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GPGPU Computing with OpenCL

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Motivation

- More data is generated, more data has to be processed and analyzed
- Despite Moore’s law, CPUs hit a performance wall
- GPU architectures *can* give a higher throughput and better performance

GPU advantages

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Why are GPUs good at what they do?

- GPUs are heavily optimized towards pixelation of 3D data
- GPUs have flexible, programmable pipelines
- Architecture consists of many but rather simple compute cores
- Instruction set is tailored towards math and image operations

Some numbers of NVIDIAs GTX Titan flagship

- 6 GB at 288.4 GB/s
- 4500 (SP) / 1500 (DP) GFLOPs (equivalent of supercomputer in 2000)
- 250 W power consumption

Limitations

There are no silver bullets

- Optimal performance with regular, parallel tasks
- High operations-per-memory-access ratios[1]
- Bus can become a bottleneck[2]
- Limited main memory, thus partitioning might be necessary

Think about your algorithm first

- Cliché quote: “premature optimization is the root of all evil”
- $O(c^n)$ is slow, no matter where you run it

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[1] 4500 GFLOPS / 288.4 GB/s = 16 FLOP/B

[2] 4500 GFLOPS / 16 GB/s (PCIe 3.0 x16) = 280 FLOP/B

History and Background

Development of GPGPU abstractions

- Early research prototypes (e.g. Brook) used OpenGL shaders
- NVIDIA presented CUDA in 2007
- OpenCL initiated by Apple first released in 2008/09
- High-level pragmas in OpenACC à la OpenMP since 2012

Why OpenCL?

- Open, vendor-neutral standard
- Cross-platform support (Linux, Windows, Mac)
- Multiple hardware platforms (CPUs, GPUs, FPGAs)

OpenCL concepts

Programming model

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Platform

- A host controls $\geq$ 1 *platforms* (e.g. vendor SDKs)
- A platform consists of $\geq$ 1 *devices*
- The host manages resources and schedules execution
- The devices execute code assigned to them by the host

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Programming model

Platform

- A host controls ≥ 1 *platforms* (e.g. vendor SDKs)
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Devices

- A device has ≥ 1 *compute units*
- Each CU has ≥ 1 *processing elements*
- How CUs and PEs are mapped to hardware is *not* specified

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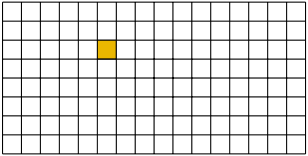
Execution model

- Work is arranged as work items on a 1D, 2D or 3D grid



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Execution model

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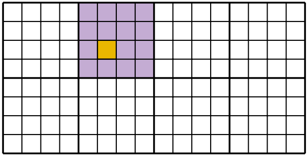
- Grid is split into work groups



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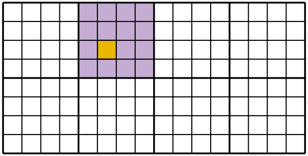

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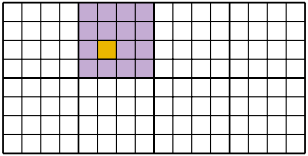
- Work is arranged as work items on a 1D, 2D or 3D grid
- Grid is split into work groups
- Work groups are scheduled on one or more CUs
- Work items are executed on PEs



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Kernel

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- A kernel is a piece of code executed by *each* work item
- In most cases it corresponds to the innermost body of a for loop, e.g. from

  ```
  for (int i = 1; i < N-1; i++)
      x[i] = sin(y[i]) + 0.5 * (x[i-1] + x[i+1]);
  ```

  you would extract the kernel

  ```
  x[i] = sin(y[i]) + 0.5 * (x[i-1] + x[i+1]);
  ```

- A kernel has implicit parameters to identify itself
  - Location relative to the work group
  - Location relative to the global grid
  - Number of work groups/items

Memory model

Memory, buffers and images

- Host *cannot* access device memory directly and vice versa
- Buffers to transfer data between host and device memory
- Images are structured buffers

Device memory

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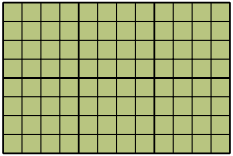
Device memory

Global host-accessible, read/write-able by *all* work items



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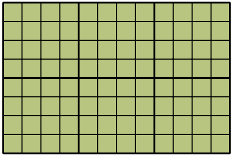
Device memory

Global host-accessible, read/write-able by *all* work items

Constant host-accessible, read-only by *all* work items



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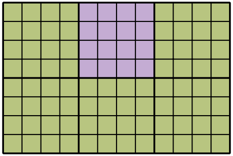
Device memory

Global	host-accessible, read/write-able by *all* work items
Constant	host-accessible, read-only by *all* work items
Local	local to a work group



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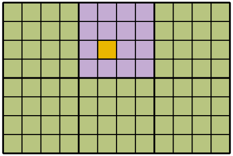
Constant	host-accessible, read-only by *all* work items
Local	local to a work group
Privat	local to a work item



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OpenCL API

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Implementations

Vendor	Rev.	GPU	CPU	FPGA	OS
NVIDIA	1.1	✓	✗	✗	Linux, Windows, Apple
AMD	1.2	✓	✓	✗	Linux, Windows, Apple
Intel	1.2	✓	✓	✗	Linux, Windows
Apple	1.1[1]	✓	✓	✗	Apple
Altera	1.0	✗	✗	✓	Linux, Windows

