Introduction to OpenCL™ Programming

Agenda

- GPGPU Overview
- Introduction to OpenCL™
- Getting Started with OpenCL™
- OpenCL™ Programming in Detail
- The OpenCL™ C Language
- Application Optimization and Porting

GPGPU Overview

GPGPU Overview

GPGPU Overview

- What is GPU Compute?
- Brief History of GPU Compute
- Heterogeneous Computing

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OpenCL™ Programming in Detail

The OpenCL™ C Language

Application Optimization and Porting

What is GPGPU?

- **G**eneral **P**urpose computation on **G**raphics **P**rocessing **U**nits

- High performance multi-core processors
  - excels at parallel computing

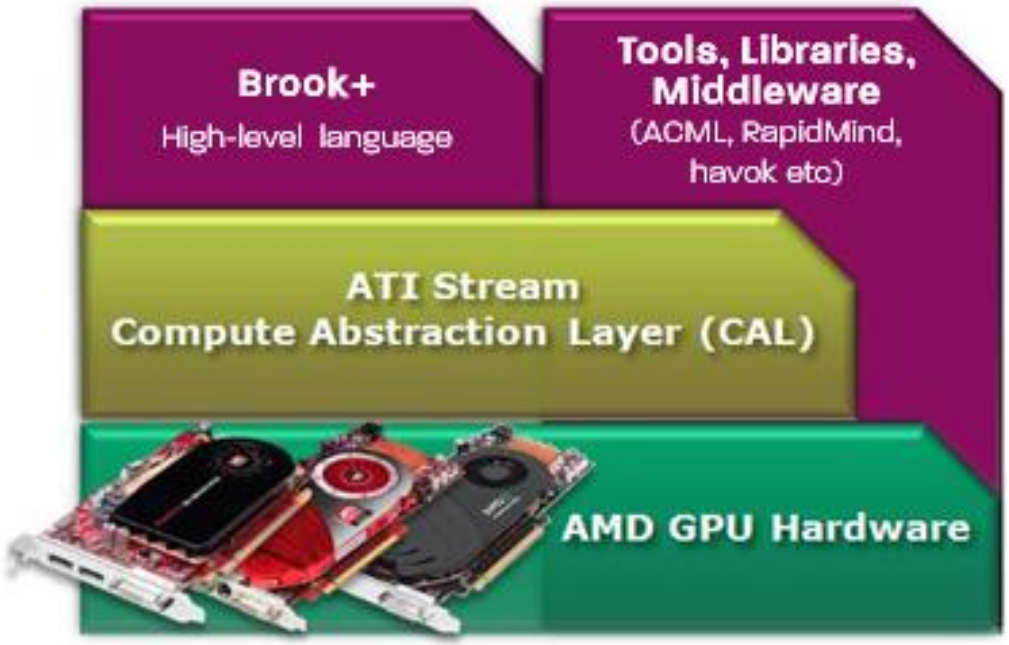
- Programmable coprocessors for other than just for graphics

Brief History of GPGPU

- **November 2006**
  - Birth of GPU compute with release of Close to Metal (CTM) API
  - Low level API to access GPU resources
  - New GPU accelerated applications
    - Folding@Home released with 20-30x speed increased

Brief History of GPGPU

- **December 2007**
  - ATI Stream SDK v1 released



Brief History of GPGPU

- **June 2008**
  - OpenCL™ working group formed under Khronos™
  - OpenCL™ 1.0 Spec released in Dec 2008
  - AMD announced adoption of OpenCL™ immediately

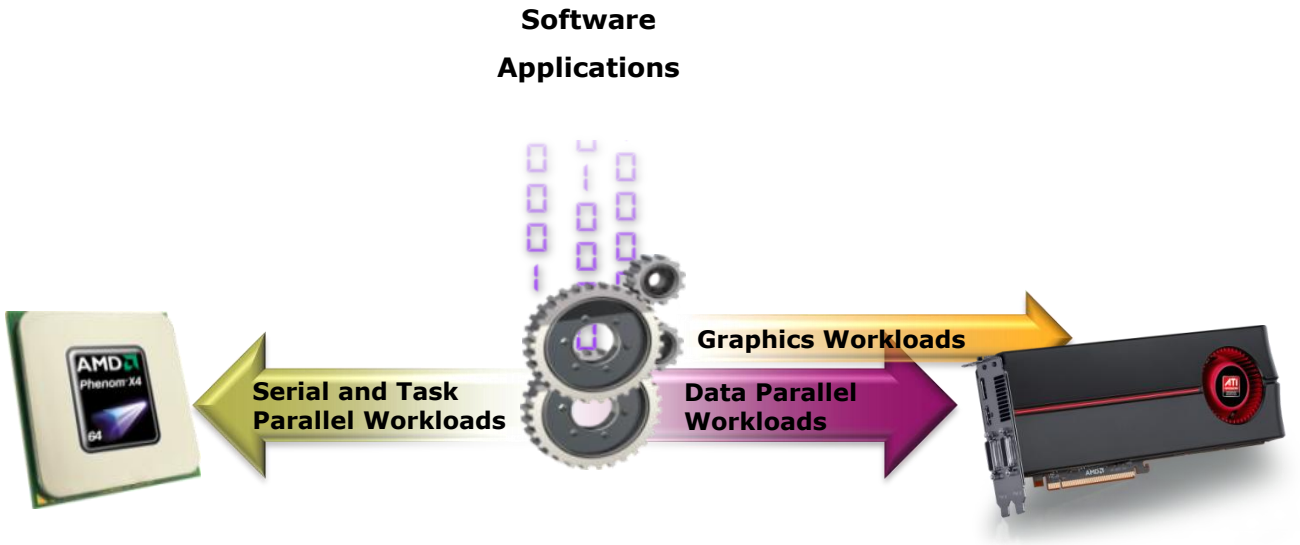
- **December 2009**
  - ATI Stream SDK v2 released
  - OpenCL™ 1.0 support

Heterogeneous Computing

- Using various types of computational units
  - CPU, GPU, DSP, etc…
- Modern applications interact with various systems (audio/video, network, etc...)
  - CPU scaling unable to keep up
  - Require specialized hardware to achieve performance

Heterogeneous Computing

- Ability to select most suitable hardware in heterogeneous system



Introduction to OpenCL™

GPGPU Overview

GPGPU Overview

Introduction to OpenCL™

- What is OpenCL™?
  - Benefits of OpenCL™
- Anatomy of OpenCL™
- OpenCL™ Architecture
  - Platform Model
  - Execution Model
  - Memory Model

Getting Started with OpenCL™

OpenCL™ Programming in Detail

The OpenCL™ C Language

Application Optimization and Porting

What is OpenCL™?

- **O**pen **C**omputing **L**anguage

- Open and royalty free API
  - Enables GPU, DSP, co-processors to work in tandem with CPU
  - Released December 2008 by Khronos™ Group

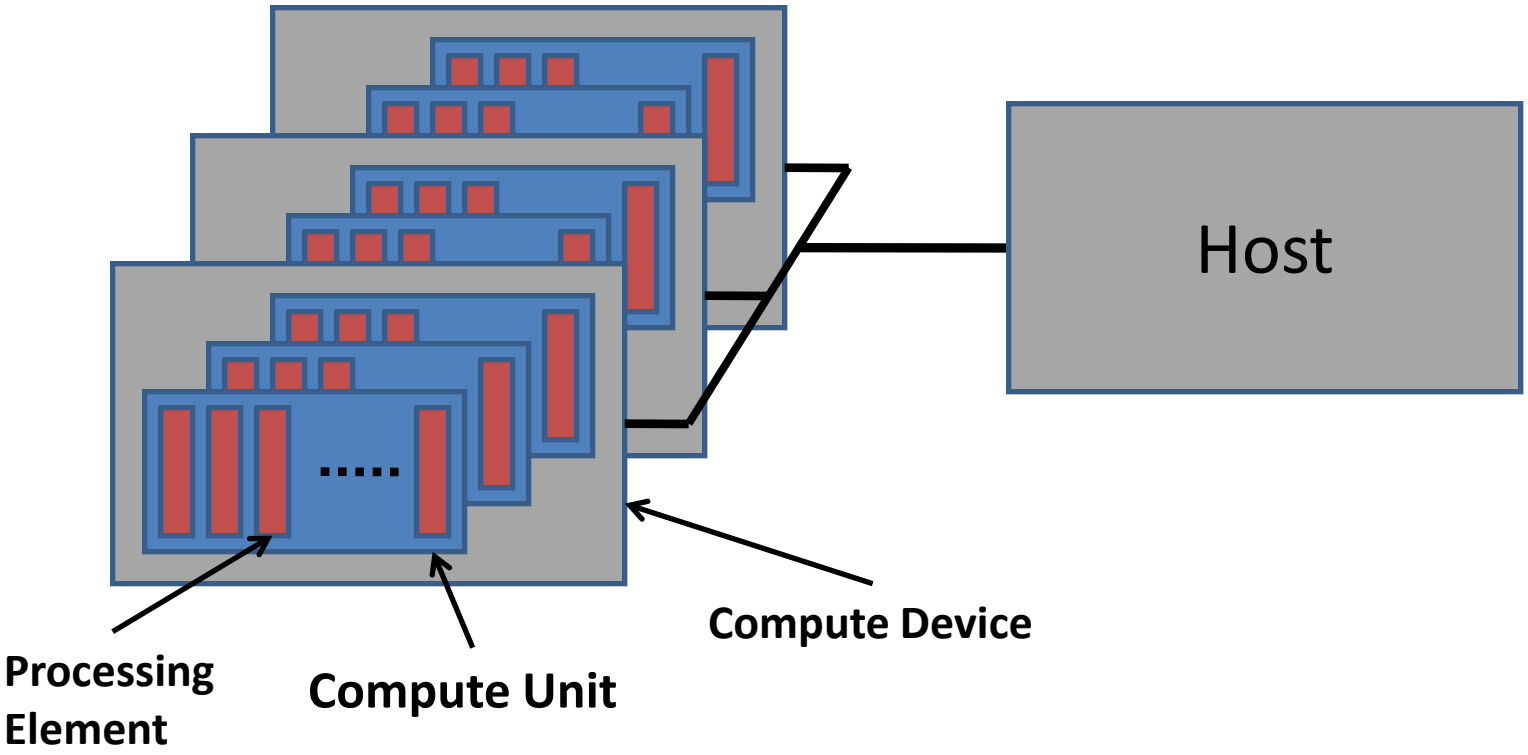
Benefits of OpenCL™

- Acceleration in parallel processing
- Allows us to manage computational resources
  - View multi-core CPUs, GPUs, etc as computational units
  - Allocate different levels of memory
- Cross-vendor software portability
  - Separates low-level and high-level software

Anatomy of OpenCL™

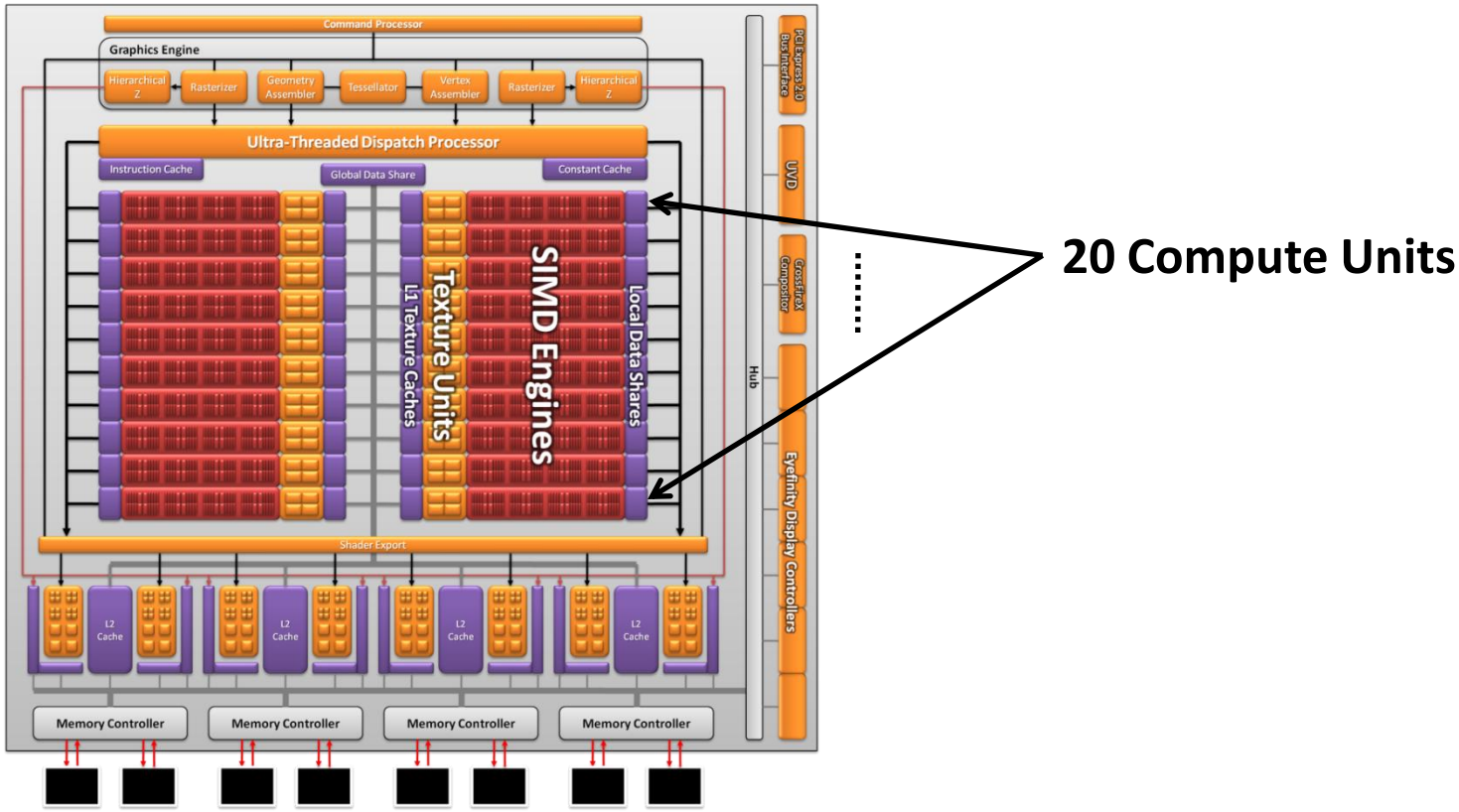
- **Language Specification**
  - Based on ISO C99 with added extension and restrictions
- **Platform API**
  - Application routines to query system and setup OpenCL™ resources
- **Runtime API**
  - Manage kernels objects, memory objects, and executing kernels on OpenCL™ devices

