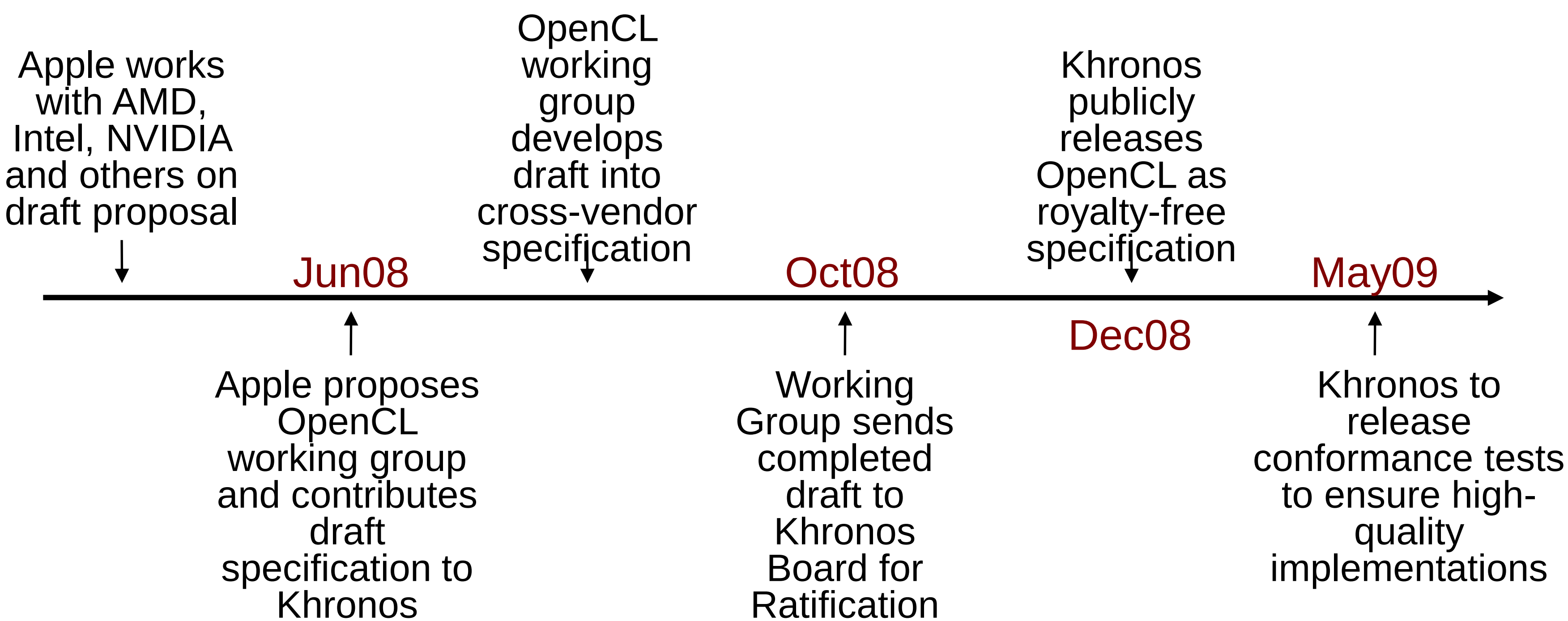
OpenCL (Open Computing Language)

* A standard based upon C for portable parallel applications.
* Task parallel and data parallel applications
* Focuses on multi platform support (multiple CPUs, GPUs, …)
* Development initiated by Apple.
* Developed by Khromos group who also managed OpenGL
* OpenCL 1.0 2008. Released with Max OS 10.6 (Snow Leopard)
* OpenCL 1.1 June 2010
* Similarities with CUDA.

