OpenCL™
Parallel computing for CPUs and GPUs

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Advanced Micro Devices

OpenCL™

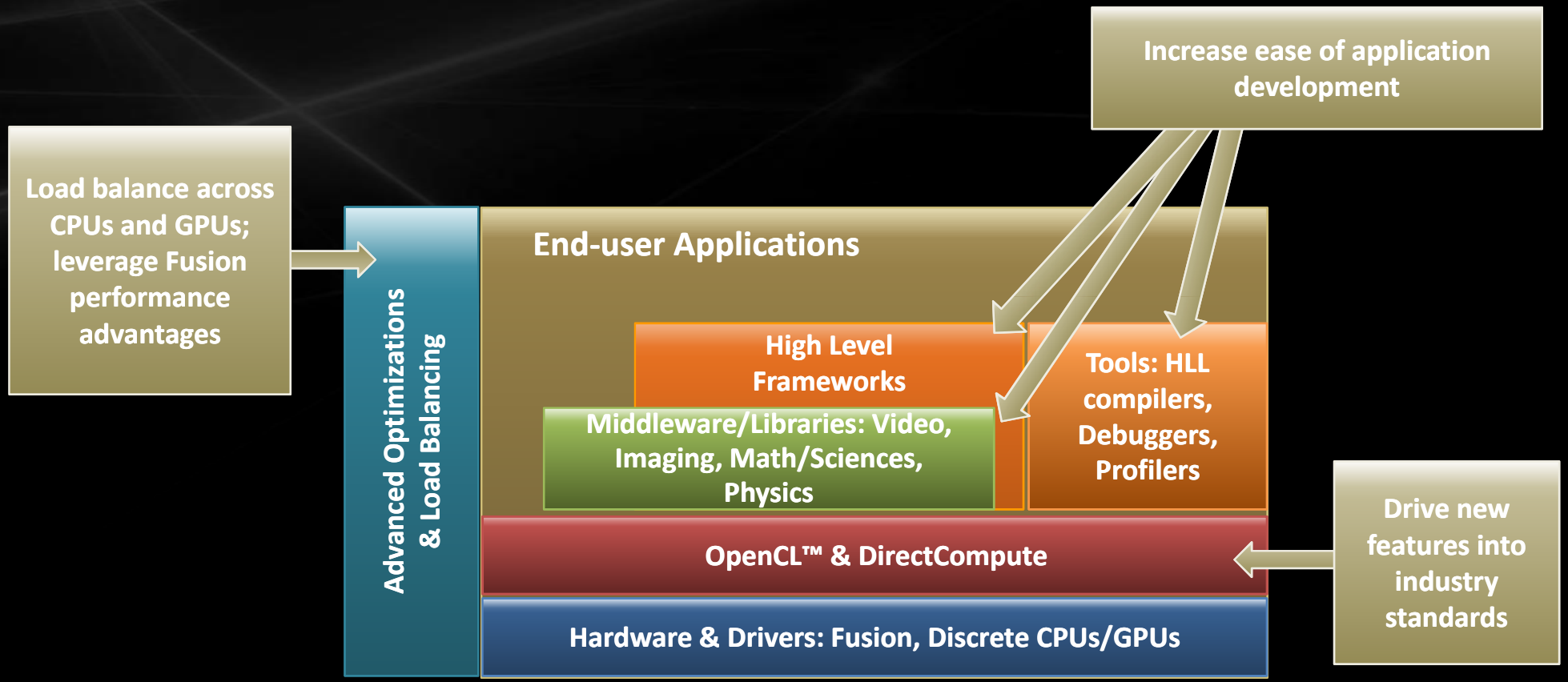
With OpenCL™ you can…

- Leverage CPUs and GPUs to accelerate parallel computation
- Get dramatic speedups for computationally intensive applications
- Write accelerated portable code across different devices and architectures

With AMD's implementations you can…

- Leverage CPUs, AMD's GPUs, to accelerate parallel computation
- OpenCL Public release for multi-core CPU and AMD's GPU's December 2009
- The closely related DirectX® 11 public release supporting DirectCompute on AMD GPUs in October 2009, as part of Win7 Launch

The Heterogeneous Computing Software Ecosystem



Outline

What is OpenCL™?

- The OpenCL Platform, Execution and Memory Model

Using the OpenCL framework

- Setup
- Resource Allocation
- Compilation and execution of kernels

The OpenCL C language

- Language Features
- Built-in Functions

An OpenCL source example

Adding abstraction: C++ bindings for OpenCL

Two examples of use:

- SPH
- Soft body simulation

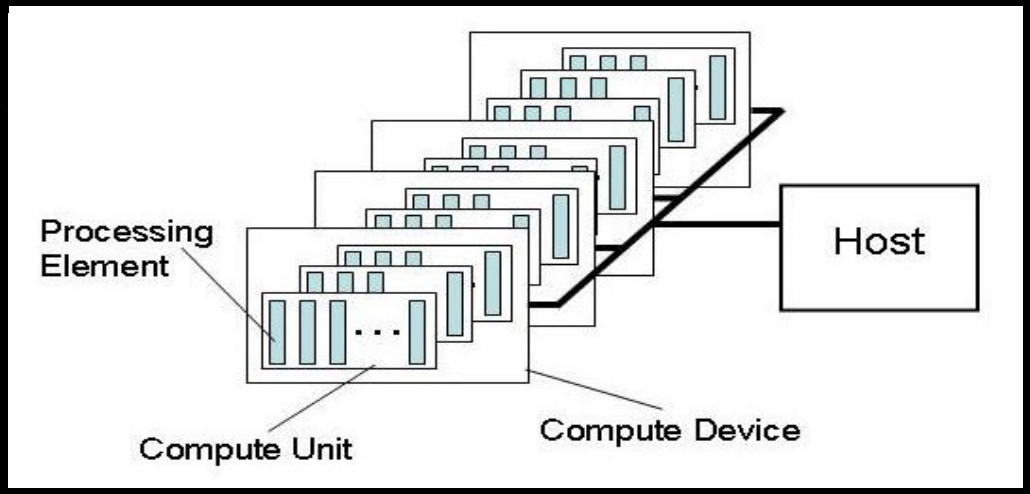
What is OpenCL™?

OpenCL™ Platform Model

A host connected to one or more OpenCL devices

An OpenCL device is

- A collection of one or more compute units (arguably cores)
- A compute unit is composed of one or more processing elements
- Processing elements execute code as SIMD or SPMD



OpenCL™ Execution Model

Kernel

- Basic unit of executable code - similar to a C function
- Data-parallel or task-parallel

Program

- Collection of kernels and other functions
- Analogous to a dynamic library

Applications queue kernel execution instances

- Queued in-order
- Executed in-order or out-of-order

Expressing Data-Parallelism in OpenCL™

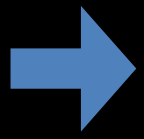
Define N-dimensional computation domain (N = 1, 2 or 3)

- Each independent element of execution in N-D domain is called a work-item
- The N-D domain defines the total number of work-items that execute in parallel

E.g., process a 1024 x 1024 image: Global problem dimensions: 1024 x 1024 = 1 kernel execution per pixel: 1,048,576 total kernel executions

Scalar

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



Data-parallel

```
kernel void
dp_mul(global const float *a,
       global const float *b,
       global float *result)
{
  int id = get_global_id(0);

  result[id] = a[id] * b[id];
}
// execute dp_mul over "n" work-items
```

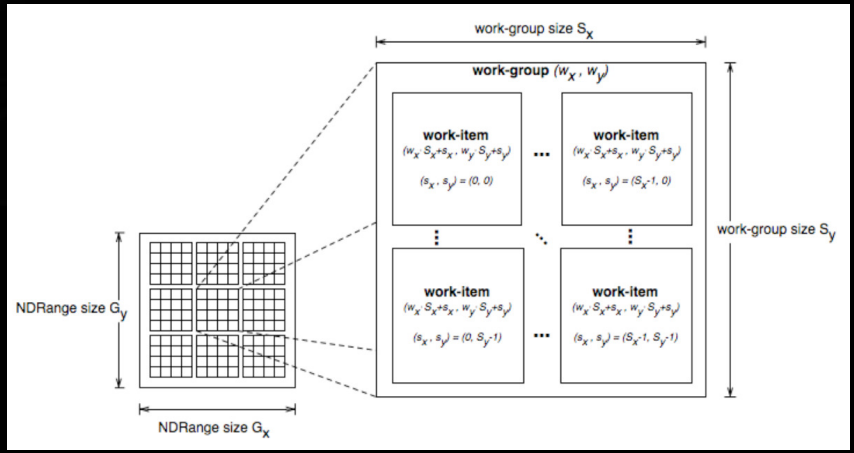
Expressing Data-Parallelism in OpenCL™ (continued)

Kernels executed across a global domain of work-items

- Global dimensions define the range of computation
- One work-item per computation, executed in parallel

Work-items are grouped in local workgroups

- Local dimensions define the size of the workgroups
- Executed together on one device
- Share local memory and synchronization



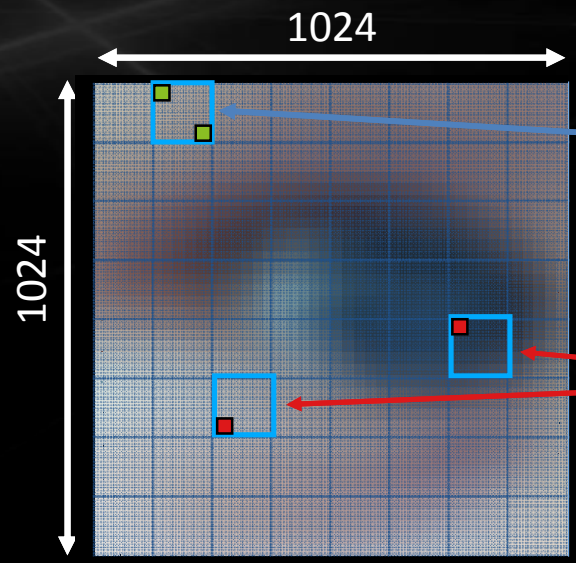
Caveats

- Global work-items must be independent: *no global synchronization*
- Synchronization can be done within a workgroup

Global and Local Dimensions

Global Dimensions: 1024 x 1024 (whole problem space)

Local Dimensions: 128 x 128 (executed together)



Synchronization between work-items possible only within workgroups: barriers and memory fences

Can not synchronize outside of a workgroup

Choose the dimensions that are “best” for your algorithm

Task-Parallelism in OpenCL™

A task kernel executes as a single work-item

- No data-parallel iteration space

Flexible source language:

- Can be written in OpenCL™ C
- Or be native compiled from C/C++

Native functions can then be queued in the OpenCL queuing model (see later…)