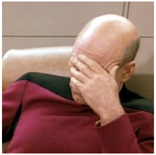
[1] OpenCL 1.2 from OS X 10.9

Prerequisites

- OpenCL is specified as a C API and a kernel language
- Link against `-lOpenCL` — generic driver loads implementation at run-time
- Header location depends on host platform ...

```
/* UNIX and Windows */
#include <CL/cl.h>

/* Apple */
#include <OpenCL/cl.h>
```



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Kernel syntax

- Written in a C99 superset
- Address space specifiers (`global` and `local`)
- Work item and math related builtins
- Vector types (e.g. `int4`, `float3`, …)

```
kernel void
scale_vector (global float *output,
              global float *input,
              float scale)
{
    int idx = get_global_id (0);    /* global location */
    output[idx] = scale * input[idx];
}
```


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Querying all platforms

```
cl_uint n_platforms;
cl_platform_id *platforms = NULL;

e = clGetPlatformIDs (0, NULL, &n_platforms);

platforms = malloc (n_platforms * sizeof (cl_platform_id));

e = clGetPlatformIDs (n_platforms, &platforms, NULL);
```


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Querying devices of one platform

```
cl_uint n_devices;
cl_device_id *devices = NULL;

e = clGetDeviceIDs (platforms[0], CL_DEVICE_TYPE_ALL,
                    0, NULL, &n_devices);

devices = malloc (n_devices * sizeof (cl_device_id);

e = clGetDeviceIDs (platforms[0], CL_DEVICE_TYPE_ALL,
                    n_devices, &devices, NULL);

/* If you don't use it anymore, decrement the reference */
e = clReleaseDevice (device);
```


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Device contexts

Resources are shared between devices in the same context, thus contexts model application specific behaviour:

```
cl_context context;

context = clCreateContext (NULL, n_devices, devices,
                           NULL, NULL, &err);
```


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Buffer objects

Buffers are created in a context. At run-time, the OpenCL environment decides when memory is transfered to a specific device.

```
size_t size;
cl_mem dev_input;
cl_mem dev_result;

size = 1024 * 1024 * sizeof (float);
dev_input = clCreateBuffer (context, CL_MEM_READ_ONLY,
                             size, NULL, &err);
dev_result = clCreateBuffer (context, CL_MEM_WRITE_ONLY,
                              size, NULL, &err);
```

Command queues

Device commands (data transfer, kernel launches ...) are enqueued in one command queue per device:

```
cl_command_queue queue;

queue = clCreateCommandQueue (context, devices[0], 0, &err);
```

The third parameter can be used to toggle out of order execution and profiling.

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Transfering data

```
e = clEnqueueWriteBuffer (queue, dev_input,
                          TRUE, /* blocking call? */
                          0, size,
                          host_input,
                          0, NULL, NULL);
```

Building kernel code

Kernel code is compiled at run-time because the target hardware is not necessarily known at compile-time (…and allows cool stunts like run-time code generation)

```
cl_program program;
cl_kernel kernel;

/* Create and build program */
program = clCreateProgramWithSource (context, 1, source,
                                     NULL, &e);
e = clBuildProgram (program, n_devices, devices,
                    NULL, NULL, NULL);

/* Extract kernel */
kernel = clCreateKernel (program, "scale_vector", &e);
```


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Launching kernels

```
size_t global_work_size[] = { 1024 };
size_t global_work_offset[] = { 0 };
cl_event event;

e = clEnqueueNDRangeKernel (queue, kernel,
                            1, /* grid dimensions */
                            global_work_offset,
                            global_work_size,
                            0, NULL, &event);
```


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Events

All commands accept and return `cl_event` objects

```
cl_int clEnqueueXXX (...,
                     cl_uint wait_list_length,
                     const cl_event *wait_list,
                     cl_event *event);
```

that can be used to

```
/* Wait for one or more events */
e = clWaitForEvents (1, &event);

/* Query event information */
e = clGetEventInfo (event, CL_EVENT_COMMAND_EXECUTION_STATUS,
                    sizeof (cl_int), &result, NULL);
```


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Kernel synchronization

Events are also used to ensure correct enqueuing order in out-of-order queues:

```
clEnqueueNDRangeKernel (queue, kernel_foo,
                        ...,
                        NULL, NULL, &foo_event);

clEnqueueNDRangeKernel (queue, kernel_bar,
                        ...,
                        1, &foo_event, &bar_event);

clReleaseEvent (foo_event);
clReleaseEvent (bar_event);
```


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Work item synchronization

Guarantee that all work items are waiting at the same point before proceeding:

```
barrier (mem_fence_flags);
```

Make sure that all the other work items read the same values:

```
mem_fence (mem_fence_flags);
write_mem_fence (mem_fence_flags);
read_mem_fence (mem_fence_flags);
```

`mem_fence_flags` must be a combination of

- `CLK_LOCAL_MEM_FENCE`: for guarantees inside a work group
- `CLK_GLOBAL_MEM_FENCE`: across all work items

Considerations

- All resources are reference-counted $\rightarrow$ release them when not used!
- Every call returns an error code $\rightarrow$ check all of them!
- Using `double` will decrease performance by factor two (if it works at all)

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