OpenCL™ Architecture – Platform Model



OpenCL™ Device Example

- ATI Radeon™ HD 5870 GPU

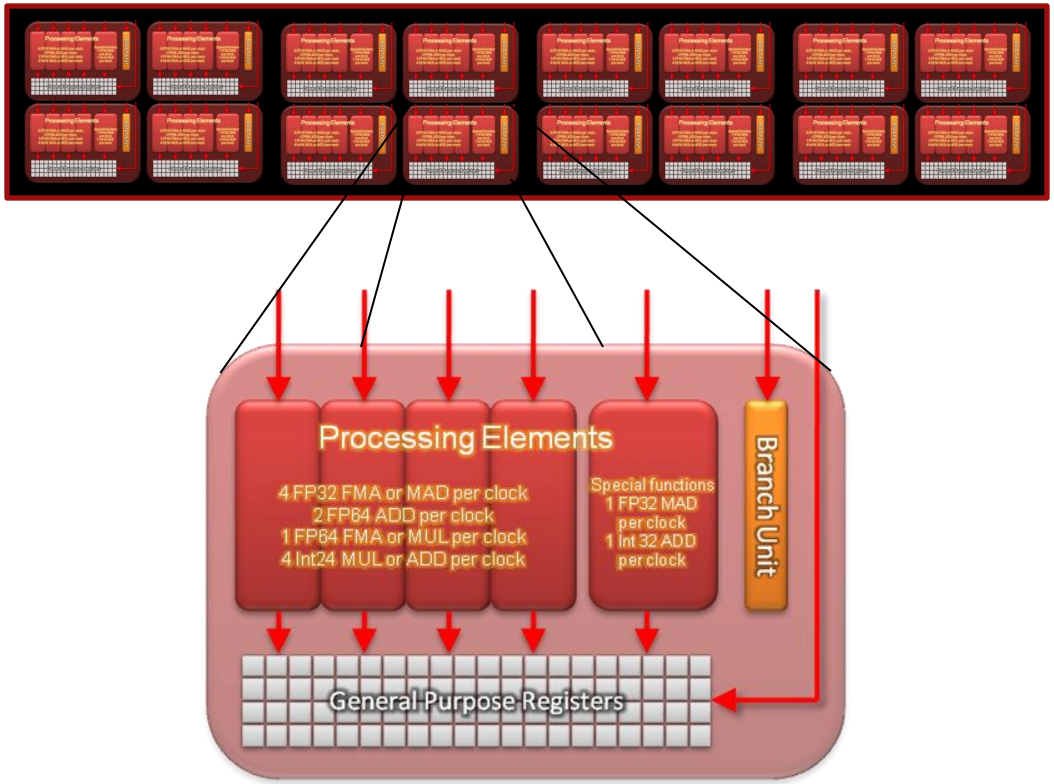


OpenCL™ Device Example

- ATI Radeon™ HD 5870 GPU

1 Compute Unit Contains 16 Stream Cores

1 Stream Core = 5 Processing Elements



OpenCL™ Architecture – Execution Model

- **Kernel**:
  - Basic unit of executable code that runs on OpenCL™ devices
  - Data-parallel or task-parallel
- **Host program**:
  - Executes on the host system
  - Sends kernels to execute on OpenCL™ devices using command queue

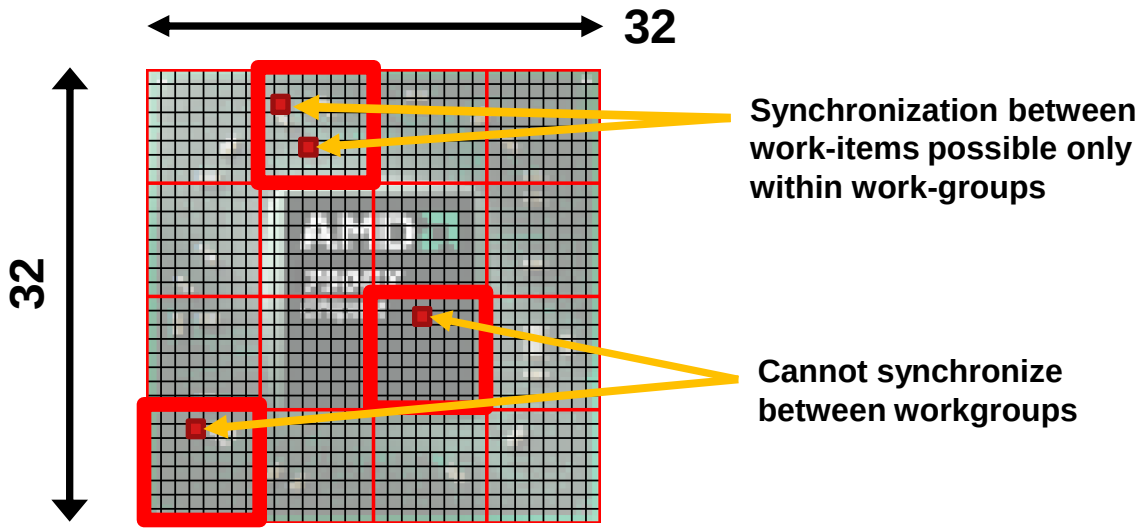
Kernels – Expressing Data-Parallelism

- Define N-dimensional computation domain
  - N = 1, 2, or 3
  - Each element in the domain is called a **work-item**
  - N-D domain (**global dimensions**) defines the total work-items that execute in parallel
  - Each work-item executes the same kernel

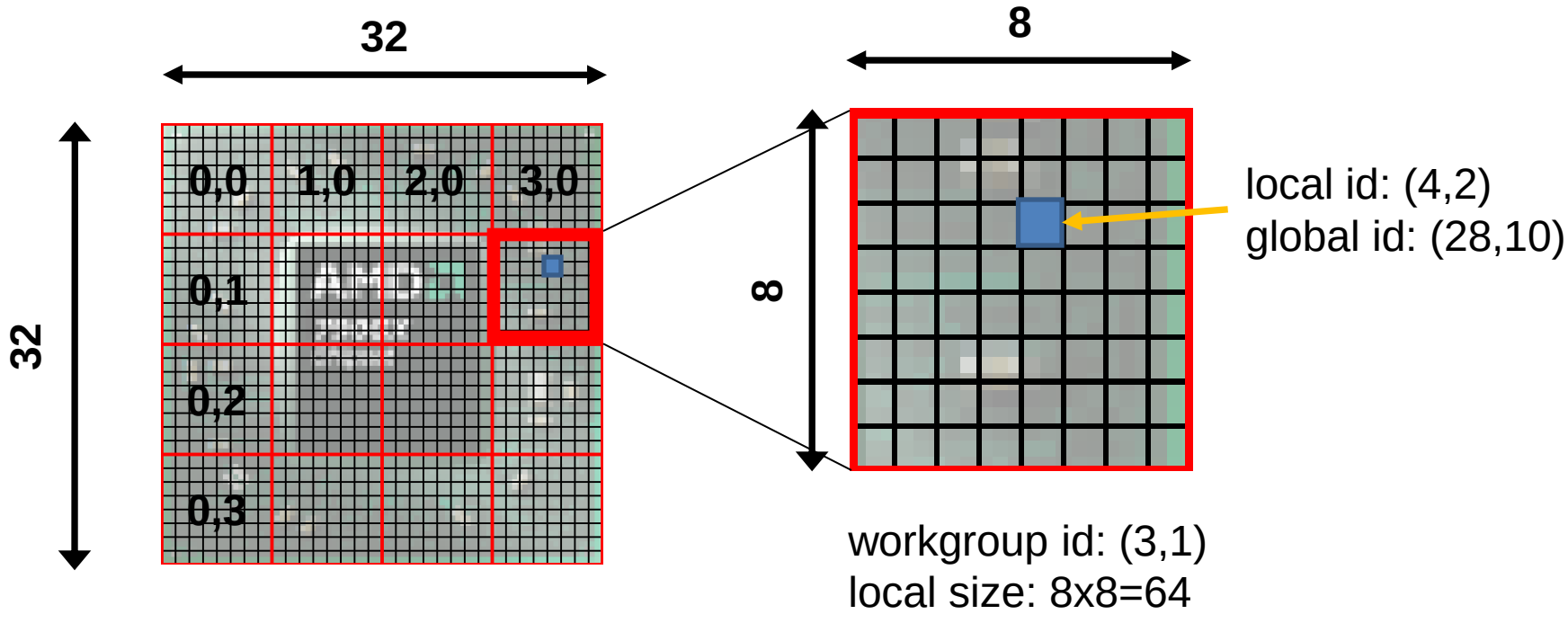
Process 1024x1024 image:
Global problem dimension: 1024x1024
1 kernel execution per pixel: 1,048,576 total executions

Kernels: Work-item and Work-group

- Work-items are grouped into **work-groups**
  - **Local dimensions** define the size of the workgroups
  - Execute together on same compute unit
  - Share local memory and synchronization



Kernels: Work-item and Work-group Example



Kernels Example

Scalar	Data-Parallel

void square(int n, const float *a,
float *result)
{
int i;
for (i=0; i<n; i++)
result[i] = a[i] * a[i];
}
	kernel dp_square (const float *a,
	float *result)
	{
	int id = get_global_id(0);
	result[id] = a[id] * a[id];
	}
	
	// dp_square executes oven “n” work-items

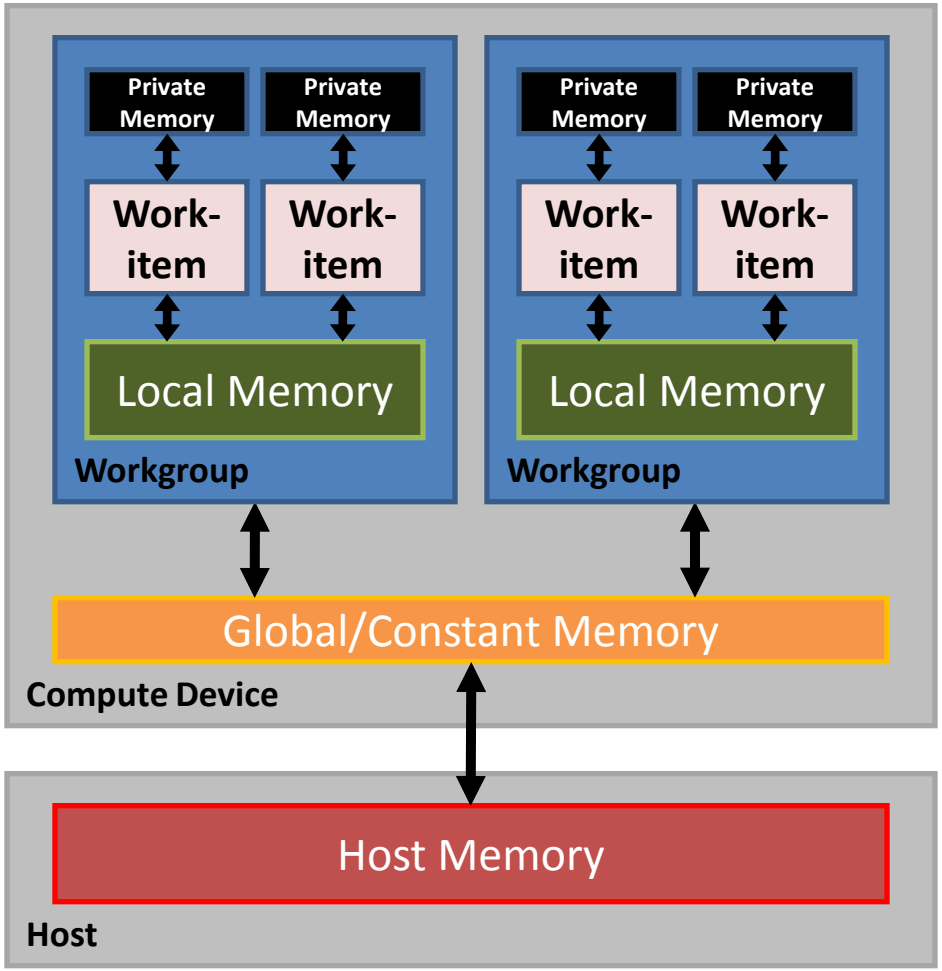
Execution Model – Host Program

- Create "Context" to manage OpenCL™ resources
  - **Devices** – OpenCL™ device to execute kernels
  - **Program Objects**: source or binary that implements kernel functions
  - **Kernels** – the specific function to execute on the OpenCL™ device
  - **Memory Objects** – memory buffers common to the host and OpenCL™ devices