OpenCL™ Memory Model

Private Memory

- Per work-item

Local Memory

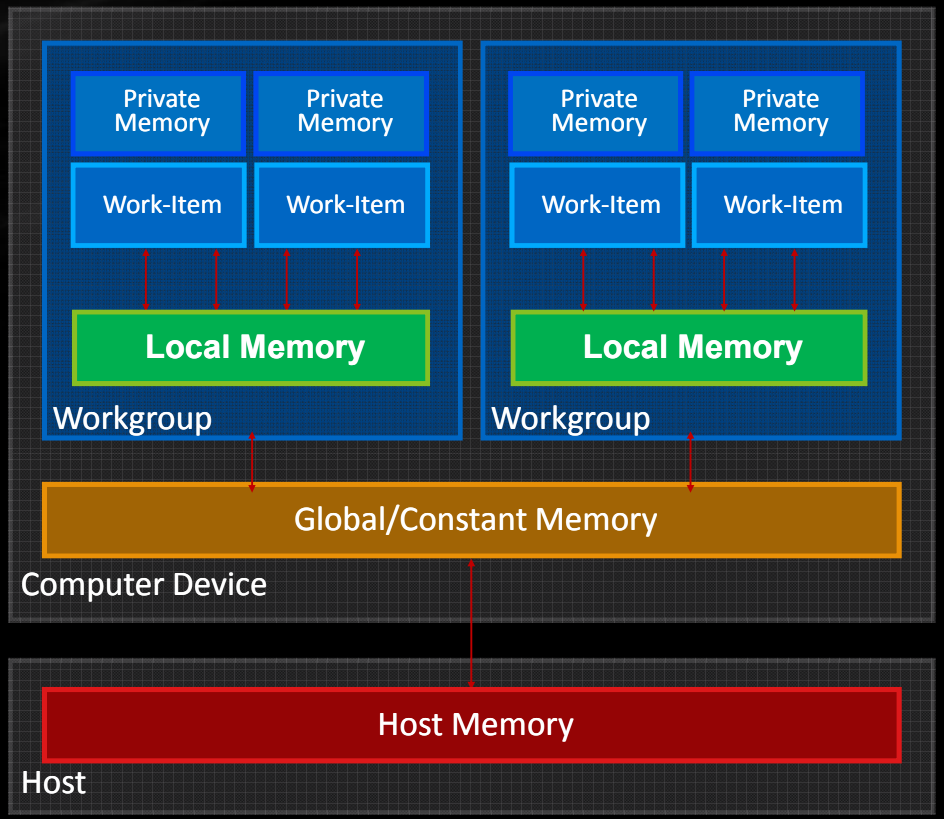
- At least 32kB split into blocks each available to any work-item in a given work-group

Local Global/Constant Memory

- Not synchronized

Host Memory

- On the CPU



Memory management is explicit :
You must move data from host -> global -> local *and* back

Compilation Model

OpenCL™ uses Dynamic/Runtime compilation model (like OpenGL®):

1. The code is complied to an Intermediate Representation (IR)
   - Usually an assembler or a virtual machine
   - Known as offline compilation
2. The IR is compiled to a machine code for execution.
   - This step is much shorter.
   - It is known as online compilation.

In dynamic compilation, step 1 is done usually only once, and the IR is stored.

The App loads the IR and performs step 2 during the App's runtime (hence the term…)

Using the OpenCL™ framework

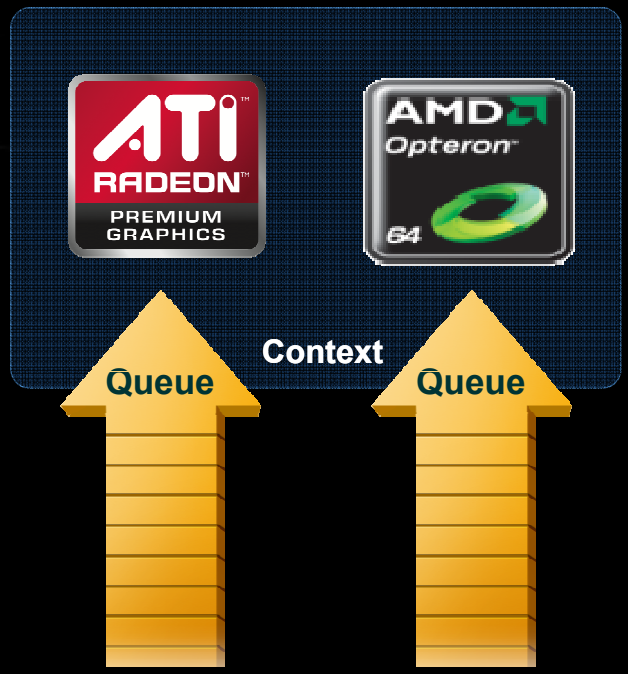
OpenCL™ Objects

Setup
- Devices — GPU, CPU, Cell/B.E.
- Contexts — Collection of devices
- Queues — Submit work to the device

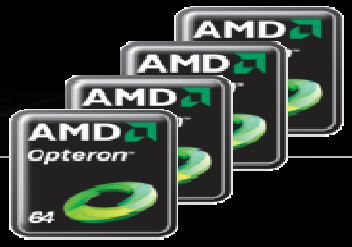
Memory
- Buffers — Blocks of memory
- Images — 2D or 3D formatted images

Execution
- Programs — Collections of kernels
- Kernels — Argument/execution instances

Synchronization/profiling
- Events



OpenCL™ Framework



Context

Programs

```
__kernel void
add(
 global const float *a,
 global const float *b,
 global float *c)
{
 int id=get_global_id(0);
 c[id]=a[id]+b[id];
}
```

add
CPU program binary

add
GPU program binary

Kernels

add

arg[0] value

arg[1] value

arg[2] value

Memory Objects

Images

Buffers

Command Queues

In Order Queue

Out of Order Queue

GPU

Compile code

Create data & arguments

Send to execution

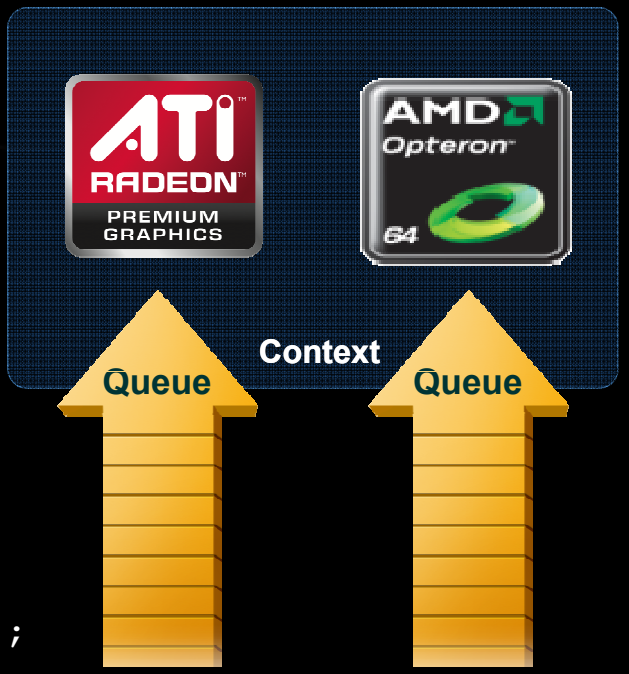
Setup

1. Get the device(s)
2. Create a context
3. Create command queue(s)

```
cl_uint num_devices_returned;
cl_device_id devices[2];
err = clGetDeviceIDs(NULL, CL_DEVICE_TYPE_GPU, 1,
                     &devices[0], &num_devices_returned);
err = clGetDeviceIDs(NULL, CL_DEVICE_TYPE_CPU,
                     &devices[1], &num_devices_returned);

cl_context context;
context = clCreateContext(0, 2, devices, NULL, NULL, &err);

cl_command_queue queue_gpu, queue_cpu;
queue_gpu = clCreateCommandQueue(context, devices[0], 0, &err);
queue_cpu = clCreateCommandQueue(context, devices[1], 0, &err);
```



Setup: Notes

Devices

- Multiple cores on CPU or GPU together are a single device
- OpenCL™ executes kernels across all cores in a data-parallel manner

Contexts

- Enable sharing of memory between devices
- To share between devices, both devices must be in the same context

Queues

- All work submitted through queues
- Each device must have a queue

Choosing Devices

A system may have several devices—which is best?

The "best" device is algorithm- and hardware-dependent

Query device info with: `clGetDeviceInfo(device, param_name, *value)`

- Number of compute units — `CL_DEVICE_MAX_COMPUTE_UNITS`
- Clock frequency — `CL_DEVICE_MAX_CLOCK_FREQUENCY`
- Memory size — `CL_DEVICE_GLOBAL_MEM_SIZE`
- Extensions — (double precision, atomics, etc.)

Pick the best device for your algorithm

Memory Resources

Buffers

- Simple chunks of memory
- Kernels can access however they like (array, pointers, structs)
- Kernels can read and write buffers

Images

- Opaque 2D or 3D formatted data structures
- Kernels access only via read_image() and write_image()
- Each image can be read or written in a kernel, but not both

Image Formats and Samplers

Formats

- Channel orders: `CL_A`, `CL_RG`, `CL_RGB`, `CL_RGBA`, etc.
- Channel data type: `CL_UNORM_INT8`, `CL_FLOAT`, etc.
- clGetSupportedImageFormats() returns supported formats

Samplers (for reading images)

- Filter mode: linear or nearest
- Addressing: clamp, clamp-to-edge, repeat, or none
- Normalized: true or false

Benefit from image access hardware on GPUs

Allocating Images and Buffers

```
cl_image_format format;
format.image_channel_data_type = CL_FLOAT;
format.image_channel_order = CL_RGBA;

cl_mem input_image;
input_image     = clCreateImage2D(context, CL_MEM_READ_ONLY, &format,
                        image_width, image_height, 0, NULL,
cl_mem output_image;
output_image    = clCreateImage2D(context, CL_MEM_WRITE_ONLY, &format,
                        image_width, image_height, 0, NULL, &err);
cl_mem input_buffer;
input_buffer    = clCreateBuffer(context, CL_MEM_READ_ONLY,
                        sizeof(cl_float)*4*image_width*image_height, NULL, &err);
cl_mem output_buffer;
output_buffer   = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
                        sizeof(cl_float)*4*image_width*image_height, NULL, &err);
```

Reading and Writing Memory Object Data

Explicit commands to access memory object data

- Read from a region in memory object to host memory
  - `clEnqueueReadBuffer(queue, object, blocking, offset, size, *ptr, ...)`
- Write to a region in memory object from host memory
  - `clEnqueueWriteBuffer(queue, object, blocking, offset, size, *ptr, ...)`
- Map a region in memory object to host address space
  - `clEnqueueMapBuffer(queue, object, blocking, flags, offset, size, ...)`
- Copy regions of memory objects
  - `clEnqueueCopyBuffer(queue, srcobj, dstobj, src_offset, dst_offset, ...)`