OpenCL Timeline

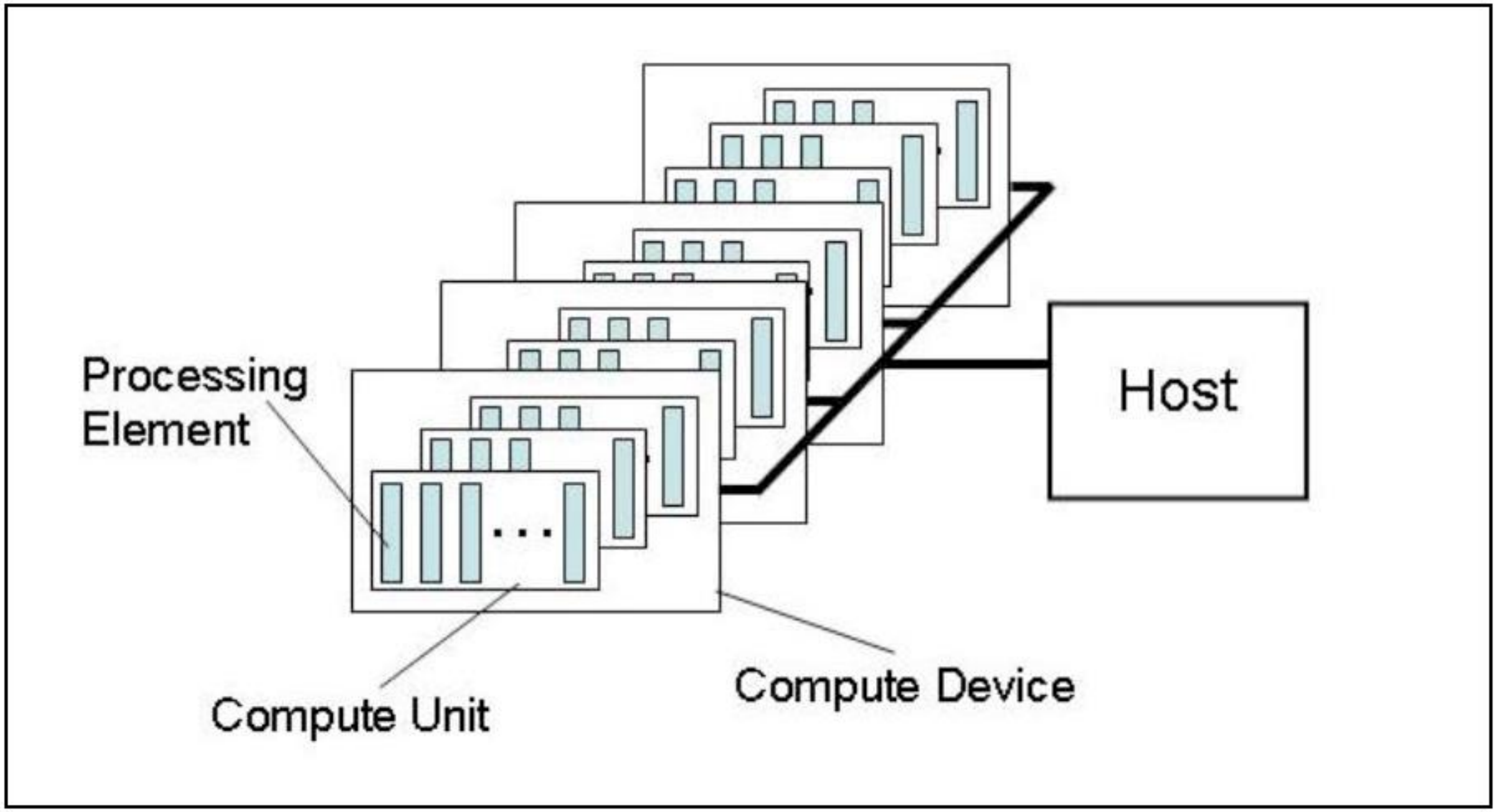
- **Six months from proposal to released specification**
  - Due to a strong initial proposal and a shared commercial incentive to work quickly
- **Apple's Mac OS X Snow Leopard will include OpenCL**
  - Improving speed and responsiveness for a wide spectrum of applications
- **Multiple OpenCL implementations expected in the next 12 months**
  - On diverse platforms