Execution Model – Command Queue

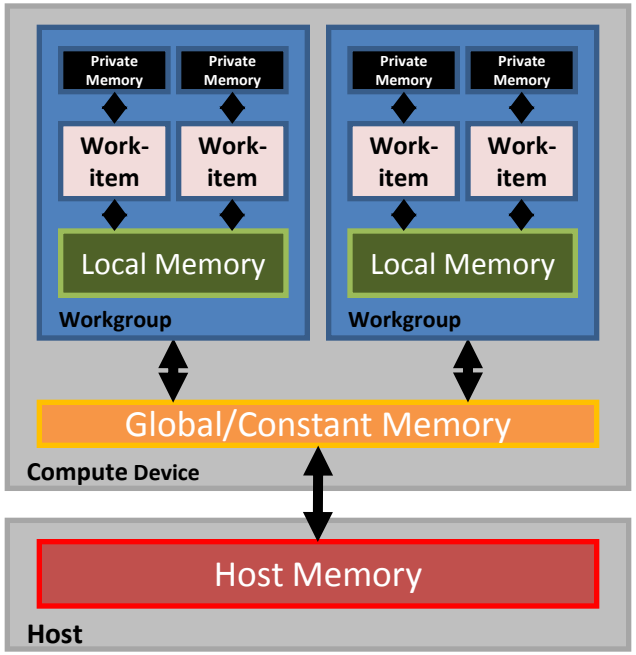
- Manage execution of kernels
- Accepts:
  - **Kernel execution commands**
  - **Memory commands**
  - **Synchronization commands**
- Queued in-order
- Execute in-order or out-of-order

Memory Model



Memory Model

- **Global** – read and write by all work-items and work-groups
- **Constant** – read-only by work-items; read and write by host
- **Local** – used for data sharing; read/write by work-items in same work-group
- **Private** – only accessible to one work-item



Memory management is explicit
Must move data from host to global to local and back

Getting Started with OpenCL™

AMD
The future is fusion

GPGPU Overview

GPGPU Overview

Introduction to OpenCL™

Getting Started with OpenCL™

- Software Development Environment
  - Requirements
  - Installation on Windows®
  - Installation on Linux®
- First OpenCL™ Program
- Compiling OpenCL™ Source

OpenCL™ Programming in Detail

The OpenCL™ C Language

Application Optimization and Porting

Software Development Kit

ATI Stream SDK v2

Download free at http://developer.amd.com/stream

File Name	Launch Date	Bitness	Description
Linux® (openSUSE™ 11.0, Ubuntu® 9.04)			
ati-stream-sdk-v2.01-lnx32.tgz (34.2MB)	03/29/2010	32-bit	ATI Stream SDK built for 32-bit Linux®
ati-stream-sdk-v2.01-lnx64.tgz (59.2MB)	03/29/2010	64-bit	ATI Stream SDK built for 64-bit Linux®
Linux® (Red Hat® Enterprise Linux® 5.3)			
ati-stream-sdk-v2.01-rhel32.tgz (35.3MB)	02/10/2010	32-bit	ATI Stream SDK built for 32-bit Red Hat® Enterprise Linux®
ati-stream-sdk-v2.01-rhel64.tgz (61.0MB)	02/10/2010	64-bit	ATI Stream SDK built for 64-bit Red Hat® Enterprise Linux®
Windows Vista® SP1 / Windows® 7			
ati-stream-sdk-v2.01-vista-win7-32.exe (49.2MB)	03/29/2010	32-bit	ATI Stream SDK built for 32-bit Microsoft® Windows Vista® and Microsoft® Windows® 7
ati-stream-sdk-v2.01-vista-win7-64.exe (91.9MB)	03/29/2010	64-bit	ATI Stream SDK built for 64-bit Microsoft® Windows Vista® and Microsoft® Windows® 7
Windows® XP SP3 (32-bit) / SP2 (64-bit)			
ati-stream-sdk-v2.01-xp32.exe (49.1MB)	03/29/2010	32-bit	ATI Stream SDK built for 32-bit Microsoft® Windows® XP
ati-stream-sdk-v2.01-xp64.exe (91.7MB)	03/29/2010	64-bit	ATI Stream SDK built for 64-bit Microsoft® Windows® XP

SDK Requirements

Supported Operating Systems:

Windows®:	• Windows® XP SP3 (32-bit), SP2 (64-bit) • Windows® Vista® SP1 (32/64-bit) • Windows® 7 (32/64-bit)
Linux®:	• openSUSE™ 11.1 (32/64-bit) • Ubuntu® 9.10 (32/64-bit) • Red Hat® Enterprise Linux® 5.3 (32/64-bit)

Supported Compilers:

Windows®:	• Microsoft® Visual Studio® 2008 Professional Ed.
Linux®:	• GNU Compiler Collection (GCC) 4.3 or later • Intel® C Compiler (ICC) 11.x

SDK Requirements

Supported GPUs:

ATI Radeon™ HD	5970, 5870, 5850, 5770, 5670, 5570, 5450 4890, 4870 X2, 4870, 4850, 4830, 4770, 4670, 4650, 4550, 4350
ATI FirePro™	V8800, V8750, V8700, V7800, V7750 V5800, V5700, V4800, V3800, V3750
AMD FireStream™	9270, 9250
ATI Mobility Radeon™ HD	5870, 5850, 5830, 5770, 5730, 5650, 5470, 5450, 5430 4870, 4860, 4850, 4830, 4670, 4650, 4500 series, 4300 series
ATI Mobility FirePro™	M7820, M7740, M5800
ATI Radeon™ Embedded	E4690 Discrete GPU

SDK Requirements

Supported GPU Drivers:

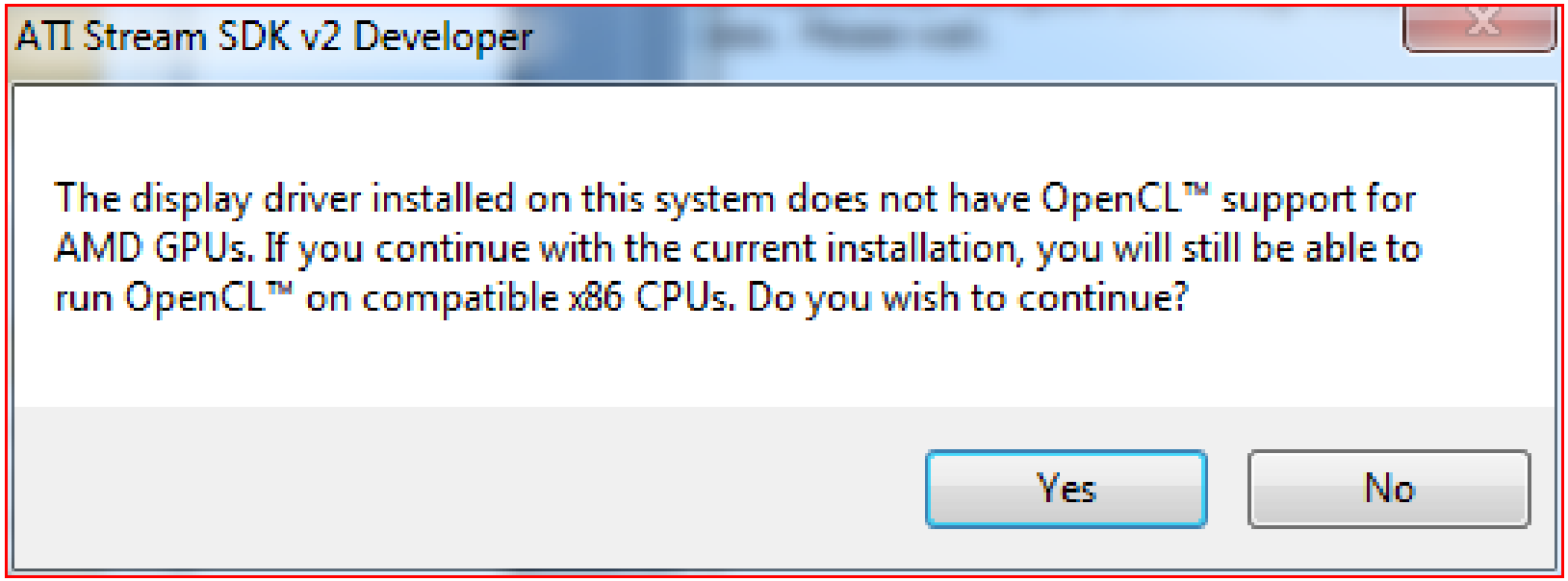
ATI Radeon™ HD	ATI Catalyst™ 10.4
ATI FirePro™	ATI FirePro™ Unified Driver 8.723
AMD FireStream™	ATI Catalyst™ 10.4
ATI Mobility Radeon™ HD	ATI Catalyst™ Mobility 10.4
ATI Mobility FirePro™	Contact the laptop manufacturer for the appropriate driver
ATI Radeon™ Embedded	Contact the laptop manufacturer for the appropriate driver

Supported Processors:

- Any X86 CPU with SSE 3.x or later

Installing SDK on Windows®

Installing SDK on Windows®



Installing SDK on Linux®

1. Untar the SDK to a location of your choice:
   - **tar –zxvf ati-stream-sdk-v2.1-lnx32.tgz**

2. Add *ATISTREAMSDKROOT* to environment variables:
   - **export ATISTREAMSDKROOT=<your_install_location>**

3. If the sample code was installed, add *ATISTREAMSDKSAMPLESROOT* to your environment variables:
   - **export ATISTREAMSDKSAMPLESROOT=<your_install_location>**

Installing SDK on Linux®

4. Add the appropriate path to the *LD_LIBRARY_PATH*:

On 32-bit systems:

- **export LD_LIBRARY_PATH=$ATISTREAMSDKROOT/lib/x86:$LD_LIBRARY_PATH**

On 64-bit systems:

- **export LD_LIBRARY_PATH=$ATISTREAMSDKROOT/lib/x86_64:$LD_LIBRARY_PATH**

Installing SDK on Linux®

5. Register the OpenCL™ ICD to allow applications to run by:
   - **sudo -s**
   - **mkdir –p /etc/OpenCL/vendors**

On all systems:

- **echo libatiocl32.so > /etc/OpenCL/vendors/atiocl32.icd**

On 64-bit systems also perform:

- **echo libatiocl64.so > /etc/OpenCL/vendors/atiocl64.icd**

First OpenCL™ Application

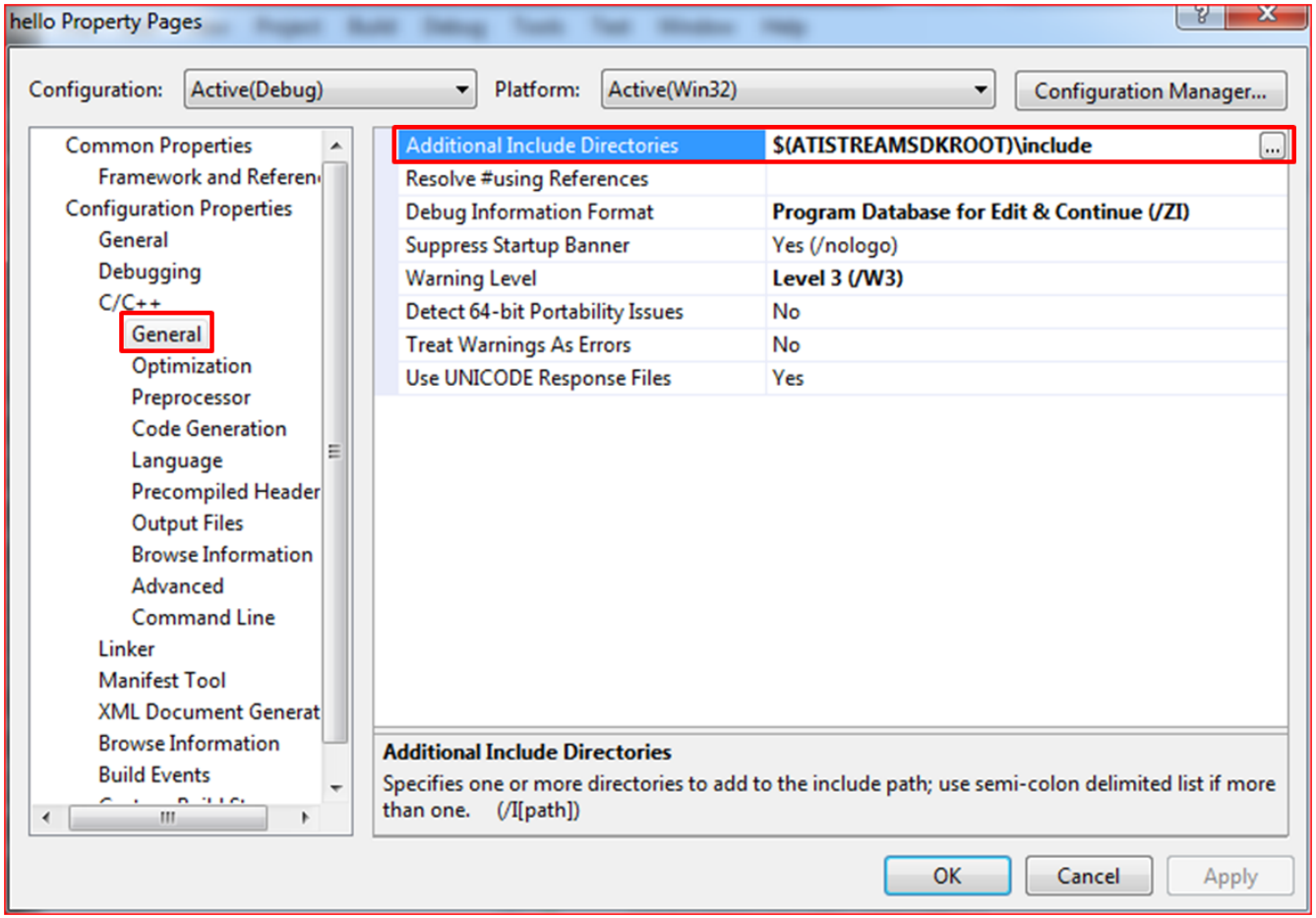
see “hello_world.c”