Operate synchronously (blocking = CL_TRUE) or asynchronously

Compilation and execution of kernels

Program and Kernel Objects

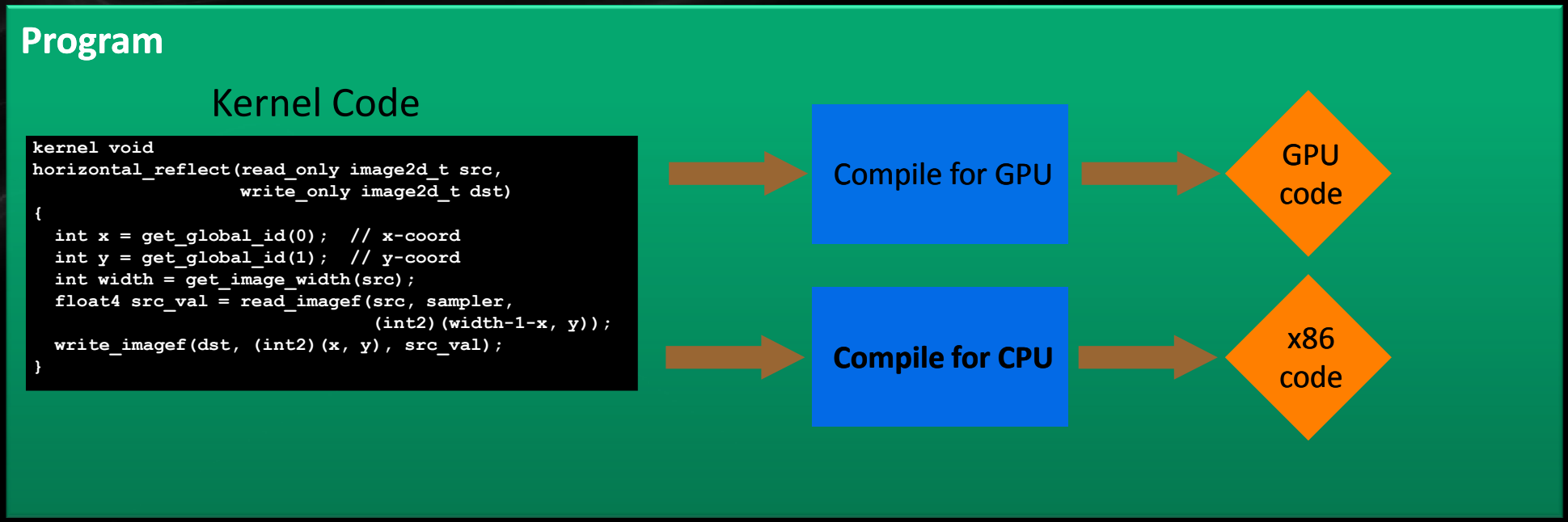
Program objects encapsulate

- a program source or binary
- list of devices and latest successfully built executable for each device
- a list of kernel objects

Kernel objects encapsulate

- a specific kernel function in a program
  - declared with the kernel qualifier
- argument values
- kernel objects created after the program executable has been built

Compile for multiple targets



Programs build executable code for multiple devices

Execute the same code on different devices

Executing Kernels

1. Set the kernel arguments
2. Enqueue the kernel

```
err = clSetKernelArg(kernel, 0, sizeof(input), &input);
err = clSetKernelArg(kernel, 1, sizeof(output), &output);
size_t global[3] = {image_width, image_height, 0};
err = clEnqueueNDRangeKernel(queue, kernel, 2  NULL, global, NULL, 0, NULL,
NULL);
```

- Note: Your kernel is executed *asynchronously*
  - Nothing may happen—you have just enqueued your kernel
- To ensure execution:
  - Use a blocking read clEnqueueRead*(... CL_TRUE ...)
  - Use events to track the execution status

OpenCL™ Synchronization: Queues & Events

OpenCL™ defines a command queue

- Created on a single device
- Within the scope of a context

Commands are enqueued to a specific queue

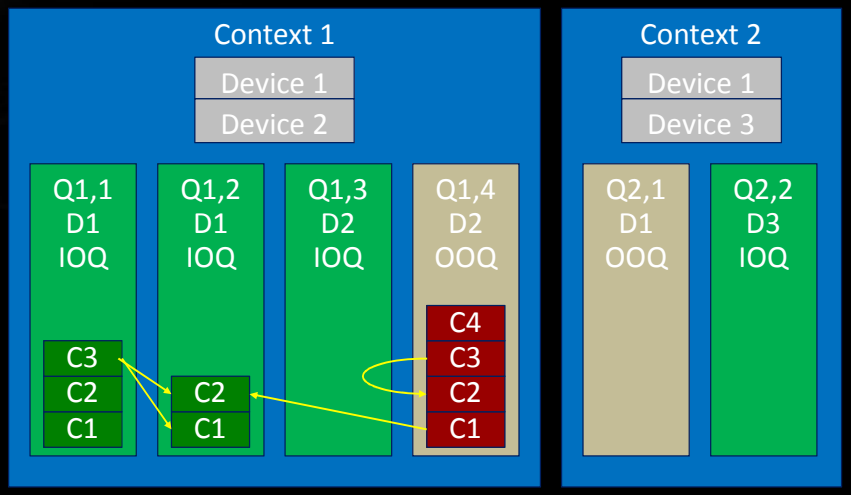
- Kernels Execution
- Memory Operations

Events

- Each command can be created with an event associated
- Each command execution can be dependent in a list of pre-created events

Two types of queues

- In order queue : commands are executed in the order of issuing
- Out of order queue : command execution is dependent only on its event list completion



Multiple queues can be created on the same device

Commands can be dependent on events created on other queues/contexts

In the example above :

- C3 from Q1,1 depends on C1 & C2 from Q1,2
- C1 from Q1,4 depends on C2 from Q1,2
- In Q1,4, C3 depends on C2

Synchronization Between Commands

Each individual queue can execute in order or out of order

- For in-order queue, all commands execute in order
- Behaves as expected (as long as you're enqueuing from one thread)

You must explicitly synchronize between queues

- Multiple devices each have their own queue
- Use events to synchronize

Events

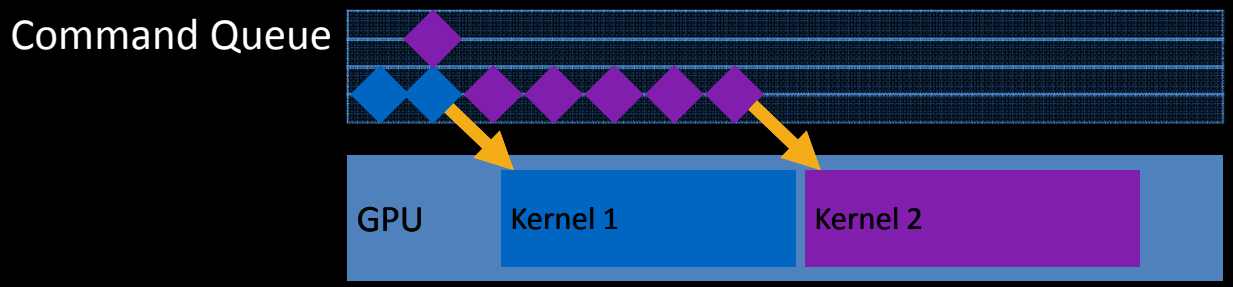
- Commands return events and obey waitlists
- `clEnqueue*(..., num_events_in_waitlist, *event_waitlist, *event_out)`

Synchronization: One Device/Queue

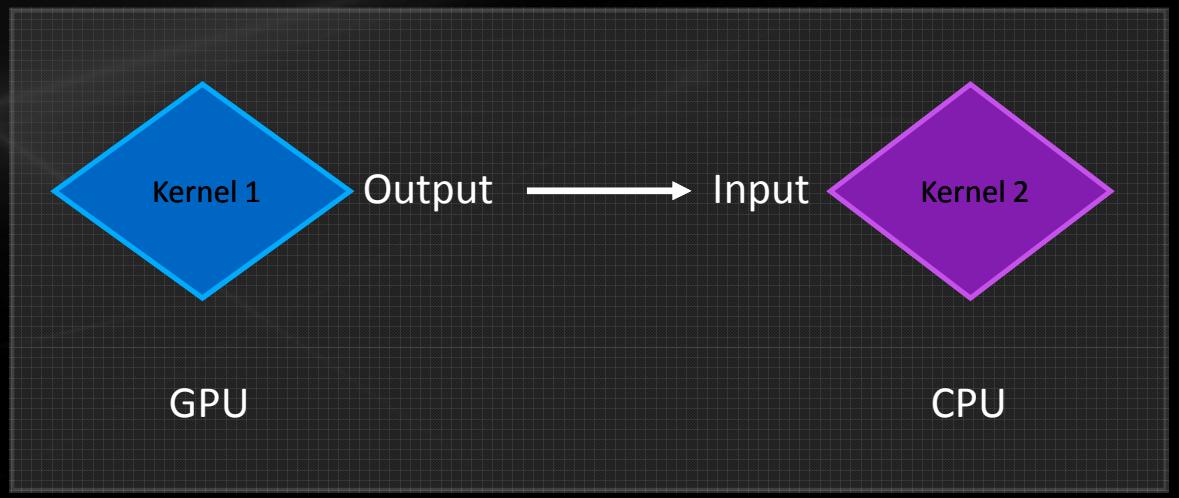
Example: Kernel 2 uses the results of Kernel 1

Enqueue Kernel 1
Enqueue Kernel 2

Kernel 2 waits in the queue until Kernel 1 is finished



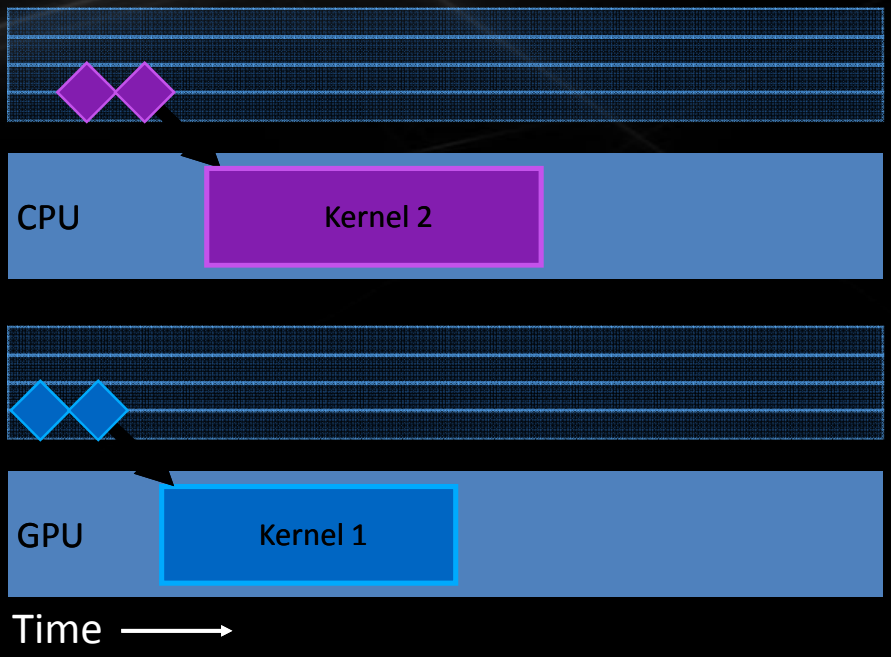
Synchronization: Two Devices/Queues



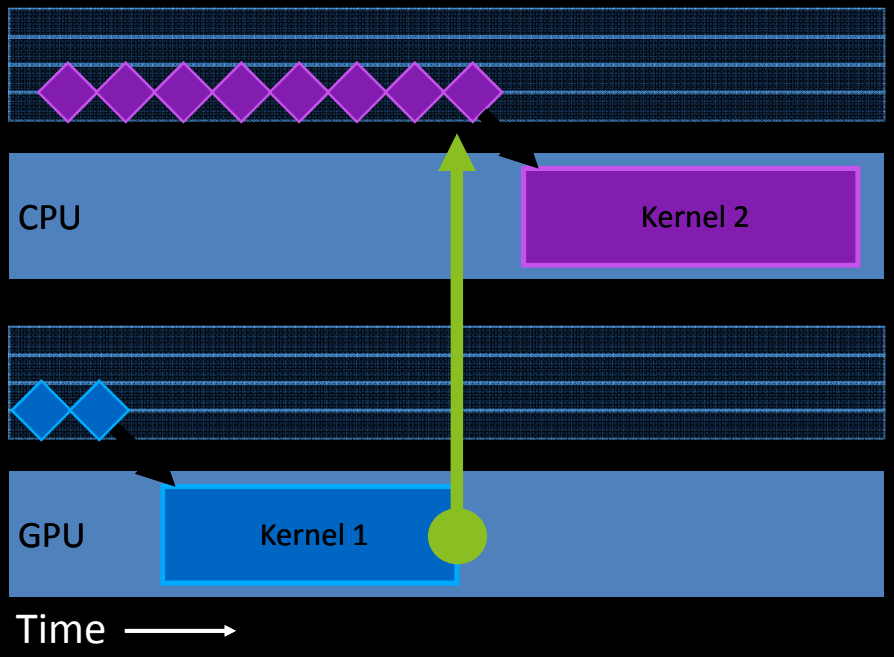
Explicit dependency: Kernel 1 must finish before Kernel 2 starts