Модель OpenCL

- Platform Model
- Memory Model
- Execution Model
- Programming Model

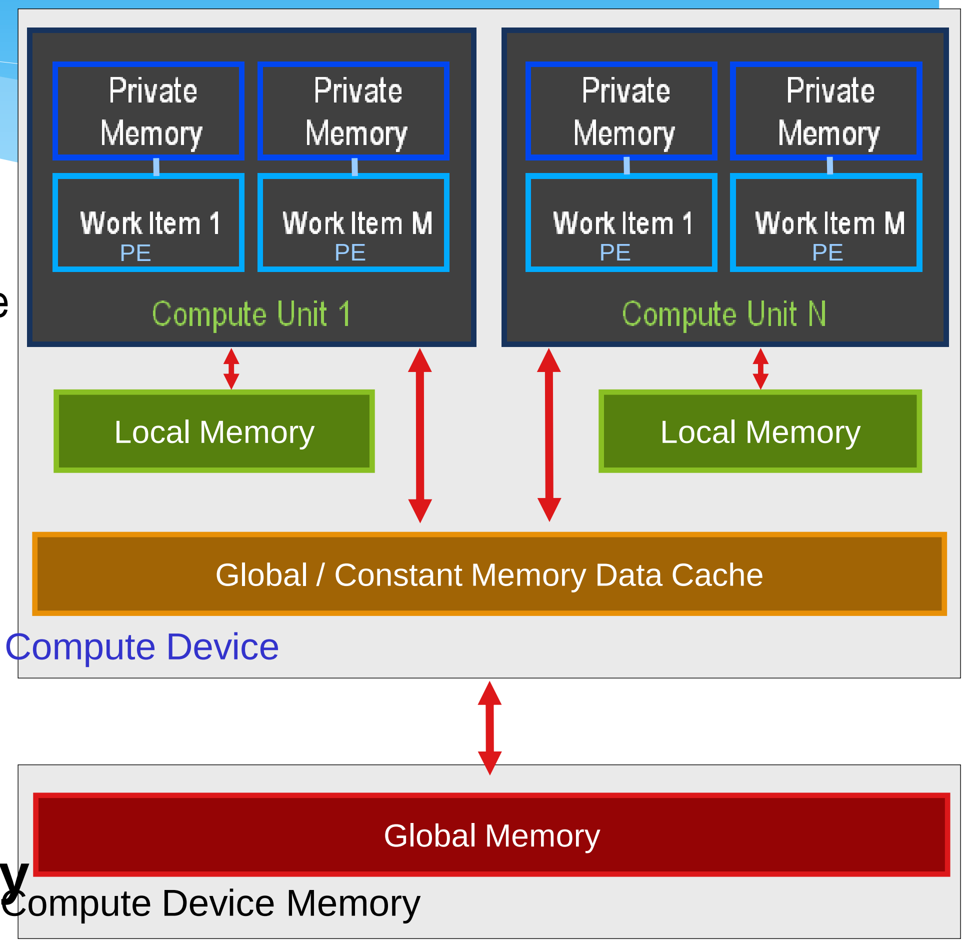
OpenCL Platform Model



- **One <u>Host</u> + one or more <u>Compute Devices</u>**
  - Each **Compute Device** is composed of one or more **Compute Units**
    - Each **Compute Unit** is further divided into one or more **Processing Elements**

OpenCL Memory Model

- **Shared memory model**
  - Relaxed consistency
- **Multiple distinct address spaces**
  - Address spaces can be collapsed depending on the device's memory subsystem
- **Address spaces**
  - Private - private to a *work-item*
  - Local - local to a *work-group*
  - Global - accessible by all work-items in all work-groups
  - Constant - read only global space
- **Implementations map this hierarchy**
  - To available physical memories