Compiling on Linux®

- To compile on Linux®:
  - **gcc –o hello_world –I$ATISTREAMSDKROOT/include –L$ATISTREAMSDKROOT/lib/x86 hello_world.c -lOpenCL**
- To execute the program:
  - Ensure *LD_LIBRARY_PATH* environment variable is set to find libOpenCL.so, then:
  - **./hello_world**

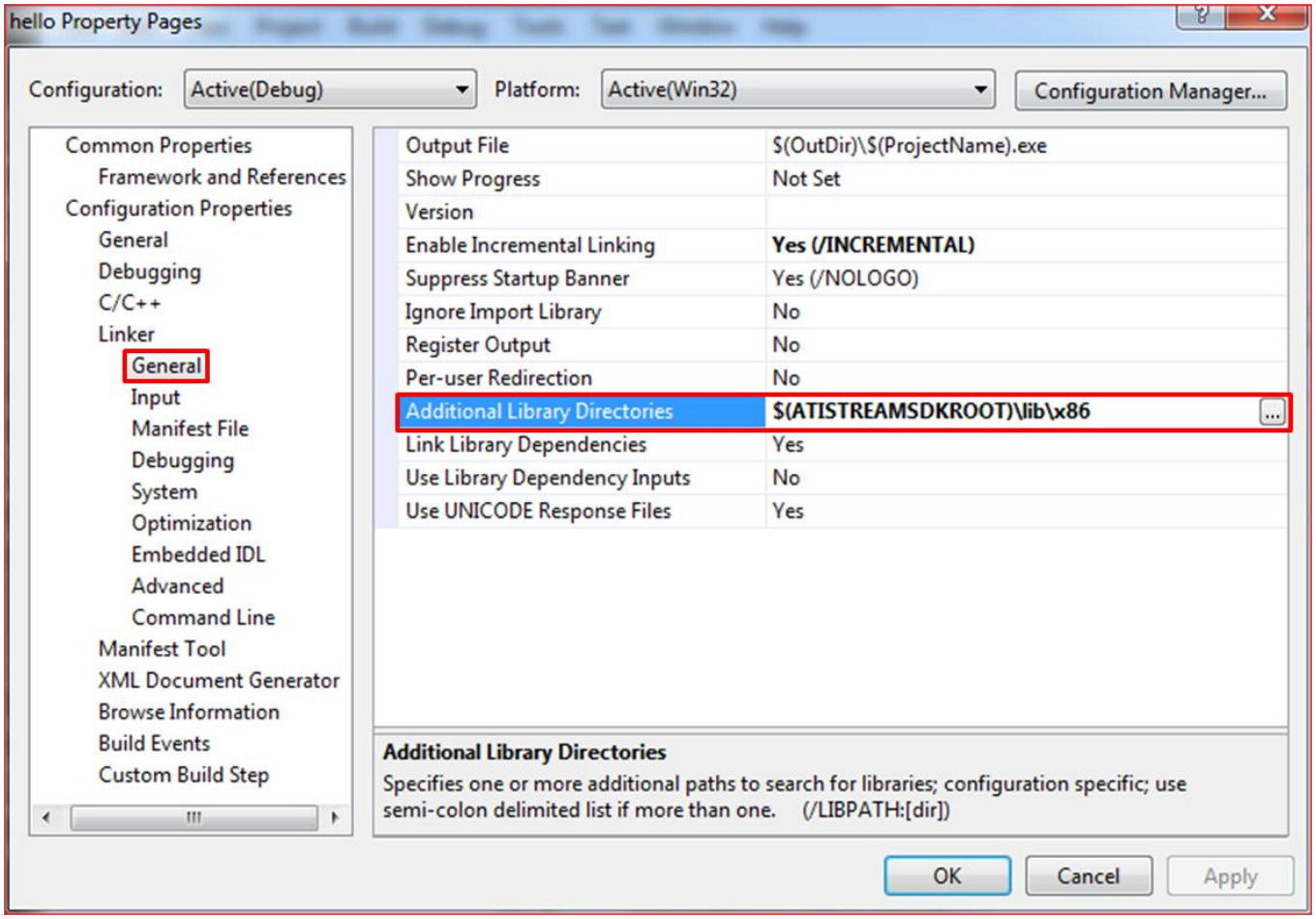
Compiling on Windows® Visual Studio®

- Set include path:



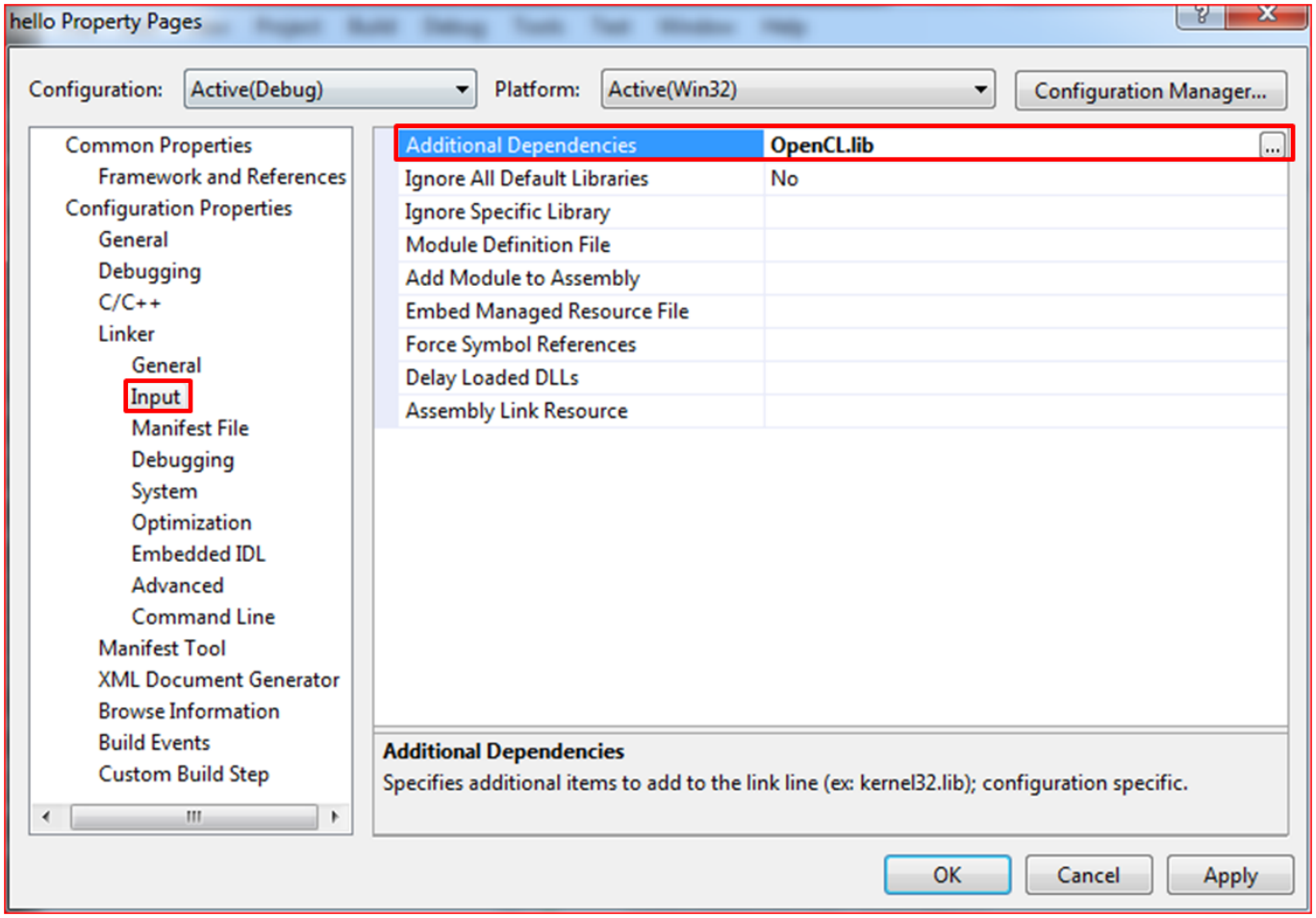
Compiling on Windows® Visual Studio®

- Set library path:



Compiling on Windows® Visual Studio®

- Set additional library to link:



OpenCL™ Programming in Detail

AMD
The future is fusion

GPGPU Overview

GPGPU Overview

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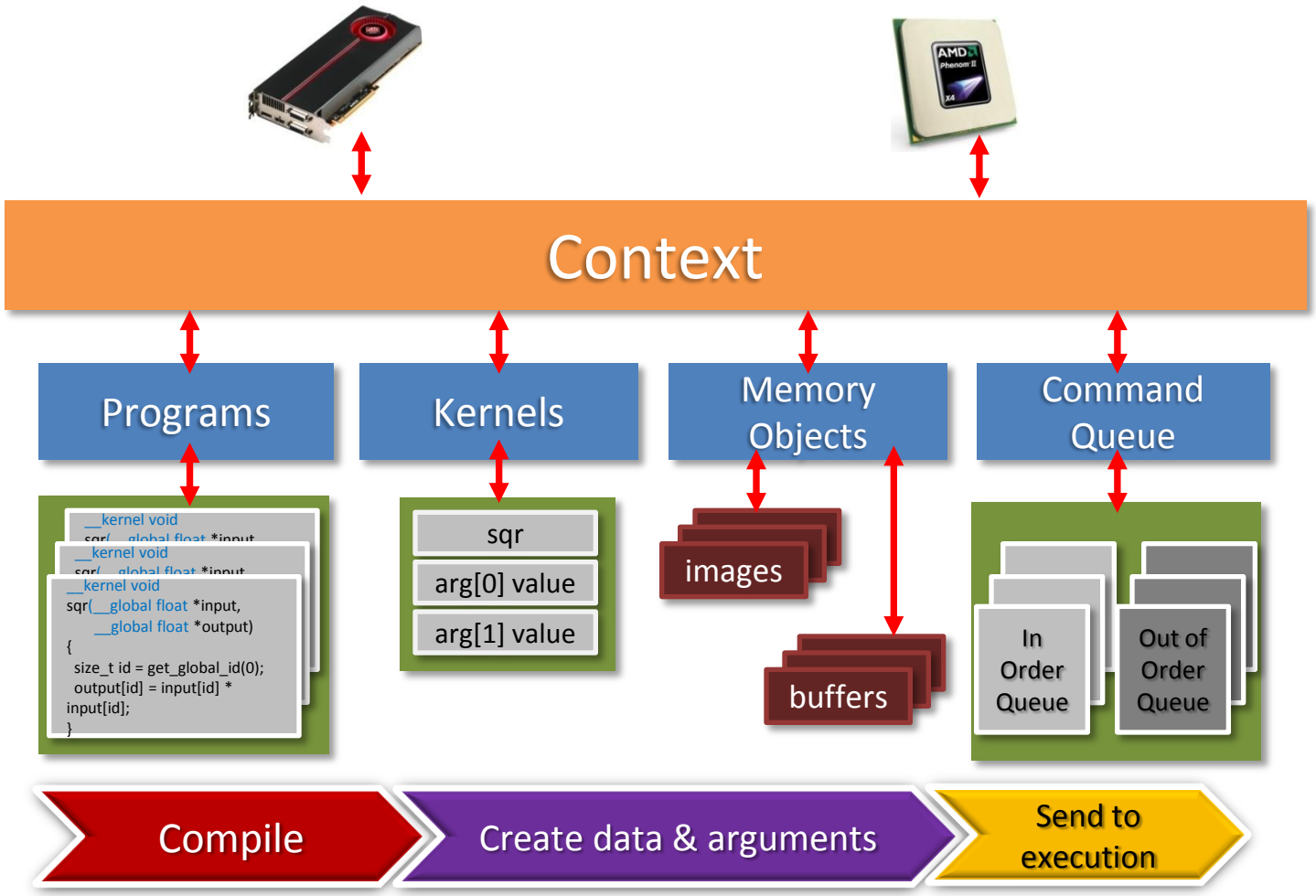
OpenCL™ Programming in Detail

- OpenCL™ Application Execution
- Resource Setup
- Kernel Programming and Compiling
- Program Execution
- Memory Objects
- Synchronization

The OpenCL™ C Language

Application Optimization and Porting

OpenCL™ Program Flow



Query for Platform IDs

- First Step in any OpenCL™ application

```
cl_platform_id platforms;
cl_uint num_platforms;

cl_int err = clGetPlatfromIDs(
            1,                  // the number of entries that can added to platforms
            &platforms,         // list of OpenCL found
            &num_platforms      // the number of OpenCL platforms available
);
```

Returns:

- **CL_INVALID_VALUE** — Platforms and *num_platforms* is NULL or the number of entries is 0.
- **CL_SUCCESS** — The function executed successfully.