Synchronization: Two Devices/Queues

Kernel 2 issued with no associated wait. Starts before the results from Kernel 1 are ready



Kernel 2 waits for an event from Kernel 1 Does not start until the results from Kernel 1 are ready



Using Events on the Host

`clWaitForEvents(num_events, *event_list)`

- Blocks until events are complete

`clEnqueueMarker(queue, *event)`

- Returns an event for a marker that moves through the queue

`clEnqueueWaitForEvents(queue, num_events, *event_list)`

- Inserts a “WaitForEvents” into the queue

`clGetEventInfo()`

- Command type and status
  `CL_QUEUED`, `CL_SUBMITTED`, `CL_RUNNING`, `CL_COMPLETE`, or error code

`clGetEventProfilingInfo()`

- Command queue, submit, start, and end times

The OpenCL™ C language

OpenCL™ C Language

Derived from ISO C99

- No standard C99 headers, function pointers, recursion, variable length arrays, and bit fields

Additions to the language for parallelism

- Work-items and workgroups
- Vector types
- Synchronization

Address space qualifiers

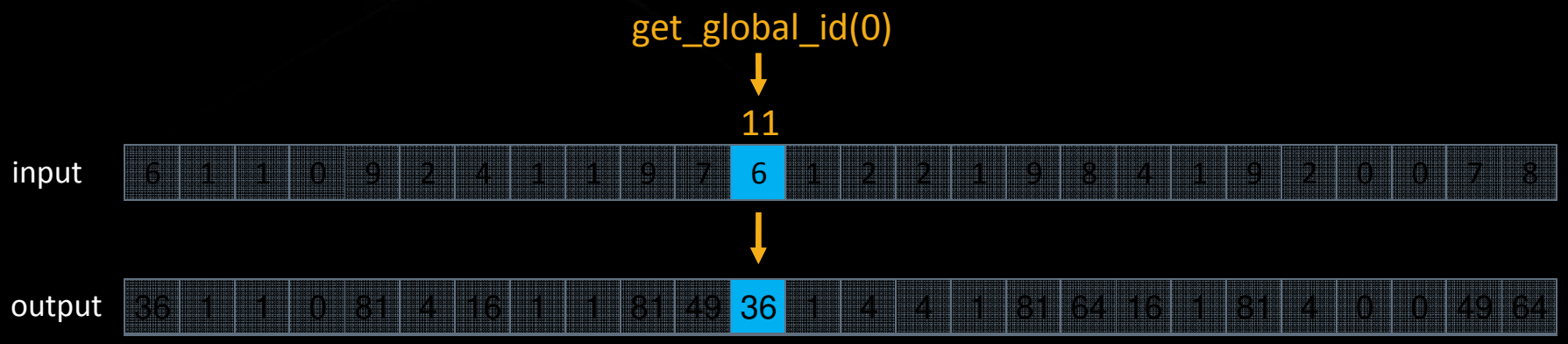
Optimized image access

Built-in functions

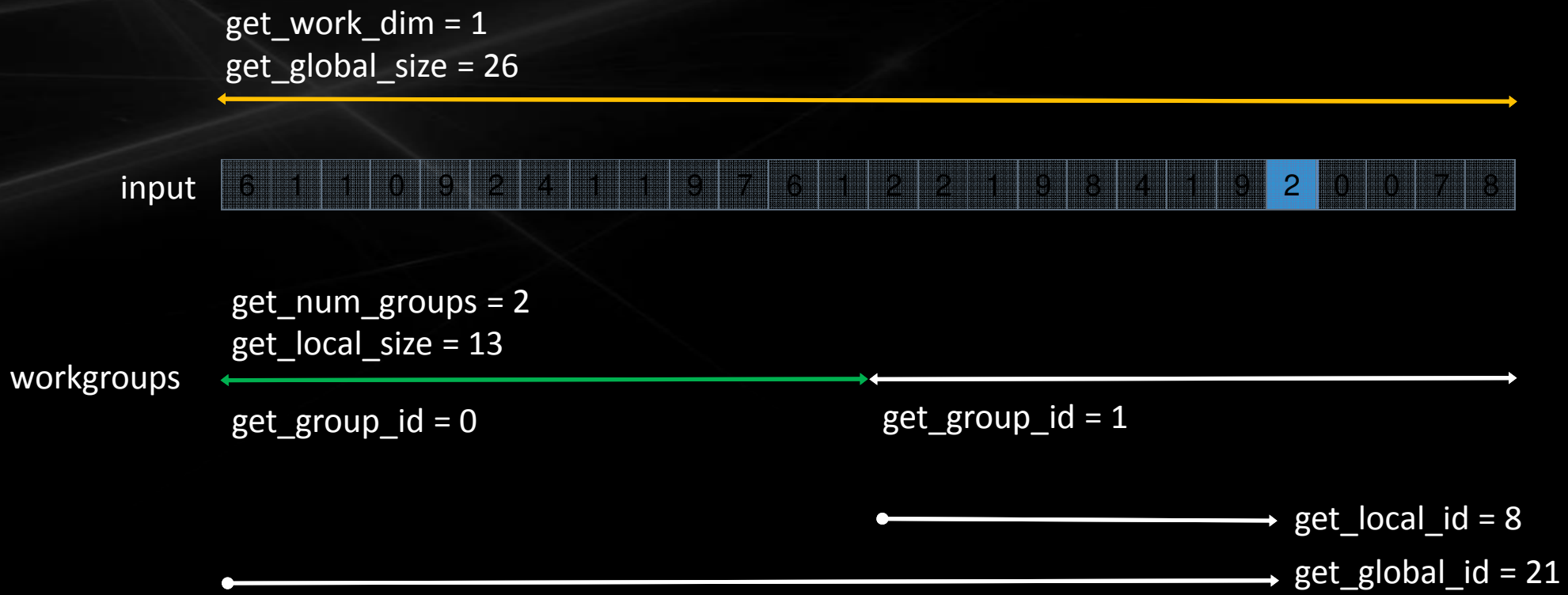
Kernel

A data-parallel function executed for each work-item

```
kernel void square(__global float* input, __global float* output)
{
  int i = get_global_id(0);
  output[i] = input[i] * input[i];
}
```



Work-Items and Workgroup Functions



Data Types

Scalar data types

- char , uchar, short, ushort, int, uint, long, ulong,
- bool, intptr_t, ptrdiff_t, size_t, uintptr_t, void, half (storage)

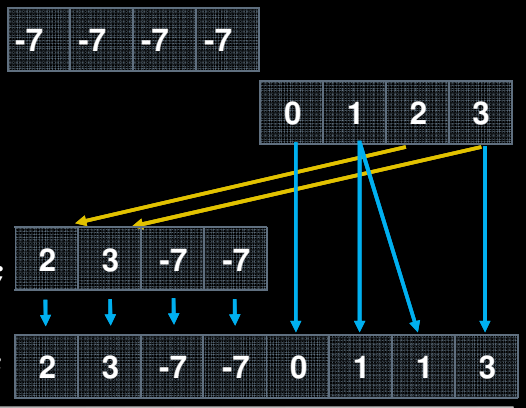
Image types

- image2d_t, image3d_t, sampler_t

Vector data types

- Vector length of 2, 4, 8, and 16
- Aligned at vector length
- Vector operations and built-in

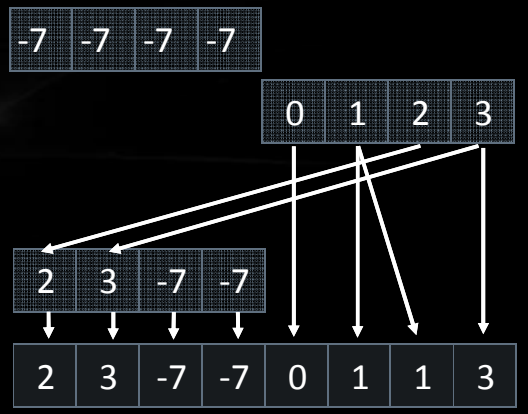
```
int4 vi0 = (int4) -7;
int4 vi1 = (int4)(0, 1, 2, 3);
vi0.lo = vi1.hi;
int8 v8 = (int8)(vi0, vi1.s01, vi1.odd);
```



Vector Operations

Vector literal

```
int4 vi0 = (int4) -7;
int4 vi1 = (int4)(0, 1, 2, 3);
```



Vector components

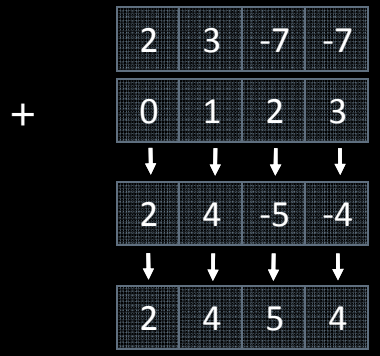
```
vi0.lo   = vi1.hi;

int8 v8  = (int8)(vi0, vi1.s01, vi1.odd);
```

Vector ops

```
vi0      += vi1;

vi0      = abs(vi0);
```



Address Spaces

Kernel pointer arguments must use global, local, or constant

- `kernel void distance(global float8* stars, local float8* local_stars)`
- `kernel void sum(private int* p)  // Illegal because it uses private`

Default address space for arguments and local variables is private

- `kernel void smooth(global float* io) { float temp; …`

image2d_t and image3d_t are always in global address space

- `kernel void average(read_only global image_t in, write_only image2d_t out)`

Address Spaces (continued)

Program (global) variables must be in constant address space

```
constant    float bigG = 6.67428E-11;
global      float time;                          // Illegal non constant
kernel      void force(global float4 mass) { time = 1.7643E18f; }
```

Casting between different address spaces is undefined

```
kernel void calcEMF(global float4* particles) {
  global float* particle_ptr = (global float*) particles;
  float* private_ptr = (float*) particles;       // Undefined behavior –
  float particle = * private_ptr;                // different address space
}
```