Memory Consistency

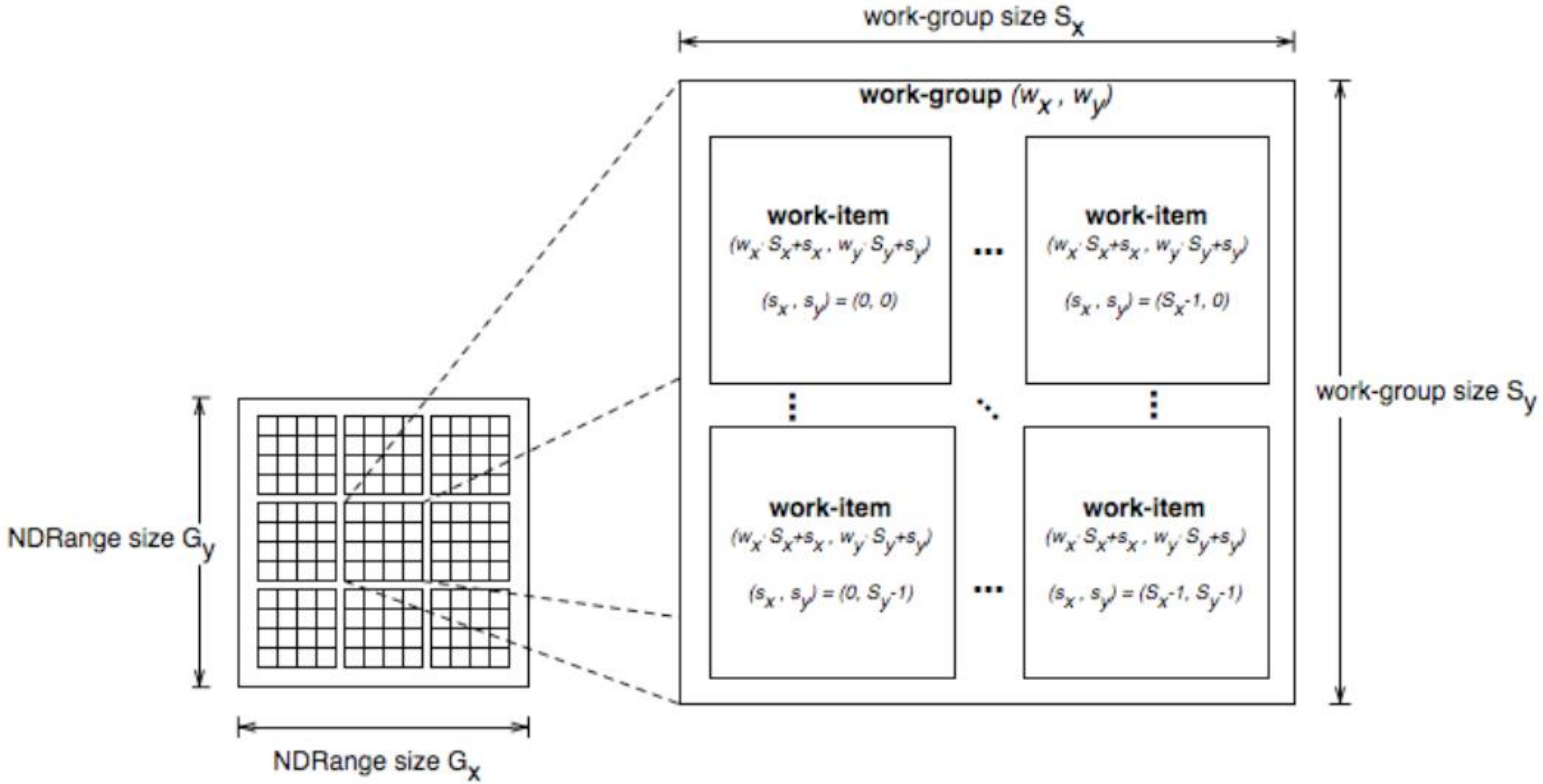
- **OpenCL uses a "relaxed consistency memory model"**
  - State of memory visible to a work-item ***not*** guaranteed to be consistent across the collection of work-items at all times
- **Memory has load/store consistency within a *work-item***
- **Local memory has consistency across work-items within a *work-group* at a barrier**
- **Global memory is consistent within a *work-group* at a barrier, but not guaranteed across different work-groups**
- **Memory consistency for objects shared between commands enforced at synchronization points**

OpenCL Execution Model

- **OpenCL *Program*:**
  - Kernels
    - Basic unit of executable code — similar to C functions, CUDA kernels, etc.
    - Data-parallel or task-parallel
  - Host Program
    - Collection of compute kernels and internal functions
    - Analogous to a dynamic library

- ***Kernel* Execution**
  - The host program invokes a kernel over an index space called an ***NDRange***
    - NDRange, “N-Dimensional Range”, can be a 1D, 2D, or 3D space
  - A single kernel instance at a point in the index space is called a ***work-item***
    - Work-items have unique global IDs from the index space
  - Work-items are further grouped into ***work-groups***
    - Work-groups have a unique work-group ID
    - Work-items have a unique local ID within a work-group