Query for Platform Information

- Get specific info. about the OpenCL™ Platform
- Use
  - **clGetPlatformInfo()**
    - **platform_profile**
    - **platform_version**
    - **platform_name**
    - **platform_vendor**
    - **platform_extensions**

```
Number of platforms:                            1
  Plaform Profile:                              FULL_PROFILE
  Plaform Version:                              OpenCL 1.0 ATI-Stream-v2.0.1
  Plaform Name:                                 ATI Stream
  Plaform Vendor:                               Advanced Micro Devices, Inc.
  Plaform Extensions:                   cl_khr_icd
```

Query for OpenCL™ Device

- Search for OpenCL™ compute devices in system

```
cl_device_id device_id;
cl_uint num_of_devices;
err = clGetDeviceIDs(
        platform_id,                // the platform_id retrieved from clGetPlatformIDs
        CL_DEVICE_TYPE_GPU,         // the device type to search for
        1,                          // the number of ids to add to device_id list
        &device_id,                 // the list of device ids
        &num_of_devices             // the number of compute devices found
);
```

Query for OpenCL™ Device

Supported device types:

- **CL_DEVICE_TYPE_CPU**
- **CL_DEVICE_TYPE_GPU**
- **CL_DEVICE_TYPE_ACCELERATOR**
- **CL_DEVICE_TYPE_DEFAULT**
- **Cl_DEVICE_TYPE_ALL**

clGetDeviceIDs() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_PLATFORM —** Platform is not valid.
- **CL_INVALID_DEVICE_TYPE** — The device is not a valid value.
- **CL_INVALID_VALUE** — num_of_devices and devices are NULL.
- **CL_DEVICE_NOT_FOUND** — No matching OpenCL of device_type was found.

Query for Device Information

- Get specific info. about the OpenCL™ Device
- Use
  - **clGetDeviceInfo()**
    - device_type
    - max_compute_units
    - max_workgroup_size
    - …

```
Device Type:                                    CL_DEVICE_TYPE_GPU
Device ID:                                      4098
Max compute units:                              8
Max work items dimensions:                      3
  Max work items[0]:                            256
  Max work items[1]:                            256
  Max work items[2]:                            256
Max work group size:                            256
Preferred vector width char:                    16
Preferred vector width short:                   8
Preferred vector width int:                     4
Preferred vector width long:                    2
Preferred vector width float:                   4
Preferred vector width double:                  0
Max clock frequency:                            750Mhz
Address bits:                                   32
Max memeory allocation:                         134217728
Image support:                                  No
Max size of kernel argument:                    1024
Alignment (bits) of base address:               4096
Minimum alignment (bytes) for any datatype:     128
Single precision floating point capability
  Denorms:                                      No
  Quiet NaNs:                                   Yes
  Round to nearest even:                        Yes
  Round to zero:                                No
  Round to +ve and infinity:                    No
  IEEE754-2008 fused multiply-add:              No
Cache type:                                     None
Cache line size:                                0
Cache size:                                     0
Global memory size:                             134217728
Constant buffer size:                           65536
Max number of constant args:                    8
Local memory type:                              Global
Local memory size:                              16384
Profiling timer resolution:                     1
Device endianess:                               Little
Available:                                      Yes
Compiler available:                             Yes
Execution capabilities:
  Execute OpenCL kernels:                       Yes
  Execute native function:                      No
Queue properties:
  Out-of-Order:                                 No
  Profiling :                                   Yes
Platform ID:                                    0xb7e06488
Name:                                           ATI RV770
Vendor:                                         Advanced Micro Devices, Inc.
Driver version:                                 CAL 1.4.519
Profile:                                        FULL_PROFILE
Version:                                        OpenCL 1.0 ATI-Stream-v2.0.1
Extensions:                                     cl_khr_icd
```

Creating Context

- Manage command queues, program objects, kernel objects, memory object

```
cl_context context;
// context properties list - must be terminated with 0
properties[0]= CL_CONTEXT_PLATFORM; // specifies the platform to use
properties[1]= (cl_context_properties) platform_id;
properties[2]= 0;

context = clCreateContext(
    properties,          // list of context properties
    1,                   // num of devices in the device_id list
    &device_id,          // the device id list
    NULL,                // pointer to the error callback function (if required)
    NULL,                // the argument data to pass to the callback function
    &err);               // the return code
```

Creating Context

clGreateContext() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_PLATFORM —** Property list is NULL or the platform value is not valid.
- **CL_INVALID_VALUE —** Either:
  - The property name in the properties list is not valid.
  - The number of devices is 0.
  - The device_id list is null.
  - The device in the device_id list is invalid or not associated with the platform.
- **CL_DEVICE_NOT_AVAILABLE —** The device in the device_id list is currently unavailable.

Creating Command Queue

- Allows kernel commands to be sent to compute devices

```
cl_command_queue command_queue;
command_queue = clCreateCommandQueue(
        context,                // a valid context
        device_id,              // a valid device associated with the context
        0,                      // properties for the queue (not used here)
        &err);                  // the return code
```

Create Command Queue

Supported Command Queue Properties:

- **CL_QUEUE_OUT_OF_ORDER_EXEC_MODE_ENABLE**
- **CL_QUEUE_PROFILING_ENABLE**

clCreateCommandQueue() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_CONTEXT** — The context is not valid.
- **CL_INVALID_DEVICE** — Either the device is not valid or it is not associated with the context.
- **CL_INVALID_VALUE** — The properties list is not valid.
- **CL_INVALID_QUEUE_PROPERTIES** — The device does not support the properties specified in the properties list.

Program Object

- **Program** – collection of kernel and helper functions
- **Function** – written in OpenCL™ C Language
- **Kernel Function** – indentified by __kernel
- **Program Object** - Encapsulates
  - Program sources or binary file
  - Latest successful-built program executable
  - List of devices for which exec is built
  - Build options and build log
- Created **online** or **offline**

Create Program Object Online

- Use **clCreateProgramWithSource**()

```
const char *ProgramSource =
"__kernel void hello(__global float *input, __global float *output)\n"\
"{\n"\
" size_t id = get_global_id(0);\n"\
" output[id] = input[id] * input[id];\n"\
"}\n";

cl_program  program;
program = clCreateProgramWithSource(
    context,                                // a valid context
    1,                                      // the number strings in the next parameter
    (const char **) &ProgramSource,         // the array of strings
    NULL,                                   // the length of each string or can be NULL terminated
    &err );                                 // the error return code
```

Create Program Object

clCreateProgramWithSource() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_CONTEXT** — The context is not valid.
- **CL_INVALID_VALUE** — The string count is 0 (zero) or the string array contains a NULL string.

- Creating program object offline
  - Use **clGetProgramInfo()** to retrieve program binary for already created program object
  - Create program object from existing program binary with **clCreateProgramWithBinary()**

Building Program Executables

- Compile and link program object created from **clCreateProgramWithSource()** or **clCreateProgramWithBinary()**
- Create using **clBuildProgram()**

```
err = clBuildProgram(
    program,                    // a valid program object
    0,                          // number of devices in the device list
    NULL,                       // device list – NULL means for all devices
    NULL,                       // a string of build options
    NULL,                       // callback function when executable has been built
    NULL                        // data arguments for the callback function
);
```

Building Program Executables

Program Build Options – passing additional options to compiler such as preprocessor options or optimization options

Example:

```
char * buildoptions = "-DFLAG1_ENABLED -cl-opt-disable "
```

clBuildProgram() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_VALUE —** The number of devices is greater than zero, but the device list is empty.
- **CL_INVALID_VALUE —** The callback function is NULL, but the data argument list is not NULL.
- **CL_INVALID_DEVICE —** The device list does not match the devices associated in the program object.
- **CL_INVALID_BUILD_OPTIONS —** The build options string contains invalid options.

Retrieving Build Log

- Access build log with clGetProgramBuildInfo()

```
if (clBuildProgram(program, 0, NULL, buildoptions, NULL, NULL) != CL_SUCCESS)
{
    printf("Error building program\n");
    char buffer[4096];
    size_t length;
    clGetProgramBuildInfo(
            program,                    // valid program object
            device_id,                  // valid device_id that executable was built
            CL_PROGRAM_BUILD_LOG,       // indicate to retrieve build log
            sizeof(buffer),             // size of the buffer to write log to
            buffer,                     // the actual buffer to write log to
            &length);                   // the actual size in bytes of data copied to buffer

    printf("%s\n",buffer);
    exit(1);
}
```

Sample Build Log

```
platform 1
platform name: ATI Stream
__kernel void square(const __global float *input0,
                     const __global float *input1,
                      __global float * out)
{
    const int Width = get_global_size(0);
    const size_t xid = get_global_id(0);
    const size_t yid = get_global_id(1);

    const int idx= id*Width + xid;
    out[idx]=input0[idx]+input1[idx];

}

-- /tmp/OCLZenMa8.cl(9): error: identifier "id" is undefined
      const int idx= id*Width + xid;
                     ^

1 error detected in the compilation of "/tmp/OCLZenMa8.cl".
```

Creating Kernel Objects

- **Kernel function** identified with qualifier __kernel
- **Kernel object** encapsulates specified __kernel function along with the arguments
- Kernel object is what get sent to command queue for execution
- Create Kernel Object with **clCreateKernel()**

```
cl_kernel kernel;
kernel = clCreateKernel(
    program,          // a valid program object that has been successfully built
    "hello",          // the name of the kernel declared with __kernel
    &err              // error return code
);
```

Creating Kernel Object

clCreateKernel() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_PROGRAM —** The program is not a valid program object.
- **CL_INVALID_PROGRAM_EXECUTABLE —** The program does not contain a successfully built executable.
- **CL_INVALID_KERNEL_NAME —** The kernel name is not found in the program object.
- **CL_INVALID_VALUE —** The kernel name is NULL.

Setting Kernel Arguments

- Specify arguments that are associated with the __kernel function
- Use **clSetKernelArg()**

```
err = clSetKernelArg(
    kernel,              // valid kernel object
    0,                   // the specific argument index of a kernel
    sizeof(cl_mem),      // the size of the argument data
    &input_data          // a pointer of data used as the argument
);
```

- Example Kernel function declaration

```
__kernel void hello(__global float *input,  __global float *output)
```

Setting Kernel Arguments

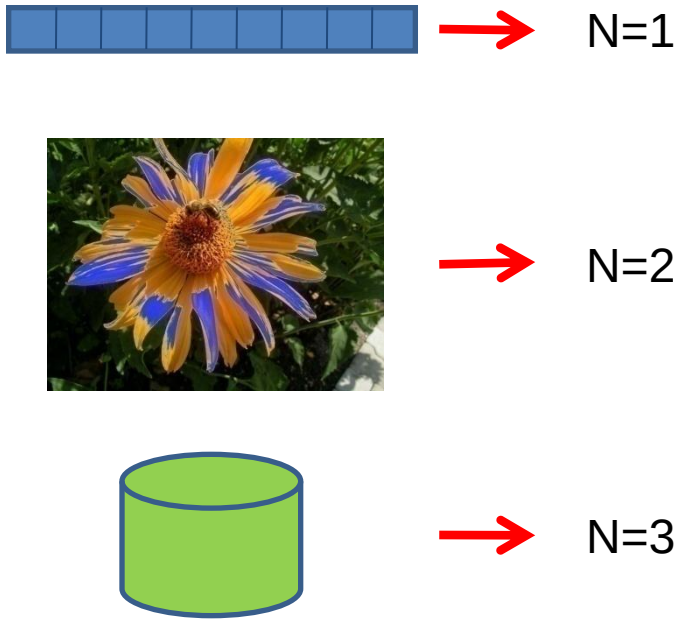
- Must use **memory object** for arguments with __global or __constant
- Must use **image object** for arguments with image2d_t or image3d_t

clSetKernelArg() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_PROGRAM** — The program is not a valid program object.
- **CL_INVALID_PROGRAM_EXECUTABLE** — The program does not contain a successfully built executable.
- **CL_INVALID_KERNEL_NAME** — The kernel name is not found in the program object.
- **CL_INVALID_VALUE** — The kernel name is NULL.

Executing Kernel

- Determine the problem space
- Determine global work size (total work-items)
- Determine local size (work-group size – work-items share memory in work-group)
- Use **clGetKernelWorkGroupInfo** to determine max work-group size



Enqueuing Kernel Commands

- Place kernel commands into command queue by using **clEnqueueNDRangeKernel()**

```
err = clEnqueueNDRangeKernel(
    command_queue,      // valid command queue
    kernel,             // valid kernel object
    1,                  // the work problem dimensions
    NULL,               // reserved for future revision - must be NULL
    &global,            // work-items for each dimension
    NULL,               // work-group size for each dimension
    0,                  // number of event in the event list
    NULL,               // list of events that needs to complete before this executes
    NULL                // event object to return on completion
);
```

size_t global[2]={512,512};

size_t local[2]={8,8};
// clGetKernelWorkGoupInfo()

Creating Kernel Object

Common **clEnqueueNDRangeKernel**() Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_PROGRAM_EXECUTABLE —** No executable has been built in the program object for the device associated with the command queue.
- **CL_INVALID_COMMAND_QUEUE —** The command queue is not valid.
- **CL_INVALID_KERNEL —** The kernel object is not valid.
- **CL_INVALID_CONTEXT —** The command queue and kernel are not associated with the same context.
- **CL_INVALID_KERNEL_ARGS —** Kernel arguments have not been set.
- **CL_INVALID_WORK_DIMENSION —** The dimension is not between 1 and 3.
- **CL_INVALID_GLOBAL_WORK_SIZE —** The global work size is NULL or exceeds the range supported by the compute device.
- **CL_INVALID_WORK_GROUP_SIZE —** The local work size is not evenly divisible with the global work size or the value specified exceeds the range supported by the compute device.
- **CL_INVALID_EVENT_WAIT_LIST —** The events list is empty (NULL) but the number of events arguments is greater than 0; or number of events is 0 but the event list is not NULL; or the events list contains invalid event objects.