Conversions

Scalar and pointer conversions follow C99 rules

- No implicit conversions for vector types

```
float4 f4 = int4_vec;          // Illegal implicit conversion
```

- No casts for vector types (different semantics for vectors)

```
float4 f4 = (float4) int4_vec;  // Illegal cast
```

- Casts have other problems

```
float x;
int i = (int)(x + 0.5f);        // Round float to nearest integer
```

Wrong for:

0.5f - 1 ulp (rounds up not down)

negative numbers (wrong answer)

- There is hardware to do it on nearly every machine

Conversions

Explict conversions: convert_destType<_sat><_roundingMode>

- Scalar and vector types
- No ambiguity

Options:

- Saturate to 0
- Round down to nearest even
- Round up to nearest value
- Saturated to 255

```
uchar4 c4 = convert_uchar4_sat_rte(f4);
```

f4	-5.0f	254.5f	254.6	1.2E9f
c4	0	254	255	255

Reinterpret Data: *as_typen*

Reinterpret the bits to another type

Types must be the same size

```
// f[i] = f[i] < g[i] ? f[i] : 0.0f
float4 f, g;
int4 is_less = f < g;
f = as_float4(as_int4(f) & is_less);
```

f	-5.0f	254.5f	254.6f	1.2E9f
g	254.6f	254.6f	254.6f	254.6f
is_less	ffffffff	ffffffff	00000000	00000000
as_int	c0a00000	42fe0000	437e8000	4e8f0d18
&	c0a00000	42fe0000	00000000	00000000
f	-5.0f	254.5f	0.0f	0.0f

OpenCL™ provides a select built-in

Built-in Math Functions

IEEE 754 compatible rounding behavior for single precision floating-point

IEEE 754 compliant behavior for double precision floating-point

Defines maximum error of math functions as ULP values

Handle ambiguous C99 library edge cases

Commonly used single precision math functions come in three flavors

- eg. log(x)
  - Full precision <= 3ulps
  - Half precision/faster. half_log—minimum 11 bits of accuracy, <= 8192 ulps
  - Native precision/fastest. native_log: accuracy is implementation defined
- Choose between accuracy and performance

Built-in Workgroup Functions

Synchronization

- barrier
- mem_fence, read_mem_fence, write_mem_fence
-

Work-group functions

- Encountered by all work-items in the work-group
- With the same argument values

```
kernel read(global int* g, local int* shared) {
  if (get_global_id(0) < 5)
    barrier(CLK_GLOBAL_MEM_FENCE);
  else
    k = array[0];
}
```

work-item 0

work-item 6

Illegal since not all work-items encounter barrier

Built-in Workgroup Functions (continued)

`async_work_group_copy`

- Copy from global to local or local to global memory
- Use DMA engine or do a memcpy across work-items in work-group
- Returns an event object

`wait_group_events`

- wait for events that identify async_work_group_copy operations to complete

Built-in Functions

Integer functions

- `abs`, `abs_diff`, `add_sat`, `hadd`, `rhadd`, `clz`, `mad_hi`,`mad_sat` ,`max`,`min`,`mul_hi`,`rotate`, `sub_sat`,`upsample`

Image functions

- `read_image[f | i | ui]`
- `write_image[f | i | ui]`
- `get_image_[width | height | depth]`

Common, Geometric and Relational Functions

Vector Data Load and Store Functions

- eg. `vload_half`,`vstore_half`,`vload_halfn`,`vstore_halfn, ...`

Extensions

Atomic functions to global and local memory

- add, sub, xchg, inc, dec, cmp_xchg, min, max, and, or, xor
- 32-bit/64-bit integers

Select rounding mode for a group of instructions at compile time

- For instructions that operate on floating-point or produce floating-point values
- `#pragma opencl_select_rounding_mode rounding_mode`
- All 4 rounding modes supported

Extension: Check `clGetDeviceInfo` with `CL_DEVICE_EXTENSIONS`

Programming advice

Performance: Overhead

Compiling programs can be expensive

- Reuse programs where possible
- Precompile binaries if this makes sense

Moving data to/from some devices can be expensive

- Discrete GPU over PCIe®
- Keep data on the device

Starting a kernel can be expensive

- Try to make individual kernels do a large amount of work

On some devices events can be expensive

- Don’t over-use them

Performance: Kernels and memory

Large global work sizes help hide memory latency and overheads

- 1000+ work items preferred

Trade off mathematics performance/precision using half/native versions of functions

Divergent execution can be bad on some devices

- Try to make all work-items in a group use the same control path

Handle data reuse using local memory where possible

Access memory sequentially across work items

- Allows memory coalescing
- Offers bandwidth improvements

Debugging

Start on the CPU

Be very careful about reading/writing out-of-bounds on the GPU

- Add explicit address checks around reads and writes if kernel is crashing

Play nicely with other apps

- GPUs are not preemptively scheduled

Use extra output buffers to record intermediate values

Set a context/call-back function to report API errors

OpenCL™ Basic Source Example

Vector Addition - Kernel

```
__kernel void vec_add (__global const float *a,
                       __global const float *b,
                       __global       float *c)
{
    int gid = get_global_id(0);
    c[gid] = a[gid] + b[gid];
}
```

Spec Guide

__kernel:	Section 6.7.1
__global:	Section 6.5.1
get_global_id():	Section 6.11.1
Data types:	Section 6.1

Vector Addition - Host API (1)

```
// Enumerate platforms
cl_context                          nPlatforms;
cl_platform_id                      platform;
err =                               clGetPlatformIDs(0,NULL,&nPlatforms);
cl_platform_id *platforms =         malloc(nPlatforms);

// get list of all platforms
err = clGetPlatformIDs(nPlatforms,platforms,NULL);
cl_context_properties p[3] = { CL_CONTEXT_PLATFORM, (cl_context_properties) platform[0], 0 };
```

Spec Guide

Platforms and platform creation: Section 4.1

Vector Addition - Host API

```
// create the OpenCL context on all devices
cl_context context = clCreateContextFromType(
            p, CL_DEVICE_TYPE_ALL, NULL, NULL, NULL);


// get the list of all devices associated with context
clGetContextInfo(context, CL_CONTEXT_DEVICES, 0, NULL, &cb);
cl_device_id *devices = malloc(cb);
clGetContextInfo(context, CL_CONTEXT_DEVICES, cb, devices, NULL);
```

Spec Guide

Contexts and context creation: Section 4.3

Vector Addition - Host API (2)

```
// create a command-queue
cl_cmd_queue cmd_queue = clCreateCommandQueue(context, devices[0], 0, NULL);


// allocate the buffer memory objects
cl_mem memobjs[3];
memobjs[0] = clCreateBuffer(context, CL_MEM_READ_ONLY |
             CL_MEM_COPY_HOST_PTR, sizeof(cl_float)*n, srcA, NULL);
memobjs[1] = clCreateBuffer(context,CL_MEM_READ_ONLY |
             CL_MEM_COPY_HOST_PTR, sizeof(cl_float)*n, srcB, NULL);
memobjs[2] = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
                                  sizeof(cl_float)*n, NULL, NULL);
```

Spec Guide

Command queues:	Section 5.1
Creating buffer objects:	Section 5.2.1

Vector Addition - Host API (3)

```
cl_program program = clCreateProgramWithSource(
   context, 1, &program_source, NULL, NULL);

cl_int err = clBuildProgram(program, 0, NULL, NULL, NULL, NULL);

cl_kernel kernel = clCreateKernel(program, “vec_add”, NULL);
err  = clSetKernelArg(kernel, 0, (void *)&memobjs[0], sizeof(cl_mem));
err |= clSetKernelArg(kernel, 1, (void *)&memobjs[1], sizeof(cl_mem));
err |= clSetKernelArg(kernel, 2, (void *)&memobjs[2], sizeof(cl_mem));
```

Spec Guide

Creating program objects:	Section 5.4.1
Building program executables:	Section 5.4.2
Creating kernel objects:	Section 5.5.1
Setting kernel arguments:	Section 5.5.2

Vector Addition - Host API (4)

```
// set work-item dimensions
size_t global_work_size[0] = n;

// execute kernel
err = clEnqueueNDRangeKernel(
   cmd_queue, kernel, 1, NULL, global_work_size, NULL, 0, NULL, NULL);

// read output array
err = clEnqueueReadBuffer(
   context, memobjs[2], CL_TRUE, 0, n*sizeof(cl_float), dst, 0, NULL, NULL);
```

Spec Guide

Executing Kernels:	Section 5.6
Reading, writing, and copying buffer objects:	Section 5.2.2

Adding abstraction

The OpenCL™ C++ bindings

Motivation

"In my experience, C++ is alive and well -- thriving, even. This surprises many people. It is not uncommon for me to be asked, essentially, why somebody would choose to program in C++ instead of in a simpler language with more extensive "standard" library support, e.g., Java or C#."

Scott Meyers

C++ offers:

- Data abstraction
- Object-oriented programming
- Generic templates

Goals

Lightweight, providing access to the low-level features of the original OpenCL™ C API

Compatible with standard C++ compilers (GCC 4.x and VS 2008)

C++ features that may be considered acceptable by all, e.g. exceptions, should not be required but may be supported by the use of polices that are not enabled by default

Should not require the use of the Standard Template Library

- Many organizations are wary of using the STL in their products

The bindings should be defined completely within a header, cl.hpp

- No linking to precompiled code should be necessary

A simple example: Hello from OpenCL™ C++ bindings

```
#define __CL_ENABLE_EXCEPTIONS
#define __NO_STD_VECTOR
#define __NO_STD_STRING
#if defined(__APPLE__) || defined(__MACOSX)
#include <OpenCL/cl.hpp>
#else
#include <CL/cl.hpp>
#endif
#include <cstdio>
#include <cstdlib>
#include <iostream>

const char * helloStr = "__kernel void  hello(void) { }\n";
```

A simple example: Hello from OpenCL™ C++ bindings (2)

```
int main(void) {
      try {
        cl::Context context(CL_DEVICE_TYPE_GPU, 0, NULL, NULL, &err);
        cl::vector<cl::Device> devices = context.getInfo<CL_CONTEXT_DEVICES>();
        cl::Program::Sources source(1, std::make_pair(helloStr,strlen(helloStr)));
        cl::Program program_ = cl::Program(context, source);
        program_.build(devices);
        cl::Kernel kernel(program_, "hello", &err);
        cl::CommandQueue queue(context, devices[0], 0, &err);
        cl::KernelFunctor func = kernel.bind(queue, cl::NDRange(4, 4),
   cl::NDRange(2, 2));
        func().wait();
     } catch (cl::Error err) {
        std::cerr << "ERROR: " << err.what() << "(" << err.err() << ")“  <<
   std::endl;
     }
      return EXIT_SUCCESS;
}
```

Real-time ocean simulator

FFTs are common algorithms

- Computationally intensive
- Data parallel

Today's GPUs are extremely good at executing FFTs

- 1k x 1k is too easy ☺
- 2k x 2k is still relatively easy, but real-time rendering becomes a challenge (~2Mn polygons)

Real-time ocean simulator (2)