Kernel Execution



- **Total number of work-items = G_x * G_y**
- **Size of each work-group = S_x * S_y**
- **Global ID can be computed from work-group ID and local ID**

Contexts and Queues

- ***Contexts* are used to contain and manage the state of the "world"**

- **Kernels are executed in contexts defined and manipulated by the host**
  - Devices
  - Kernels - OpenCL functions
  - Program objects - kernel source and executable
  - Memory objects

- **Command-queue** - coordinates execution of kernels
  - Kernel execution commands
  - Memory commands: Transfer or map memory object data
  - Synchronization commands: Constrain the order of commands

- **Applications queue instances of compute kernel execution**
  - Queued in-order
  - Executed in-order or out-of-order
  - Events are used to synchronization execution instances as appropriate

Programming Model

Data-Parallel Model

- **Must be implemented by *all* OpenCL compute devices**

- **Define N-Dimensional computation domain**
  - Each independent element of execution in an N-Dimensional domain is called a *work-item*
  - N-Dimensional domain defines total # of work-items that execute in parallel
    = *global work size*

- **Work-items can be grouped together — *work-group***
  - Work-items in group can communicate with each other
  - Can synchronize execution among work-items in group to coordinate memory access

- **Execute multiple work-groups in parallel**
  - Mapping of global work size to work-group can be implicit or explicit

Programming Model

Task-Parallel Model

- **Some compute devices can also execute task-parallel compute kernels**

- **Execute as a *single* work-item**
  - A compute kernel written in OpenCL
  - A native C / C++ function

Basic OpenCL Program Structure

- **Host program**
  - Query compute devices
  - Create contexts
  - Create memory objects associated to contexts
  - Compile and create kernel program objects
  - Issue commands to command-queue
  - Synchronization of commands
  - Clean up OpenCL resources
- **Kernels**
  - C code with some restrictions and extensions

Platform Layer

Runtime

Language

OpenCL C Language Restrictions

- Pointers to functions not allowed
- Pointers to pointers allowed within a kernel, but not as an argument
- Bit-fields not supported
- Variable-length arrays and structures not supported
- Recursion not supported
- Double types - OpenCL 1.2 and newer

- Some restrictions are addressed through extensions

https://www.khronos.org/registry/OpenCL/specs/3.0-unified/html/OpenCL_C.html#restrictions

OpenCL vs. CUDA

- C for CUDA Kernel Code:

```
__global__ void
    vectorAdd(const float * a, const float * b, float * c){
        // Vector element index
        int nIndex = blockIdx.x * blockDim.x + threadIdx.x;
        c[nIndex] = a[nIndex] + b[nIndex];
    }
```

- OpenCL Kernel Code

```
__kernel void
    vectorAdd(__global const float * a,
              __global const float * b,
              __global       float * c){
        // Vector element index
        int nIndex = get_global_id(0);
        c[nIndex] = a[nIndex] + b[nIndex];
    }
```

Group and grid size in OpenCL

- `get_local_id()`
- `get_work_dim()`
- `get_global_size()`
- `get_global_id()`

OpenCL vs. CUDA. Initialization

- CUDA

```
cuInit(0);
cuDeviceGet(&hDevice, 0);
cuCtxCreate(&hContext, 0, hDevice);
```

- OpenCL

```
cl_context hContext;
  hContext = clCreateContextFromType(0, CL_DEVICE_TYPE_GPU,
                                     0, 0, 0);
  size_t nContextDescriptorSize;
  clGetContextInfo(hContext, CL_CONTEXT_DEVICES,
                   0, 0, &nContextDescriptorSize);
  cl_device_id * aDevices = malloc(nContextDescriptorSize);
  clGetContextInfo(hContext, CL_CONTEXT_DEVICES,
                   nContextDescriptorSize, aDevices, 0);
  cl_command_queue hCmdQueue;
  hCmdQueue = clCreateCommandQueue(hContext, aDevices[0],
  0,0);
```