Cleaning Up

- Release resources when execution is complete

```
clReleaseMemObject(input);
clReleaseMemObject(output);
clReleaseProgram(program);
clReleaseKernel(kernel);
clReleaseCommandQueue(command_queue);
clReleaseContext(context);
```

- **clRelease** functions decrement reference count
- Object is deleted when reference count reaches zero

Memory Objects

- Allows packaging data and easy transfer to compute device memory
- Minimizes memory transfers from host and device
- Two types of memory objects:
  - Buffer object
  - Image object

Creating Buffer Object

```
cl_mem input;
input = clCreateBuffer(
    context,                                    // a valid context
    CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,    // bit-field flag to specify
                                                // the usage of memory
    sizeof(float) * DATA_SIZE,                  // size in bytes of the buffer to allocated
    inputsrc,                                   // pointer to buffer data to be copied from host
    &err                                        // returned error code
);
```

Memory usage flag
CL_MEM_READ_WRITE
CL_MEM_WRITE_ONLY
CL_MEM_READ_ONLY
CL_MEM_USE_HOST_PTR
CL_MEM_COPY_HOST_PTR
CL_MEM_ALLOC_HOST_PTR

Reading/Writing Buffer Objects

```
err = clEnqueueReadBuffer(
    command_queue, // valid command queue
    output,        // memory buffer to read from
    CL_TRUE,       // indicate blocking read
    0,
    sizeof(float) *DA
    results,
    0,
    NULL,
    NULL
);
```

```
err = clEnqueueWriteBuffer(
    command_queue, // valid command queue
    input,         // memory buffer to write to
    CL_TRUE,       // indicate blocking write
    0,             // the offset in the buffer object to write from
    sizeof(float) *DATA_SIZE, // size in bytes of data being read
    host_ptr,      // pointer to buffer in host mem to read data from
    0,             // number of event in the event list
    NULL,          // list of events that needs to complete before this executes
    NULL           // event object to return on completion
);
```

Read/Writing Buffer Objects

clEnqueueReadBuffer and **clEnqueueWriteBuffer** () Returns:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_COMMAND_QUEUE —** The command queue is not valid
- **CL_INVALID_CONTEXT —** The command queue buffer object is not associated with the same context.
- **CL_INVALID_VALUE —** The region being read/write specified by the offset is out of bounds or the host pointer is NULL.
- **CL_INVALID_EVENT_WAIT_LIST —** Either:
  - The events list is empty (NULL), but the number of events argument is greater than 0
  - The number of events is 0, but the event list is not NULL
  - The events list contains invalid event objects.

Creating Image Object

- Built in support for representing image data

```
image2d = clCreateImage2D( )
    context,          // valid context
    flags,            // bit-field flag to specify usage of memory
    image_format,     // ptr to struct that specifies image format properties
    width,            // width of the image in pixels
    height,           // height of the image in pixels
    row_pitch,        // scan line row pitch in bytes
    host_ptr,         // pointer to image data to be copied from host
    &err              // error return code
);
```

- For 3D image object use **clCreateImage3D**()
  - Specify depth, and slice pitch

Channel Order and Channel Data Type

- Built in support for representing image data

```
// Example:
cl_image_format image_format;
image_format.image_channel_data_type = CL_FLOAT;
image_format.image_channel_order = CL_RGBA;
```

- Channel Ordering:
  - CL_RGB, CL_ARGB, CL_RGBA, CL_R, etc…
- Channel Data Types:
  - CL_SNORM_INT8,CL_UNORM_INT16, CL_FLOAT, CL_UNSIGNED_INT32

Reading/Writing Image Objects

```
err = clEnqueueReadImage (
    command_queue, // valid command queue
    image,
    blockin
    origin_
    region,
    row_pi
    slice_p
    host_p
    num_e
    event_
    &even
);
```

```
err = clEnqueueWriteImage (
    command_queue, // valid command queue
    image,              // valid image object to write to
    blocking_read,      // blocking flag, CL_TRUE or CL_FALSE
    origin_offset,      // (x,y,z) offset in pixels to write to z=0 for 2D image
    region,             //(width,height,depth) in pixels to write to, depth=1 for 2D image
    row_pitch,          // length of each row in bytes
    slice_pitch,        // size of each 2D slice in the 3D image in bytes, 0 for 2D image
    host_ptr,           // host memory pointer to store read data from
    num_events,         // number of events in events list
    event_list,         // list of events that needs to complete before this executes
    &event              // event object to return on completion
);
```

Reading/Writing Image Objects

Common **clEnqueueReadImage**( ) and **clEnqueueWriteImage**( ) Return Codes:

- **CL_SUCCESS** — The function executed successfully.
- **CL_INVALID_COMMAND_QUEUE —** The command queue is not valid.
- **CL_INVALID_CONTEXT —** The command queue and image object are not associated with the same context.
- **CL_INVALID_MEM_OBJECT —** The image object is not valid
- **CL_INVALID_VALUE —** The region being read/write specified by the origin_offset and region is out of bounds or the host pointer is NULL.
- **CL_INVALID_VALUE —** The image object is 2D and origin_offset[2] (y component) is not set to 0, or region[2] (depth component) is not set to 1.
- **CL_INVALID_EVENT_WAIT_LIST —** Either: The events list is empty (NULL), but the number of events argument is greater than 0; or number of events is 0, but the event list is not NULL; or the events list contains invalid event objects.

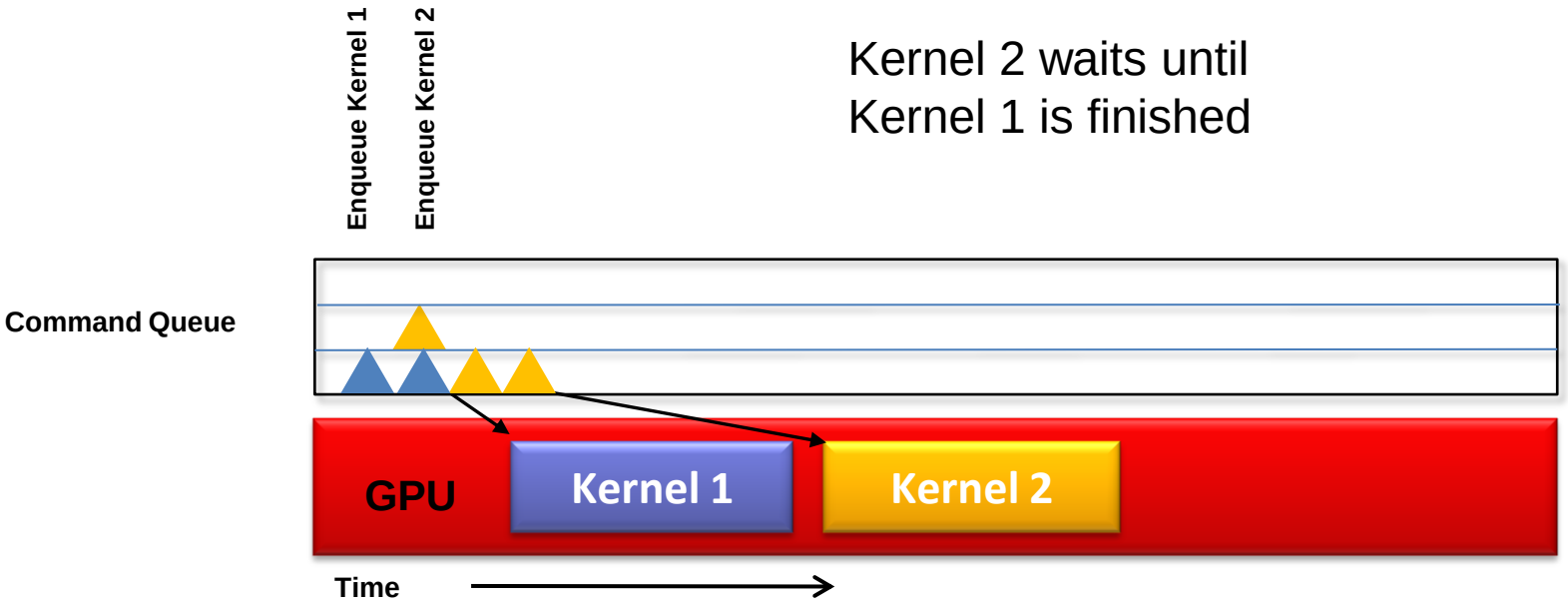
Retaining and Releasing Memory Objects

- On creation reference counter set to “1”
- Counter used to track the number of references to the particular memory object
- Object retain reference by using:
  - **clRetainMemObject**()
- Object decrement reference by using:
  - **clReleaseMemObject** ()
- Memory Object freed when reference counter = 0

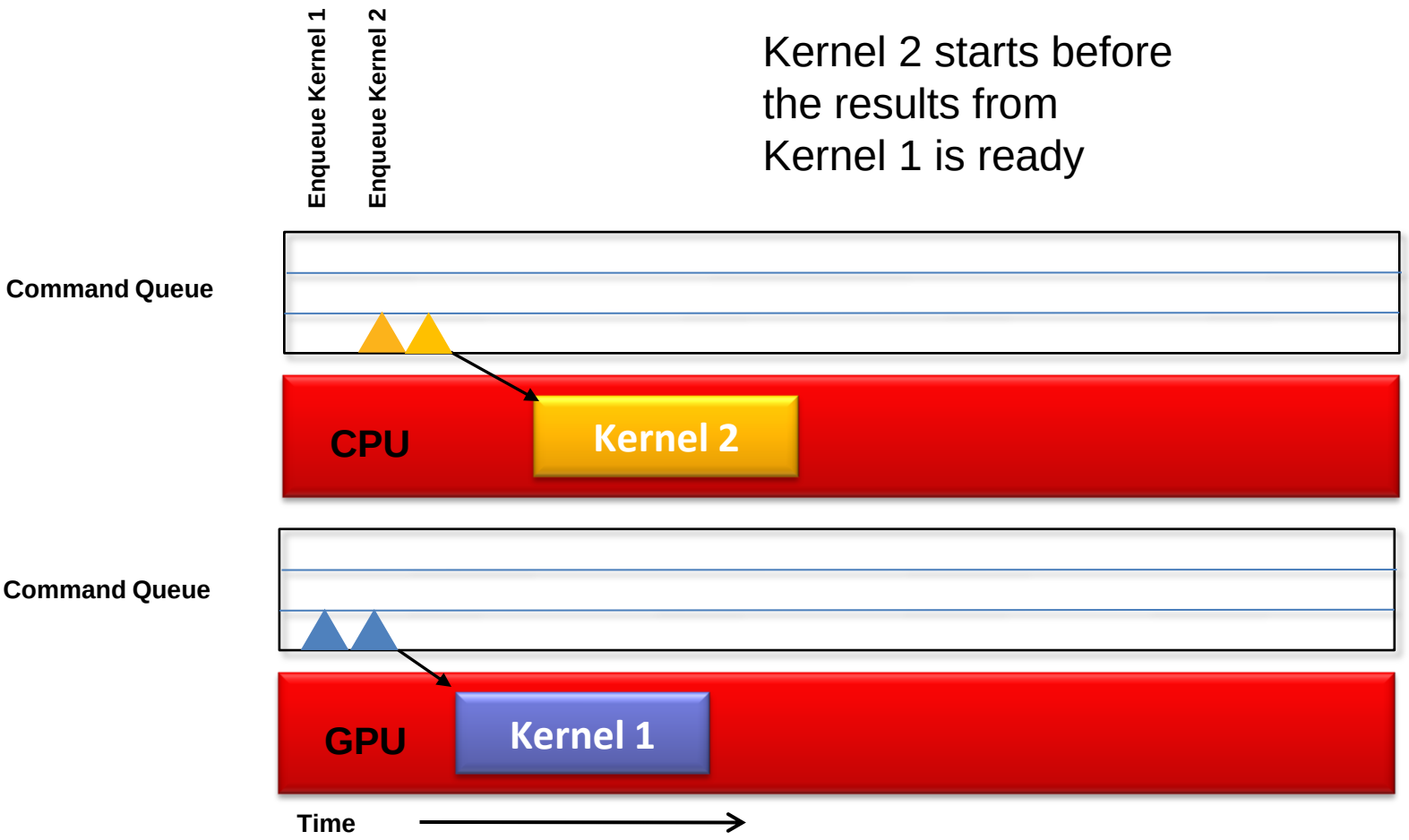
Synchronization

- Kernel queued may not execute immediately
- Force kernel execution by using blocking call
  - Set **CL_TRUE** flag for clEuqueueRead*/Write*
- Use event to track execution status of kernels without blocking host application
- Queue can execute commands
  - **in-order**
  - **out-of-order**
- **clEnqueue***(...,num_events, events_wait_list, event_return)
  - Number of events to wait on
  - A list of events to wait on
  - Event to return