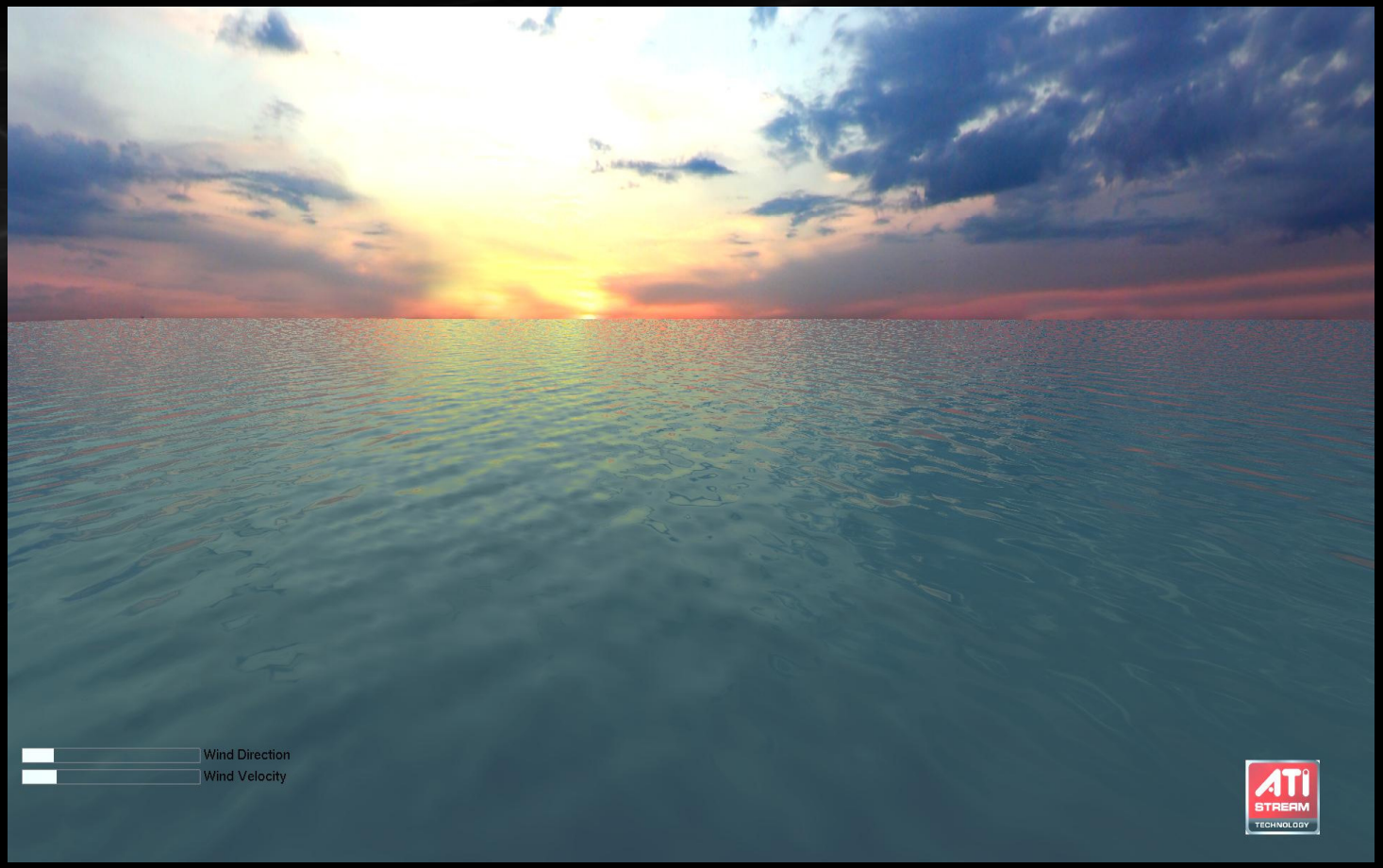
Jerry Tenssendorf's work:

- Simulating Ocean Water, SIGGRAPH 1999
- Waterworld, Titanic, and many others (2kx2k FFTs)
- Works with sums of sinusoids but starts in Fourier domain
- Can evaluate at any time t without having to evaluate other times
- Use the Phillips Spectrum
  - Roughness of waves is a function of wind velocity

Jason L. Mitchell's work:

- Real-Time Synthesis and Rendering of Ocean Water, 2005
- DX-9 Demo 256x256 FFTs, low and high frequencies separated

Real-time ocean simulator (3)



Real-time ocean simulator: Platforms

The first task is to obtain a platform.

```
cl::vector<cl::Platform> platforms;
err = cl::Platform::get(&platforms);

checkErr(err && (platforms.size() == 0 ? -1 : CL_SUCCESS), "cl::Platform::get()");

// As cl::vector (implements std::vector interface) straightforward to determine
   number of
// platforms, no need for additional variables as required by clGetPlatformIDs.
std::cout << "Number of platforms:\t " << platforms.size() << std::endl;

for (cl::vector<cl::Platform>::iterator i=platforms.begin(); i!=platforms.end();
   ++i) {
   // pick a platform and do something
   std::cout << "  Platform Name: " << (*i).getInfo<CL_PLATFORM_NAME>().c_str()
        << std::endl;
}
```

Real-time ocean simulator: Getting device information

clGetXInfo functions are provided in two flavors

- A static version of the form:

```
template <cl_int name> typename
    detail::param_traits<detail::cl_device_info, name>::param_type
    getInfo(cl_int* err = NULL) const
```

- A dynamic version of the form:

```
template <typename T>   cl_int getInfo(cl_device_info name, T* param) const
```

Unlike the C API the C++ bindings return info values directly:

- No need to call info function to find memory requirements
- Mapping from cl_X_info enums to C++ types, so for cl_platform_info:

```
F(cl_platform_info, CL_PLATFORM_PROFILE, STRING_CLASS) \
F(cl_platform_info, CL_PLATFORM_VERSION, STRING_CLASS) \
F(cl_platform_info, CL_PLATFORM_NAME, STRING_CLASS) \
F(cl_platform_info, CL_PLATFORM_VENDOR, STRING_CLASS) \
F(cl_platform_info, CL_PLATFORM_EXTENSIONS, STRING_CLASS)
```

Real-time ocean simulator: Context

Continue by creating a context over the platform's set of devices

```
cl::vector<cl::Platform>::iterator p = platforms.begin();
…
// Get all GPU devices supported by a particular platform
cl::vector<cl::Device> devices;
p->getDevices(CL_DEVICE_TYPE_GPU | CL_DEVICE_TYPE_CPU, &devices);

// Create a single context for all devices
cl::Context context(devices, NULL, NULL, NULL, &err);
checkErr(err, "Conext::Context()");

// Create work-queues for CPU and GPU devices
queueCPU = cl::CommandQueue(context, devices[0], 0, &err);
checkErr(err, "CommandQueue::CommandQueue(CPU)");
queueGPU = cl::CommandQueue(context, devices[1], 0, &err);
checkErr(err, "CommandQueue::CommandQueue(GPU)");
```

Real-time ocean simulator: Programs

Load and build a program for the devices

```
std::ifstream file("ocean_kernels.cl");
checkErr(file.is_open() ? CL_SUCCESS : -1, "reading ocean_kernels.cl");
std::string prog(std::istreambuf_iterator<char>(file),
    (std::istreambuf_iterator<char>()));

cl::Program::Sources source(1, std::make_pair(prog.c_str(),prog.length()+1));
cl::Program program(context, source);
err = program.build(devices);

if (err != CL_SUCCESS) {
    std::cout << "Info: " << program.getBuildInfo<CL_PROGRAM_BUILD_LOG>(devices);
    checkErr(err, "Program::build()");
}
```

Real-time ocean simulator: Kernels

The program consists of four kernels

- Two data-parallel FFT kernels

```
__kernel __attribute__((reqd_work_group_size (64,1,1)))
void kfft(__global float *greal, __global float *gimag)

__kernel __attribute__((reqd_work_group_size (64,1,1)))
void  ktran(__global float *greal, __global float *gimag)
```

- One kernel for calculating the partial differences, i.e slopes, that is used to calculate the normals from the height map for light shading

```
__kernel void kPartialDiffs
    (__global float* h, __global float2 *slopeOut, uint width, uint height)
```

- One (task) kernel for generating Phillips Spectrum

```
__kernel  void phillips
    (__global float2 * buffer, __global float2 *const randomNums, float windSpeed,
    float windDir,  unsigned int height, unsigned int width)
```

Real-time ocean simulator: Building kernels

The kernels must be built and invariant arguments may be set

```
kfftKernel = cl::Kernel(program, "kfft", &err);
checkErr(err, "Kernel::Kernel(kfft)");

ktranKernel = cl::Kernel(program, "ktran", &err);
checkErr(err, "Kernel::Kernel(ktrans)");

phillipsKernel = cl::Kernel(program, ”kphillips", &err);
checkErr(err, "Kernel::Kernel(kphillips)");

partialDiffsKernel = cl::Kernel(program, “kPartialDiffs", &err);
checkErr(err, "Kernel::Kernel(kPartialDiffs)");
```

Real-time ocean simulator: Allocating memory buffers

Memory buffers are allocated for a specific device and will later be passed to kernels for use

```
imag = cl::Buffer(context, CL_MEM_READ_WRITE,1024*1024*sizeof(float), 0, &err);
checkErr(err, "Buffer::Buffer(imag)");

spectrum = cl::Buffer(context, CL_MEM_READ_WRITE, 1024*1024*sizeof(cl_float2), 0,
   &err);
checkErr(err, "Buffer::Buffer(spectrum)");

// Height map and partial differences (i.e. slopes) generated directly into a GL
// buffer for rendering
real = cl::BufferGL(context,CL_MEM_READ_WRITE, heightVBO,&err);
checkErr(err, "BufferGL::BufferGL(height)");

slopes = cl::BufferGL(context, CL_MEM_READ_WRITE, partialDiffsVBO, &err);
checkErr(err, "BufferGL::BufferGL(partialDiffs)");
```

Real-time ocean simulator: Doing the work

At some point all of this setup must be put to good use… first by waiting for the phillips computation to complete and then by acquiring the OpenGL® output buffer

```
// make sure spectrum is up-to-date, i.e. account for wind changes. in practice
// we double buffer to avoid causing delays due to continual wind changes
phillipsEvent.wait();

cl::vector<cl::Memory> v;
v.push_back(real); v.push_back(partialDifs);

err = queueGPU.enqueueAcquireGLObjects(&v);
checkErr(err, "Queue::enqueueAcquireGLObjects()");
```

Real-time ocean simulator: Doing the work (2)

Then continue by executing the FFT kernel itself

```
// other arguments are invariant and set once during setup
err = kfftKernel.setArg(0, real);
err = queueGPU.enqueueNDRangeKernel(kfftKernel, cl::NullRange,
                        cl::NDRange(1024*64), cl::NDRange(64));
checkErr(err, "CommandQueue::enqueueNDRangeKernel(kfftKernel1)");

// other arguments are invariant and set once during setup
err = ktranKernel.setArg(0, real);
err = queueGPU.enqueueNDRangeKernel(ktranKernel, cl::NullRange,
                         cl::NDRange(128*129/2 * 64), cl::NDRange(64));
checkErr(err, "CommandQueue::enqueueNDRangeKernel(ktranKernel1)");
```

Real-time ocean simulator: Doing the work (3)