OpenCL vs. CUDA. Creating kernel

- CUDA

```
CUmodule hModule;
cuModuleLoad(&hModule, “vectorAdd.cubin”);
cuModuleGetFunction(&hFunction, hModule, "vectorAdd");
```

- OpenCL

Количество строк

Код ошибки

```
cl_program hProgram;
hProgram = clCreateProgramWithSource(hContext, 1,
                              sProgramSource, 0, 0);
clBuildProgram(hProgram, 0, NULL, NULL, NULL, NULL);
```

Код ошибки

```
cl_kernel hKernel;
hKernel = clCreateKernel(hProgram, “vectorAdd”, 0);
```

OpenCL vs. CUDA. Memory allocation

- CUDA

```
CUdeviceptr pDevMemA, pDevMemB, pDevMemC;
cuMemAlloc(&pDevMemA, cnDimension * sizeof(float));
cuMemAlloc(&pDevMemB, cnDimension * sizeof(float));
cuMemAlloc(&pDevMemC, cnDimension * sizeof(float));
// copy host vectors to device
cuMemcpyHtoD(pDevMemA, pA, cnDimension * sizeof(float));
cuMemcpyHtoD(pDevMemB, pB, cnDimension * sizeof(float));
```

OpenCL vs. CUDA. Memory allocation

- OpenCL

```
cl_mem hDevMemA, hDevMemB, hDevMemC;
  hDevMemA = clCreateBuffer(hContext,
                          CL_MEM_READ_ONLY |
  CL_MEM_COPY_HOST_PTR,
                          cnDimension * sizeof(cl_float),
                          pA,
                          0);
hDevMemB = clCreateBuffer(hContext,
                        CL_MEM_READ_ONLY |
  CL_MEM_COPY_HOST_PTR,
                        cnDimension * sizeof(cl_float),
                        pA,
                        0);
hDevMemC = clCreateBuffer(hContext,
                          CL_MEM_WRITE_ONLY,
                          cnDimension * sizeof(cl_float),0, 0);
```

Код ошибки

Код ошибки

OpenCL vs. CUDA. Kernel parameters

- CUDA

```
cuParamSeti(cuFunction, 0,  pDevMemA);
cuParamSeti(cuFunction, 4,  pDevMemB);
cuParamSeti(cuFunction, 8,  pDevMemC);
cuParamSetSize(cuFunction,  12);
```

- OpenCL:

```
clSetKernelArg(hKernel, 0, sizeof(cl_mem),
                        (void *)&hDevMemA);
clSetKernelArg(hKernel, 1, sizeof(cl_mem),
                        (void *)&hDevMemB);
clSetKernelArg(hKernel, 2, sizeof(cl_mem),
                        (void *)&hDevMemC);
```

OpenCL vs. CUDA. Launching kernel

- CUDA

```
cuFuncSetBlockShape(cuFunction, cnBlockSize, 1, 1);
cuLaunchGrid       (cuFunction, cnBlocks, 1);
```

- OpenCL

```
clEnqueueNDRangeKernel(hCmdQueue, hKernel, 1, 0,
               &cnDimension, &cnBlockSize, 0, 0, 0);
```

OpenCL vs. CUDA. Copy result back

- CUDA

```
cuMemcpyDtoH((void*)pC, pDevMemC,
  cnDimension*sizeof(float));
```

- OpenCL

```
clEnqueueReadBuffer(hContext, hDeviceC, CL_TRUE, 0,
                    cnDimension * sizeof(cl_float),
                    pC, 0, 0, 0);
```

Release resourses

- **OpenCL**

```
clReleaseMemObject(hDevMemA);
clReleaseMemObject(hDevMemB);
clReleaseMemObject(hDevMemC);
free (aDevices);
clReleaseKernel (hKernel);
clReleaseProgram (hProgram);
clReleaseCommandQueue (hCmdQueue);
clReleaseContext (hContext);
```

Recourses OpenCL

- Khronos OpenCL Homepage
  http://www.khronos.org/opencl
- OpenCL 3.0 Specification
  https://www.khronos.org/registry/OpenCL/specs
- OpenCL at NVIDIA
  http://www.nvidia.com/object/cuda_opencl.html