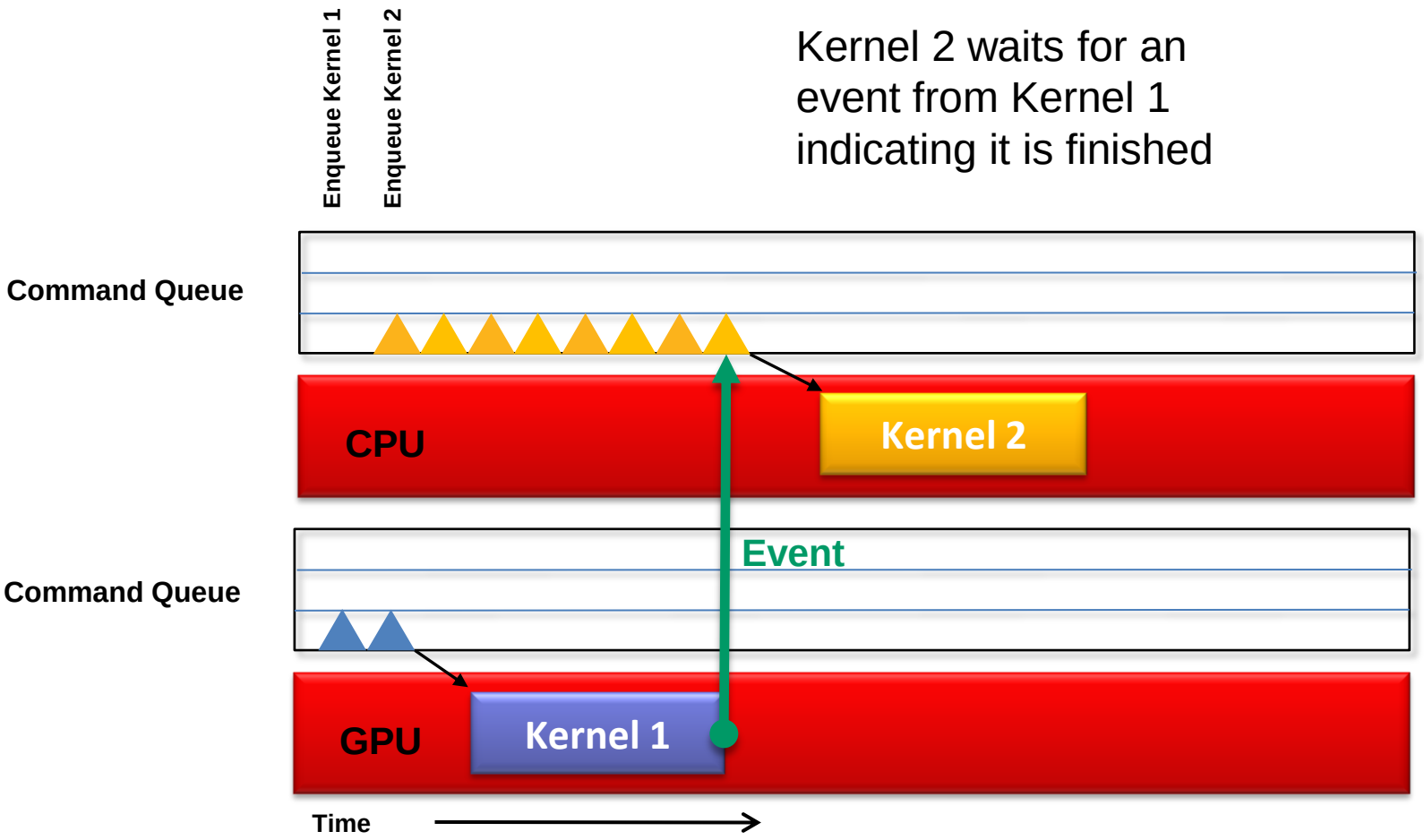
Synchronization Example 1: In-order Queue



Two Command Queues Unsynchronized



Two Command Queues Synchronized



Additional Event Functions

- Host block until all events in wait list are complete
  - **clWaitForEvents**(num_events, event_list)
- OpenCL block until all events in wait list are complete
  - **clEnqueueWaitForEvents**(queue,num_events, event_list)
- Tracking events by using event marker
  - **clEnqueueMarker**(queue, *event_return)

Query Event Information

- Get status of command associated with event
  - **clEventInfo**(event, param_name, param_size, …)

CL_EVENT_COMMAND_QUEUE	Command queue associated with event
CL_EVENT_COMMAND_TYPE	CL_COMMAND_NDRANGE_KERNEL, CL_COMMAND_READ_BUFFER CL_COMMAND_WRITE_BUFFER …
CL_EVENT_COMMAND_ EXECUTION_STATUS	CL_QUEUED, CL_SUBMITTED, CL_RUNNING, CL_COMPLETE
CL_EVENT_REFERENCE_COUNT	Reference counter of the event object

Exercise 1

Complete code to swap 2 arrays.
See "e1/exercise1.c"

OpenCL™ C Language

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OpenCL™ Programming in Detail

The OpenCL™ C Language

- Restrictions
- Data Types
- Type Casting and Conversions
- Qualifiers
- Built-in Functions

Application Optimization and Porting

OpenCL™ C Language

- Language based on ISO C99
  - Some restrictions
- Additions to language for parallelism
  - Vector types
  - Work-items/group functions
  - Synchronization
- Address Space Qualifiers
- Built-in Functions

OpenCL™ C Language Restrictions

- Key restriction in the OpenCL™ language are:
  - **No** function pointers
  - **No** bit-fields
  - **No** variable length arrays
  - **No** recursion
  - **No** standard headers

Data Types

Scalar Type	Vector Type (n = 2, 4, 8, 16)	API Type for host app
char, uchar	charn, ucharn	cl_char<n>, cl_uchar<n>
short, ushort	shortn, ushortn	cl_short<n>, cl_ushort<n>
int, uint	intn, uintn	cl_int<n>, cl_uint<n>
long, ulong	longn, ulongn	cl_long<n>, cl_ulong<n>
float	floatn	cl_float<n>

Using Vector Types

- Creating vector from a set of scalar set

```
float4 f = (float4)(1.0f, 2.0f, 3.0f, 4.0f);

uint4 u = (uint4)(1);  // u will be (1, 1, 1, 1)

float4 f = (float4)((float2)(1.0f, 2.0f), (float2)(3.0f, 4.0f));

float4 f = (float4)(1.0f, 2.0f); // error
```

Accessing Vector Components

- Accessing components for vector types with 2 or 4 components
  - <vector2>.xy, <vector4>.xyzw

```
float2 pos;
pos.x = 1.0f;
pos.y = 1.0f;
pos.z = 1.0f ; // illegal since vector only has 2 components

float4 c;
c.x = 1.0f;
c.y = 1.0f;
c.z = 1.0f;
c.w = 1.0f;
```

Accessing Vector with Numeric Index

Vector components	Numeric indices
2 components	0, 1
4 components	0, 1, 2, 3
8 components	0, 1, 2, 3, 4, 5, 6, 7
16 components	0, 1, 2, 3, 4, 5, 6, 7, 8, 9, a, A, b, B, c, C, e, E, f, F

```
float8 f;
f.s0 = 1.0f; // the 1st component in the vector
f.s7 = 1.0f; // the 8th component in the vector

float16 x;
f.sa = 1.0f; // or f.sA is the 10th component in the vector
f.sF = 1.0f; // or f.sF is the 16th component in the vector
```

Handy addressing of Vector Components

Vector access suffix	Returns
.lo	Returns the lower half of a vector
.hi	Returns the upper half of a vector
.odd	Returns the odd components of a vector
.even	Returns the even components of a vector

```
float4 f = (float4) (1.0f, 2.0f, 3.0f, 4.0f);
float2 low, high;
float2 o, e;

low = f.lo;       // returns f.xy (1.0f, 2.0f)
high = f.hi;      // returns f.zw (3.0f, 4.0f)
o = f.odd;        // returns f.yw (2.0f, 4.0f)
e = f.even;       // returns f.xz (1.0f, 3.0f)
```

Vector Operations

- Support all typical C operator **+,-,*,/,&,|** etc.
  - Vector operations performed on each component in vector independently

```
// example 1:

int4 vi0, vi1;
int v;
vi1 = vi0 + v;

//is equivalent to:
vi1.x = vi0.x + v;
vi1.y = vi0.y + v;
vi1.z = vi0.z + v;
vi1.w = vi0.w + v;
```

```
// example 2:
float4 u, v, w;
w = u + v
w.odd = v.odd + u.odd;

// is equivalent to:
w.x = u.x + v.x;
w.y = u.y + v.y;
w.z = u.z + v.z;
w.w = u.w + v.w;

w.y = v.y + u.y;
w.w = v.w + u.w;
```

Type Casting and Conversions

- Implicit conversion of scalar and pointer types
- **Explicit** conversion required for vector types

```
// implicit conversion
int i;
float f = i;

int4 i4;
float4 =  i4;        // not allowed

// explicit conversion through casting
float x;
int i = (int)x;

int4  i4;
float4 f = (float4) i4;          // not allowed
```

Explicit Conversions

- Use built-in conversion functions for explicit conversion (support scalar & vector data types)
  - **convert_<destination_type>**(source_type)

```
int4 i;
float4 f = convert_float4(i); // converts an int4 vector to float4

float f;
int i = convert_int(f); // converts a float scalar to an integer scalar

int8 i;
float4 f = convert_float4(i); // illegal – components in each vectors must be the same
```

Rounding Mode and Out of Range Conversions

convert_<destination_type><_sat><_roundingMode>(source_type)

- _sat clamps out of range value to nearest representable value
  - Support only integer type
  - Floating point type following IEEE754 rules
- <_roundingMode> specifies the rounding mode

_rte	round to nearest even
_rtz	round to nearest zero
_rtp	round towards positive infinity
_rtn	round towards negative infinity
no modifier	default to _rtz for integer defaults to _rte for float point

Rounding Examples

```
float4    f = (float4)(-1.0f, 252.5f, 254.6f, 1.2E9f);
uchar4   c = convert_uchar4_sat(f);
// c = (0, 253, 255, 255)
// negative value clamped to 0, value > TYPE MAX is set to the type MAX
// -1.0 clamped to 0, 1.2E9f clamped to 255

float4    f = (float4)(-1.0f, 252.5f, 254.6f, 1.2E9f);
uchar4   c = convert_uchar4_sat_rte(f);
// c = (0, 252, 255, 255)
// 252.5f round down to near even becomes 252

int4    i;
float4 = convert_float4(i);
// convert to floating point using the default rounding mode

int4    i;
float4 = convert_float4_rtp(i);
// convert to floating point. Integers values not representable as float
// is round up to the next representable float
```

Reinterpret Data

- Scalar and Vector data can be reinterpreted as another data type
  - **as_<typen>**(value)
- Reinterpret bit pattern in the source to another without modification

```
uint x = as_uint(1.0f);
// x will have value 0x3f800000

uchar4  c;
int4  d = as_int4(c); // error. result and operand have different size
```

Address Space Qualifiers

- **__global**
  - memory objects allocated in global memory pool
- **__local**
  - fast local memory pool
  - sharing between work-items
- **__constant**
  - read-only allocation in global memory pool
- **__private**
  - accessible by work-item
  - kernel arguments are private

Address Space Qualifiers

- All functions including the **__kernel** function and their arguments variable are **__private**
- Arguments to **__kernel** function declared as a pointer must use **__global**, **__local**, or **__constant**
- Assigning pointer address from on space to another is not allowed;
- Casting from one space to another can cause unexpected behavior.

```
__global float *ptr          // the pointer ptr is declared in the __private address space and
                             // points to a float that is in the __global address space

int4 x                       // declares an int4 vector in the __private address
```

Image Qualifiers

- Access qualifier for image memory object passed to __kernel can be:
  - **__read_only** (default)
  - **__write_only**
- Kernel cannot read and write to same image memory object

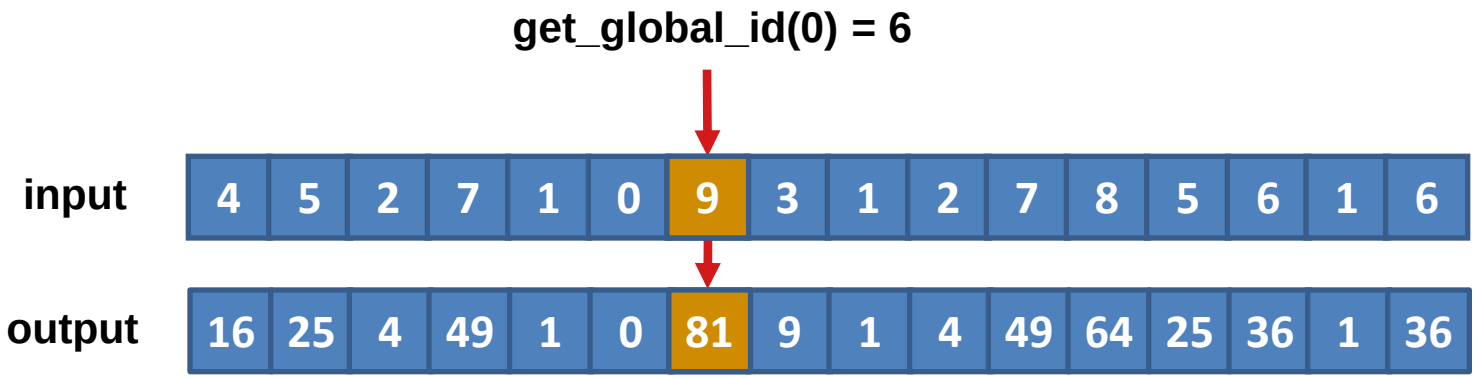
```
__kernel void myfunc(__read_only  image2d_t inputImage,
                     __write_only image2d_t outputImage)
```

Work-item Functions

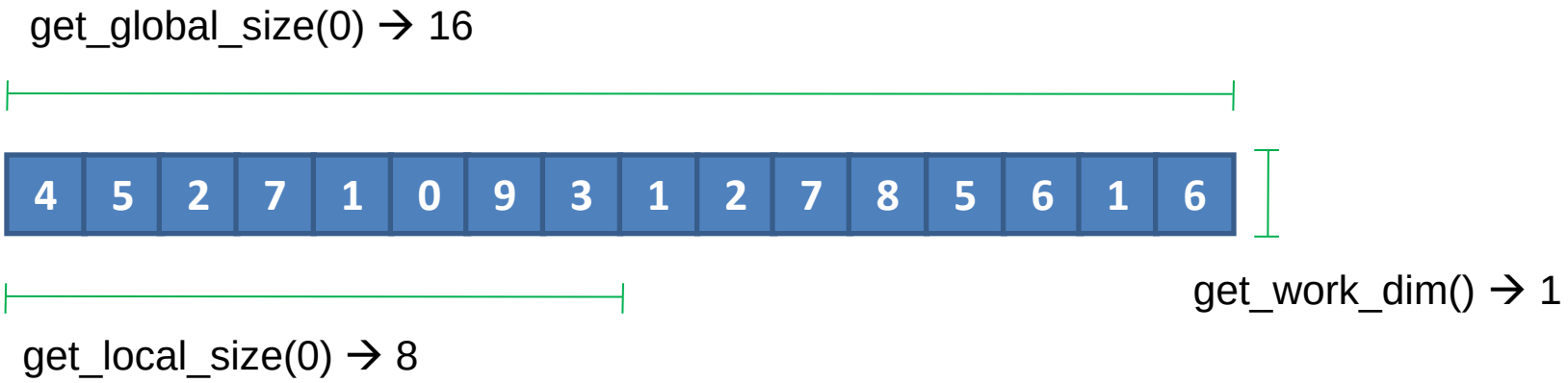
```
// returns the number of dimensions of the data problem space
uint get_work_dim()

// returns the number total work-items for the specified dimension
size_t get_global_size(dimidx)

// returns the number of local work-items in the work-group specified by dimension
size_t get_local_size(dimidx)

// returns the unique global work-item ID for the specified dimension
size_t get_global_id(dimidx)

// returns the unique local work-item ID in the work-group for the specified dimension
size_t get_local_id(dimidx)

// returns the number of work-groups for the specified dimension
size_t get_num_groups(dimidx)

// returns the unique ID of the work-group being processed by the kernel
size_t get_group_id(dimidx)
```