Execute the FFT kernels again

```
// note, no need to set argument as they persist from previous calls
err = queueGPU.enqueueNDRangeKernel(kfftKernel, cl::NullRange,
                                    cl::NDRange(1024*64), cl::NDRange(64));
checkErr(err, "CommandQueue::enqueueNDRangeKernel(kfftKernel2)");

err = queueGPU.enqueueNDRangeKernel(ktranKernel, cl::NullRange,
                                    cl::NDRange(128*129/2 * 64), cl::NDRange(64));
checkErr(err, "CommandQueue::enqueueNDRangeKernel(ktranKernel2)");
```

Real-time ocean simulator: Doing the work (4)

Then calculate slopes and partial differences

```
err  = calculateSlopeKernel.setArg(0, real); err |= partialDiffsKernel.setArg(1,
   slopes);
err |= calculateSlopeKernel.setArg(2, width); err |= partialDiffsKernel.setArg(3,
   height);
checkErr(err, "Kernel::setArg(partialDiffsKernel)");

err = queueGPU.enqueueNDRangeKernel(partialDiffsKernel, cl::NullRange,
                                    cl::NDRange(width,height), cl::NDRange(8,8));
checkErr(err, "CommandQueue::enqueueNDRangeKernel(partialDiffsKernel)");
```

Real-time ocean simulator: Releasing OpenGL® objects

To allow the rendering code to display the output we must release the OpenGL® objects obtained earlier

```
// Do the release
err = queueGPU.enqueueReleaseGLObjects(&v);
checkErr(err, "Queue::enqueueReleaseGLObjects(GPU)");
// Finish the operations in the GPU queue - including the release
queueGPU.finish();
```

And if the wind changes we must execute the appropriate correction code…

```
queueCPU.enqueueTask(phillipsKernel, NULL, &phillipsEvent);
```

The phillipsEvent will be correctly caught by the next run through the pipeline if it is created.

Optional features: Exceptions

Exceptions are controversial so inclusion is optional

They can be enabled by defining:

```
#define __CL_ENABLE_EXCEPTIONS
```

Before including cl.hpp

API calls that perviously returned a cl_int err will now throw cl::Error

```
catch (cl::Error err)
{
    std::cerr << "ERROR: " << err.what()
     << "(" << err.err() << ")" << std::endl;
}
```

err.what() returns an error string; err.err() returns the error code

Optional features: STL

Not everyone wants to use the STL in their applications

The OpenCL™ C++ bindings use std::string and std::vector

Support alternative versions:

- `cl::string`
- `cl::vector`

Also allow user defined replacements

Optional features: Replacing std::vector

Before including cl.hpp define:

```
#define __NO_STD_VECTOR
```

There is a new vector template that takes the same template parameters as `std::vector`

```
template cl::vector< typename T, unsigned int N = __MAX_DEFAULT_VECTOR_SIZE >;
```

`__MAX_DEFAULT_VECTOR_SIZE` defaults to 10. Can be overridden by defining before including cl.hpp:

```
#define __MAX_DEFAULT_VECTOR_SIZE 5
```

Developer can provide own version of vector class by defining:

```
#define __USE_DEV_VECTOR
#define VECTOR_CLASS userVector
```

Where `userVector` must be a template of the form given above for `cl::vector`

Optional features: Replacing std::string

Before including cl.hpp define:

```
#define __NO_STD_STRING
```

There is a new vector template that takes the same template parameters as `std::string`

`cl::string`

`__MAX_DEFAULT_VECTOR_SIZE` defaults to 10. Can be overridden by defining before including cl.hpp:

```
#define __MAX_DEFAULT_VECTOR_SIZE 5
```

Developer can provide own version of string class by defining:

```
#define __USE_DEV_STRING
#define STRING_CLASS userString
```

Where `userString` must be a class supporting the same interface as `std::string`.

Incorporation into the standard

Planned for adoption as part of OpenCL™ 1.1

Can already be downloaded from the Khronos web site:

- http://www.khronos.org/registry/cl

Multiple platform and vendor through use of underlying C API

A pair of examples

GPU Cloth and Fluid Simulations in Bullet Physics

OpenCL™ Fluid Simulation in Bullet Physics

Bullet Physics

Games Physics Simulation (http://bulletphysics.com)

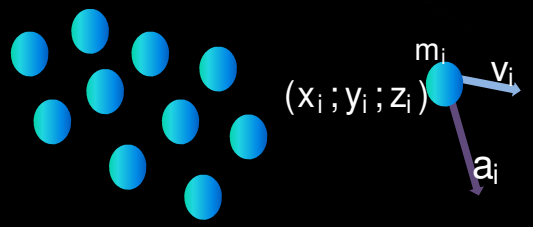
- Open source engine (Zlib license)
- Rigid body dynamics, e.g.
  - Ragdolls, destruction, and vehicles
- Soft body dynamics
  - Cloth, rope, and deformable volumes
- Current version is 2.76 and is CPU only
- Future versions will add a turbo injection, with the help of OpenCL

Open Physics – OpenCL™ and Bullet

- Rigid body dynamics
  - Erwin Coumans and Sony team developing accelerated version
  - 2D/3D Demos already exist and work on productization
- Soft body dynamics
  - AMD developing DC/OpenCL™ Cloth acceleration
- Fluid simulation
  - Does not currently exist in Bullet
  - AMD developing OpenCL/DC SPH implementation
- DMM Finite Element method
  - Pixelux working on Bullet integration

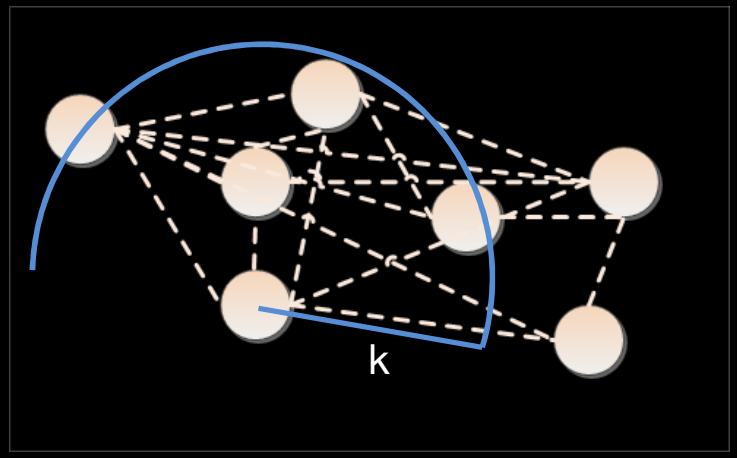
Fluids and particle systems the basics

- Simply, highly parallel, thus map well to the GPU
- Particles store position, mass, velocity, age, density, etc
- Particles are moved by time stepping:
  - Euler or Leapfrog integration $\frac{dv_i}{dt} = a_i$
  - Acceleration a_i has contributions from gravity, pressure gradient, and viscosity



Particle-Particle Interaction

- For correct simulation of fluids, inter-particle forces are required
- Naïve implementation leads to a complexity of $O(n^2)$
- [Muller03] reduce this to linear complexity by introducing a cutoff distance *k*



Smoothed Particle Hydrodynamics – Algorithm

Build spatial grid on particles
- Allow fast neighbor finding

For each particle
- Find neighbors

For each particle
- Compute density and pressure

For each particle
- Compute acceleration

For each particle
- Integrate

On the GPU each particle is worked on in parallel

SPH – Reducing $O(n^2)$ to O(n) with spatial hashing

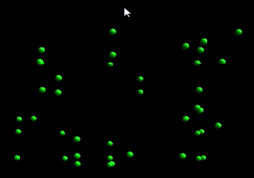
Fill particles into a grid with spacing 2*interaction distance

Search potential neighbors in adjacent cells only

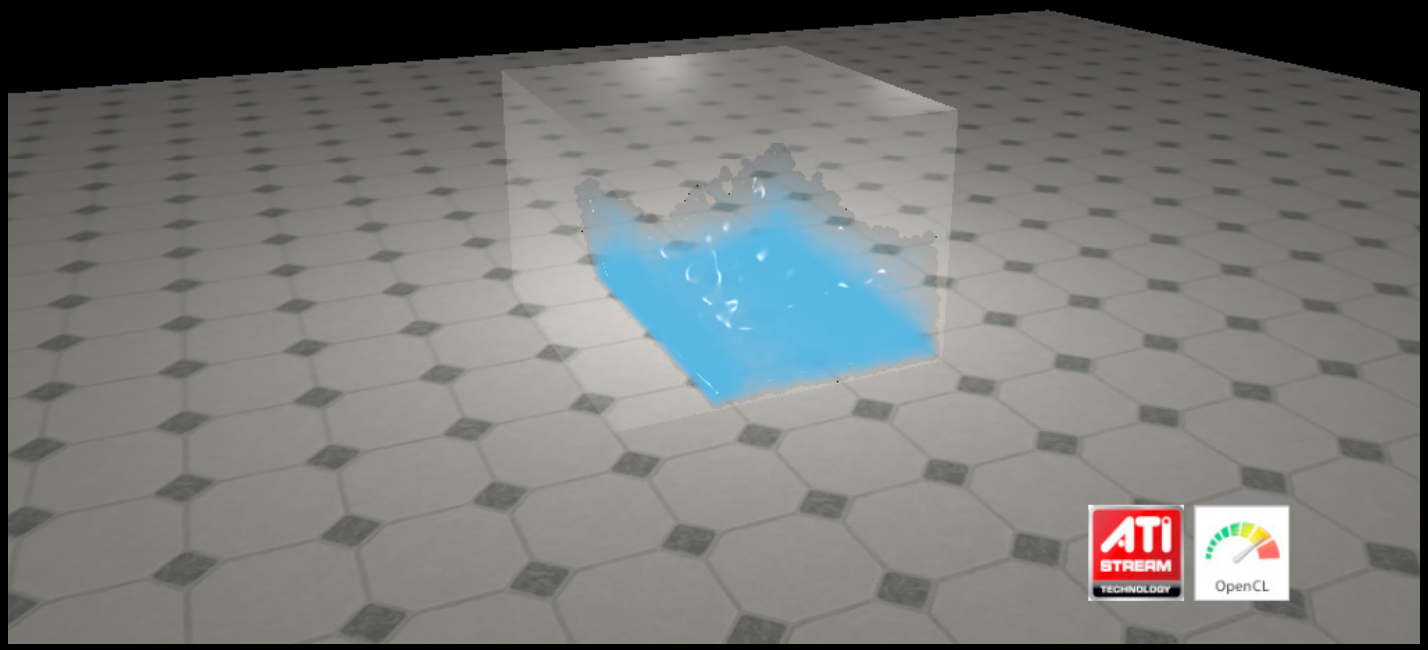
Map cells [i,j,k] into 1D array via hash function h(i,j,k) [teschner03]

Implementation:

- Infinite 3D grid is mapped to finite grid
  - 10 * 10 * 10 in the unit cube
  - (x,y,z) maps (x%11,y%11,z%11)
- Finding neighbors is fast
- Requires fast GPU sort
  - Today Radixsort
  - Future other sorts, work still needed to study s



SPH – Early prototype



SPH – Next Generation

Reverted to pure streaming implementation

- Data is always read coherently

Pipeline is automatically generated

- Using sequence description file
- Predict memory bandwidth, automatically

Still in early development, running but:

- Simulation still unstable, this is a maths issue so:
  - Problem is memory bound and so – 256,000 particles @ 60Hz doable!