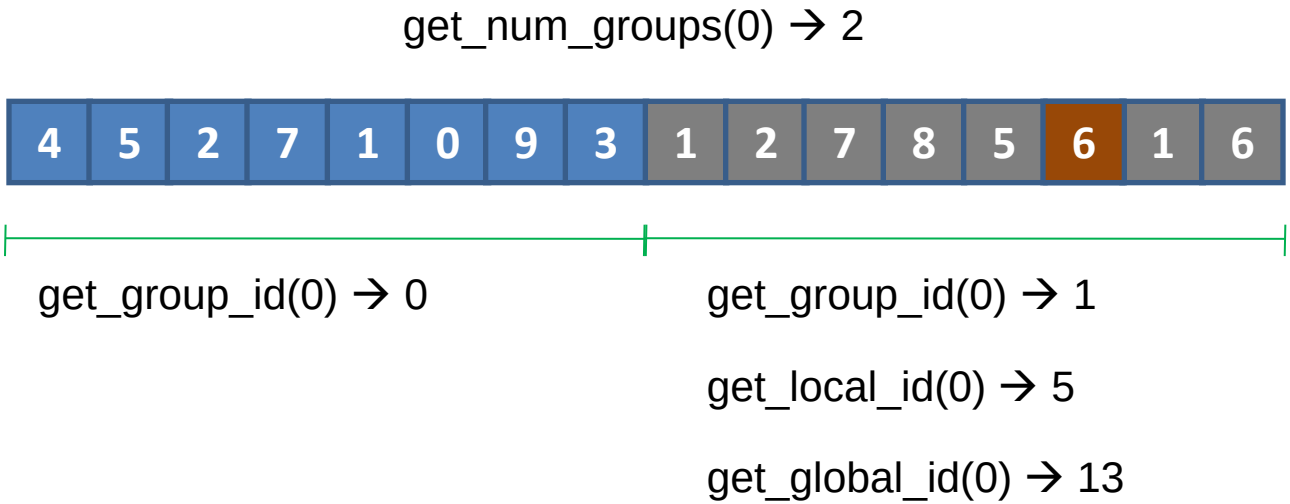
Example Work-item Functions

```
__kernel void square(__global int *input, __global int *output)
{
        size_t id = get_global_id(0);
        output[id] = input[id] * input[id];
}
```



Example Work-item Functions





Synchronization Functions

- Used to synchronize between work-items
- Synchronization occur only within work-group
- OpenCL uses **barrier** and **fence**
- **Barrier** – blocks current work-item until all work-item in the work-group hits the barrier

```
void barrier(mem_fence_flag)
```

- **Fence** – ensures all reads or writes before the memory fence have committed to memory

```
void mem_fence(mem_fence_flag)  // orders read and writes operations before the fence
void read_mem_fence(mem_fence_flag)  // orders only reads before the fence
void write_mem_fence(mem_fence_flag) // orders only writes before the fence
```

Exercise 2

Complete kernel function perform matrix tranpose.
See "e2/transposeMatrix_kernel.cl"

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- Debugging OpenCL™
- Performance Measurement
- General Optimization Tips
- Porting CUDA to OpenCL™

Debugging OpenCL™

- Debugging OpenCL™ kernels in Linux® using GDB
- Setup:
  - Enable debugging when building program object

```
err = clBuildProgram(program, 1, devices, "-g", NULL, NULL);
```

  - Without modifying source, set environment var

```
export CPU_COMPILER_OPTIONS=-g
```

  - Set kernel to execute on CPU device ensure kernel is executed deterministically

```
export CPU_MAX_COMPUTE_UNITS=1
```

Using GDB

- Setting Breakpoints:

```
b linenumber
b function_name | kernel_function_name
```

- Setting Breakpoint for a kernel function
  - Use construct __OpenCL_***function***_kernel

```
__kernel void square(__global int *input, __global int * output)

b __OpenCL_square_kernel
```

- Conditional breakpoint

```
b __OpenCL_square_kernel  if  get_global_id(0) == 5
```

Performance Measurement

- Built-in mechanism for timing kernel execution
- Enable profiling when creating queue with queue properties **CL_QUEUE_PROFILING_ENABLE**
- Use clGetEvenProfilingInfo() to retrieve timing information

```
err = clGetEventProfilingInfo(
        event,                  // the event object to get info for
        param_name              // the profiling data to query - see list below
        param_value_size        // the size of memory pointed by param_value
        param_value             // pointer to memory in which the query result is returned
        param_actual_size       // actual number of bytes copied to param_value
);
```

- ATI Stream Profiler plug-in for Visual Studio®

Get Profiling Data with Built-in functions

Profiling Data	ulong counter (nanoseconds)
CL_PROFILING_COMMAND_QUEUE	When command is enqueued
CL_PROFILING_COMMAND_SUBMIT	When the command has been submitted to device for execution
CL_PROFILING_COMMAND_START	When command started execution
CL_PROFILING_COMMAND_END	When command finished execution

```
cl_event myEvent;
cl_ulong startTime, endTime;

clCreateCommandQueue (…, CL_QUEUE_PROFILING_ENABLE, NULL);
clEnqueueNDRangeKernel(…, &myEvent);
clFinish(myCommandQ);    // wait for all events to finish

clGetEventProfilingInfo(myEvent, CL_PROFILING_COMMAND_START,
                        sizeof(cl_ulong), &startTime, NULL);
clGetEventProfilingInfo(myEvent, CL_PROFILING_COMMAND_END,
                        sizeof(cl_ulong), &endTime, NULL);
cl_ulong elapsedTime = endTime-startTime;
```

General Optimization Tips

- Use local memory
- Specific work-group size
- Loop Unrolling
- Reduce Data and Instructions
- Use built-in vector types

General Optimization Tips

- Use local memory
  - Local memory order of magnitude faster
  - Work-items in the same work-group share fast local memory
  - Efficient memory access using collaborative read/write to local memory

General Optimization Tips

- Work-group division
  - Implicit
  - Explicit – recommended
  - AMD GPUs optimized for work-group size multiple of 64.
  - Use **clGetDeviceInfo()** or **clGetKernelWorkGroupInfo()** to determine max group size

General Optimization Tips

- Loop unrolling
  - Overhead to evaluate control-flow and execute branch instructions
  - ATI Stream SDK OpenCL™ compiler performs simple loop unroll
  - Complex loop benefit from manual unroll
  - Image Convolution tutorial of loop unrolling at

http://developer.amd.com/gpu/ATIStreamSDK/ImageConvolutionOpenCL/Pages/ImageConvolutionUsingOpenCL.aspx

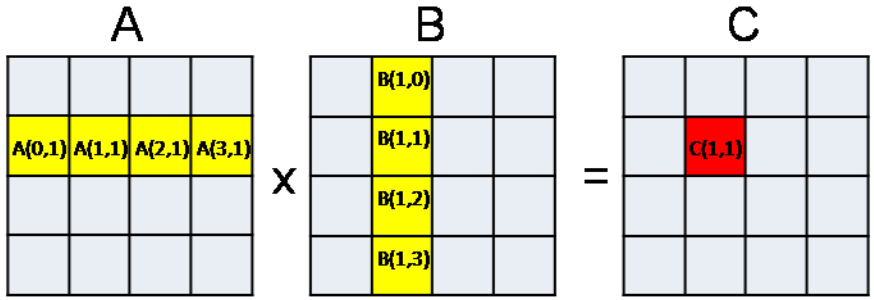
General Optimization Tips

- Use built-in vector types
  - Generate efficiently-packed SSE instructions
  - AMD CPUs and GPUs benefit from vectorization
- Reduce Data and Instructions
  - Use smaller version of data set for easy debugging and optimization
  - Performance optimization for smaller data set benefits full-size data set
  - Use profiler data to time data set

Exercise 3

Complete kernel function perform matrix multiplication using local memory.
See "e3/multMatrix_kernel.cl"

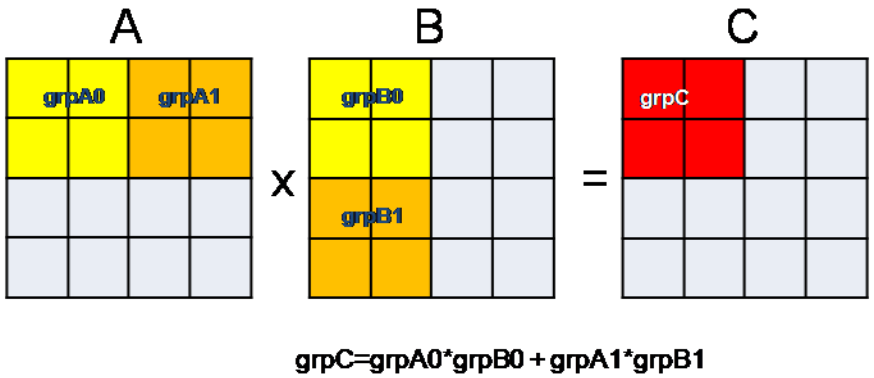
Matrix Multiplication



C(1,1)=A(0,1)*B(1,0)+A(1,1)*B(1,1)+A(2,1)*B(1,2)+A(3,1)*B(1,3)

```
// simple matrix multiplication
__kernel void multMatrixSimple(__global float *mO, __global float *mA, __global float *mB,
                               uint widthA, uint widthB)
{
        int globalIdx = get_global_id(0);
        int globalIdy = get_global_id(1);
        float sum =0;
        for (int i=0; i< widthA; i++)
        {
                float tempA = mA[globalIdy * widthA + i];
                float tempB = mB[i * widthB + globalIdx];
                sum += tempA * tempB;
        }
        mO[globalIdy * widthA + globalIdx] = sum;
}
```

Optimizing Matrix Multiplication



Matrix Multiplication using local memory

Porting CUDA to OpenCL™

- General terminology

C for CUDA Terminology	OpenCL™ Terminology
Thread	Work-item
Thread block	Work-group
Global memory	Global memory
Constant memory	Constant memory
Shared memory	Local memory
Local memory	Private memory

Porting CUDA to OpenCL™

- Qualifiers

C for CUDA Terminology	OpenCL™ Terminology
__global__ function	__kernel function
__device__function	function (no qualifier required)
__constant__ variable declaration	__constant variable declaration
__device__ variable declaration	__global variable declaration
__shared__ variable declaration	__local variable declaration

Porting CUDA to OpenCL™

- Kernel Indexing

C for CUDA Terminology	OpenCL™ Terminology
gridDim	get_num_groups()
blockDim	get_local_size()
blockIdx	get_group_id()
threadIdx	get_local_id()
No direct global index – needs to be calculated	get_global_id()
No direct global size – needs to be calculated	get_global_size()

Porting CUDA to OpenCL™

- Kernel Synchronization

C for CUDA Terminology	OpenCL™ Terminology
__syncthreads()	barrier()
__threadfence()	no direct equivalent
__threadfence_block()	mem_fence()
No direct equivalent	read_mem_fence()
No direct equivalent	write_mem_fence()

Porting CUDA to OpenCL™

- General API Terminology

C for CUDA Terminology	OpenCL™ Terminology
CUdevice	cl_device_id
CUcontext	cl_context
CUmodule	cl_program
CUfunction	cl_kernel
CUdeviceptr	cl_mem
No direct equivalent	cl_command_queue

Porting CUDA to OpenCL™

C for CUDA Terminology	OpenCL™ Terminology
cuInit()	No OpenCL™ initialization required
cuDeviceGet()	clGetContextInfo()
cuCtxCreate()	clCreateContextFromType()
No direct equivalent	clCreateCommandQueue()
cuModuleLoad() Requires pre-compiled binary.	clCreateProgramWithSource() or clCreateProgramWithBinary()
No direct equivalent. CUDA programs are compiled off-line	clBuildProgram()
cuModuleGetFunction()	clCreateKernel()
cuMemAlloc()	clCreateBuffer()

Porting CUDA to OpenCL™

C for CUDA Terminology	OpenCL™ Terminology
cuMemcpyHtoD()	clEnqueueWriteBuffer()
cuMemcpyDtoH()	clEnqueueReadBuffer()
cuFuncSetBlockShape()	No direct equivalent; functionality is part of clEnqueueNDRangeKernel()
cuParamSeti()	clSetKernelArg()
cuParamSetSize()	No direct equivalent; functionality is part of clSetKernelArg()
cuLaunchGrid()	clEnqueueNDRangeKernel()
cuMemFree()	clReleaseMemObj()

Please forward all feedback or information requests regarding this training course to **streamcomputing@amd.com**

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