SPH – Rendering

No ‘good’ solution to date

Screen-space Curvature Flow

- [Malladi at el, 1995, Van der Laan at el, 2009]
- Evolve surface along normal direction with speed determined by mean surface curvature
- Flow moves surface only in Z
- Needs a lot of particles to look good!

Almost all post rendering processing (geometry shader is used to render screen point sprites), so:

- Why not use OpenCL™?
  - OpenCL C Geometry and Fragment Shaders, with fixed function rasterization

OpenCL™ Soft Body simulation

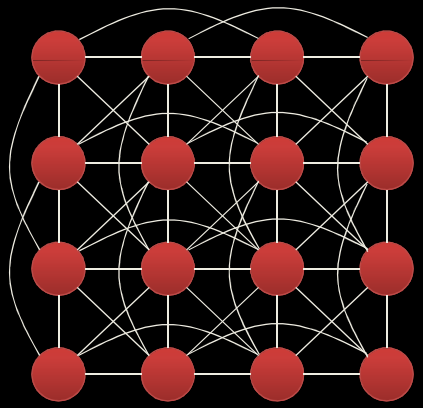
Particle-based soft body simulation

Mass/spring system:

- Large collection of masses or particles
- Connect using springs
- Layout and properties of springs changes properties of soft body

General spring types:

- Structural springs
- Shearing springs
- Bending springs



Simulating a cloth

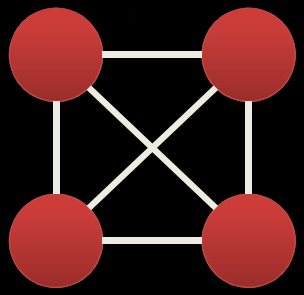
Subset of full range of soft bodies.

Large number of particles lends itself to parallel processing.

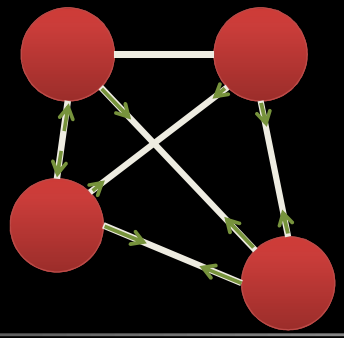
- Force from a given link must be applied to both particles
- Requires batching to correctly update particles

Basic stages of simulation:

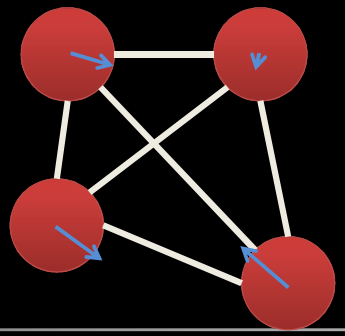
Original layout



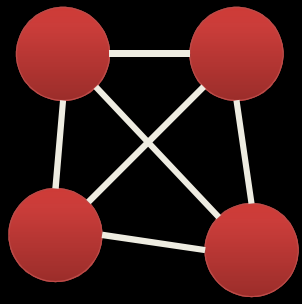
Current layout:
Compute forces as stretch from rest length



Apply forces to masses and compute velocities



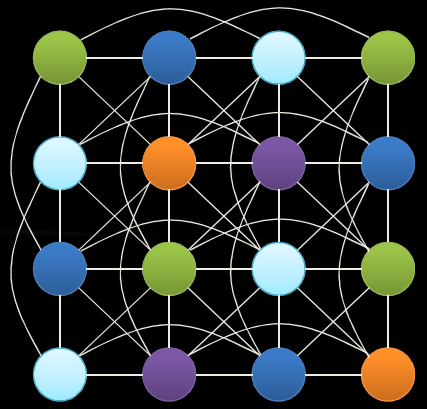
Compute new positions based on velocities



Apply simulation stages in batches

Batch the nodes based on their inteconnections:

- Graph colouring
- Complicated link structure = many batches



Compute the velocity:

- Over each batch in turn
- Over multiple cycles to allow solution to converge

Update positions, faces, normals etc based on computed velocities in a single pass

Adding wind to the simulation

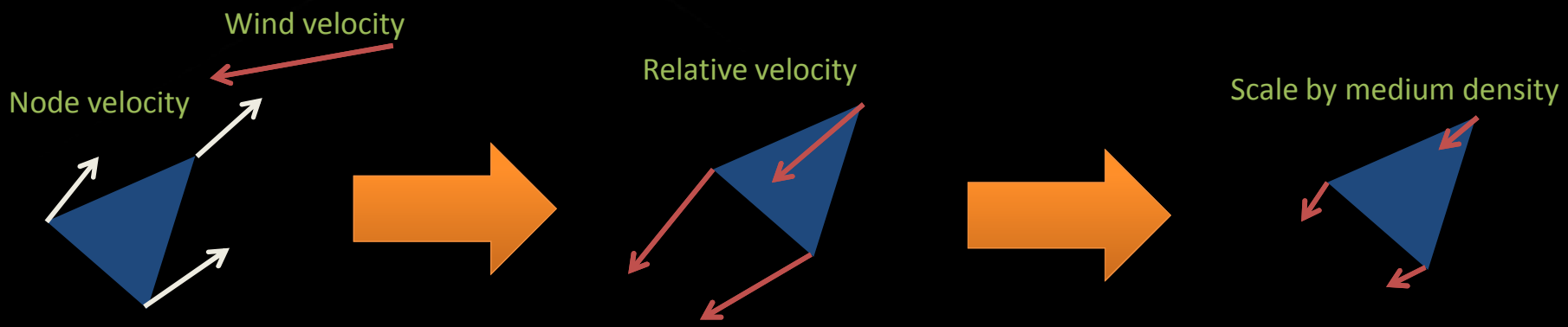
Compute normals on a per-face basis

Number of faces can be optimised to improve performance

- We use a face per node triangle in the obvious fashion

Node normals and areas computed from surrounding faces

Compute wind force interaction based on velocity and density of the wind medium



The “Übercloth”

Multi-pass multi-phase algorithm

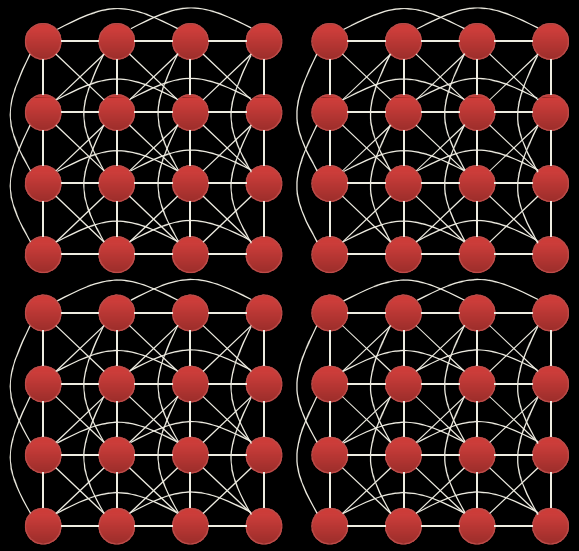
- Large number of overall passes

Multiple cloths require all passes to be computed for each

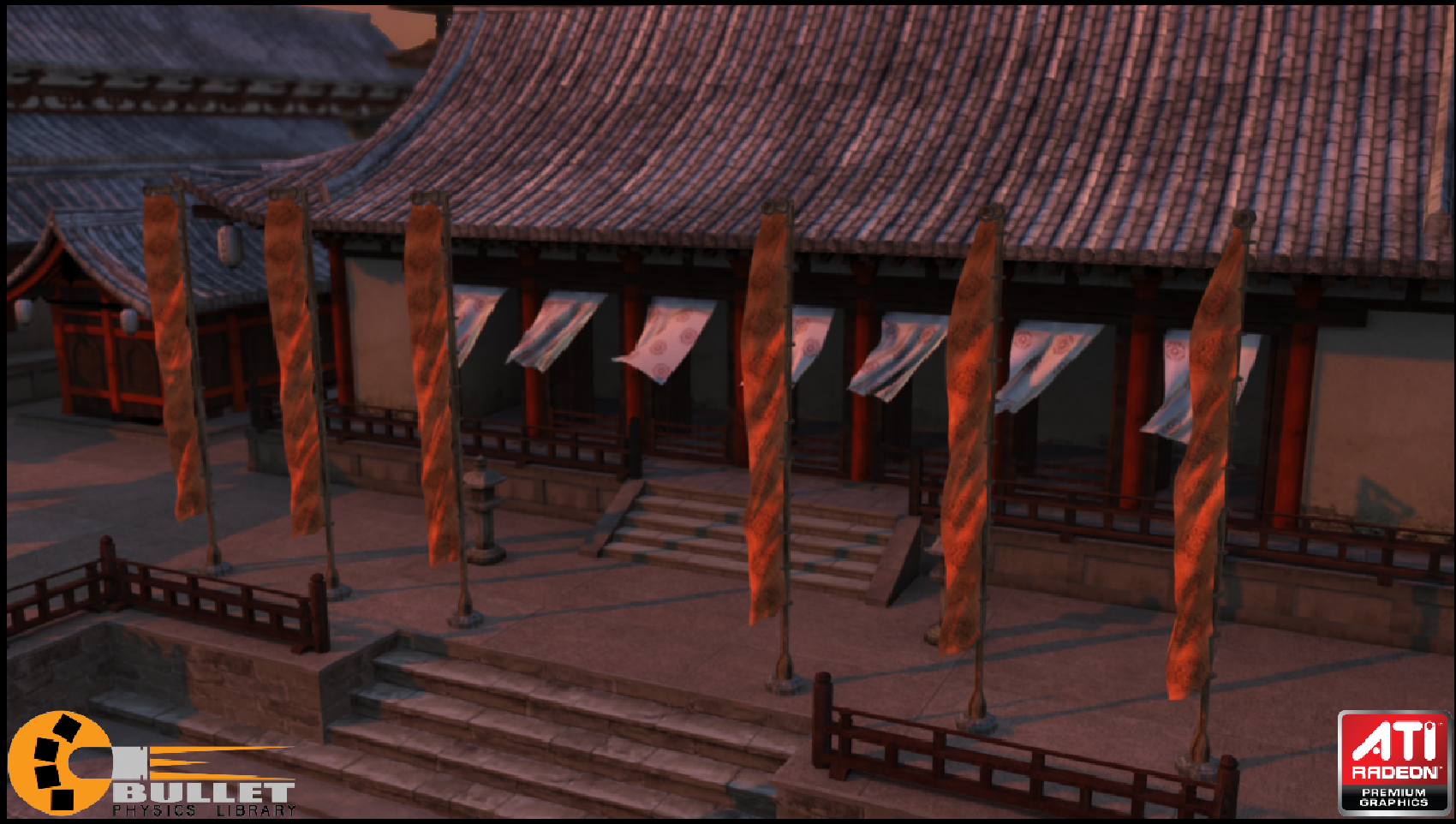
- Separate kernel issues can end up being small

Merge cloths into single simulated cloth object

- Inefficient on the CPU due to caching
- Highly efficient on the GPU:
  - Higher occupancy
  - Massively parallel



Cloth



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