Illinois UPCRC Summer School 2010

The OpenCL Programming Model

Part 1: Basic Concepts

Wen-mei Hwu and John Stone
with special contributions from
Deepthi Nandakumar

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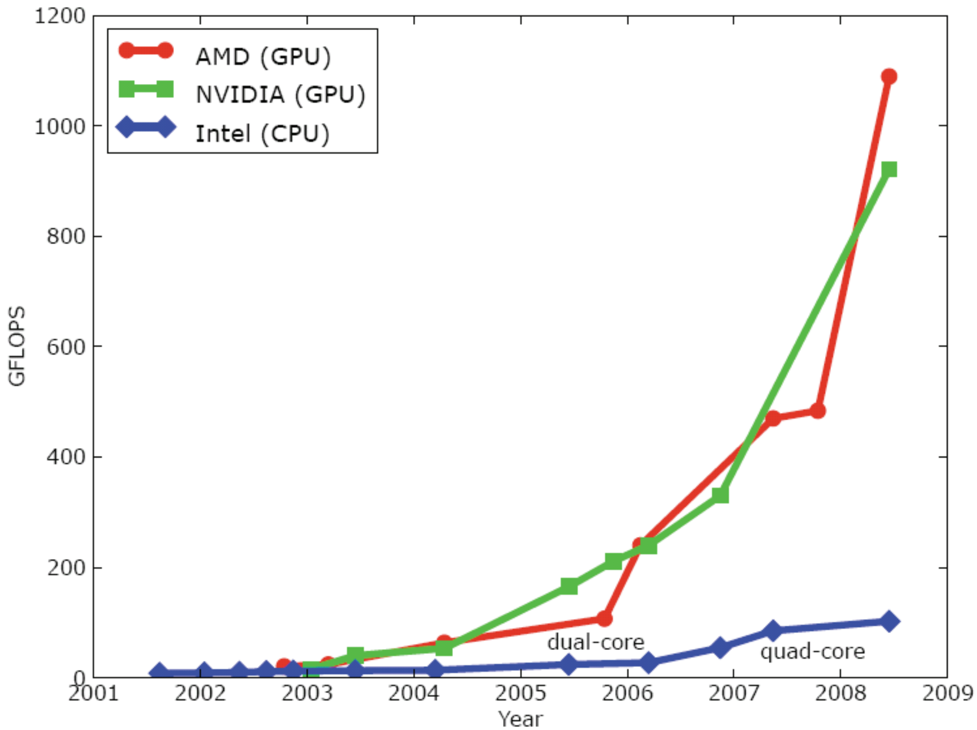
Why GPU Computing

- An enlarging peak performance advantage:
  - Calculation: 1 TFLOPS vs. 100 GFLOPS
  - Memory Bandwidth: 100-150 GB/s vs. 32-64 GB/s



Courtesy: John Owens

  - GPU in every PC and workstation – massive volume and potential impact

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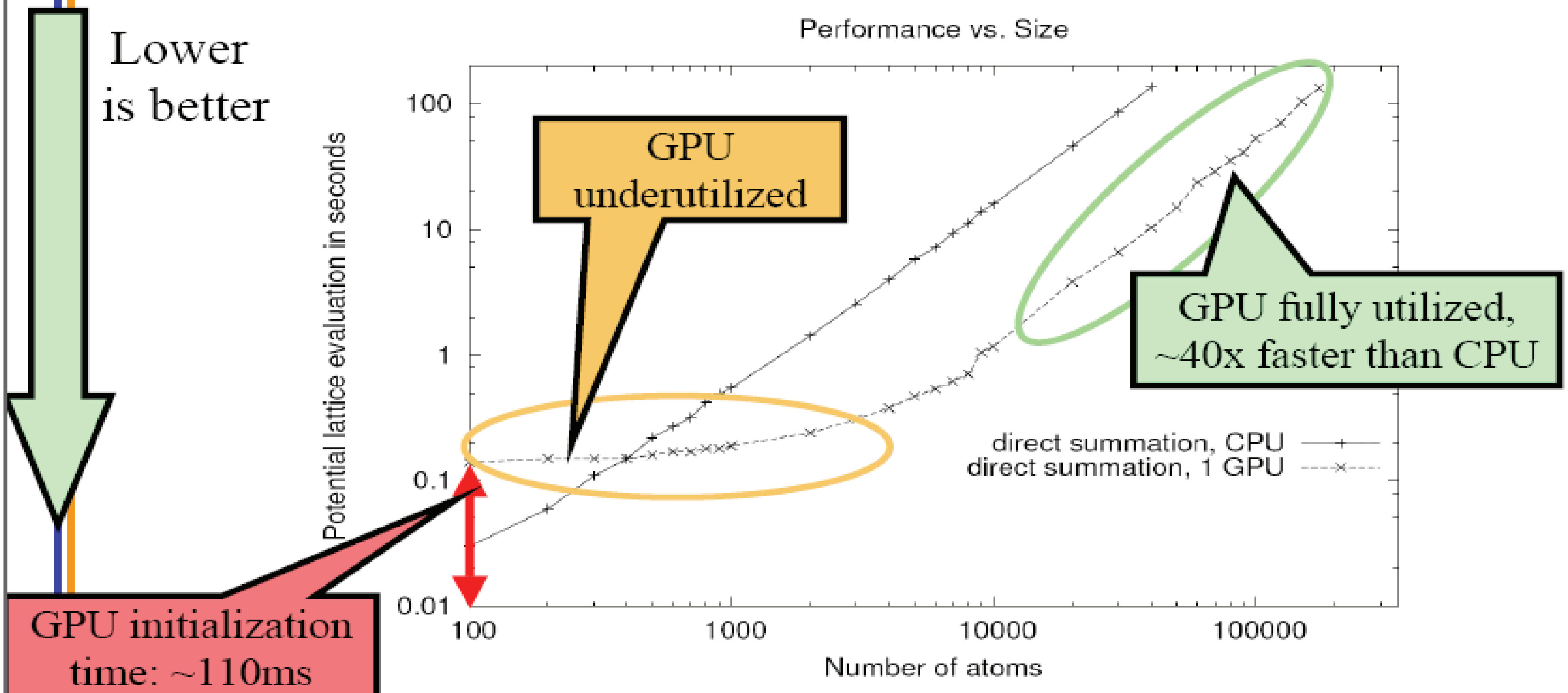
Role of GPUs - large data sets

Direct Coulomb Summation Runtime



Accelerating molecular modeling applications with graphics processors. J. Stone, J. Phillips, P. Freddolino, D. Hardy, L. Trabuco, K. Schulten. *J. Comp. Chem.*, 28:2618-2640, 2007.

Future Apps Reflect a Concurrent World

- Exciting applications in future computing have been traditionally considered "supercomputing applications"
  - Video and audio synthesis/analysis, 3D imaging and visualization, consumer game physics, virtual reality products, computational financing, molecular dynamics simulation, computational fluid dynamics
  - These "Super-apps" represent and model the physical, concurrent world
- Various granularities of parallelism exist, but…
  - programming model must not hinder scalable implementation
  - data delivery needs careful management

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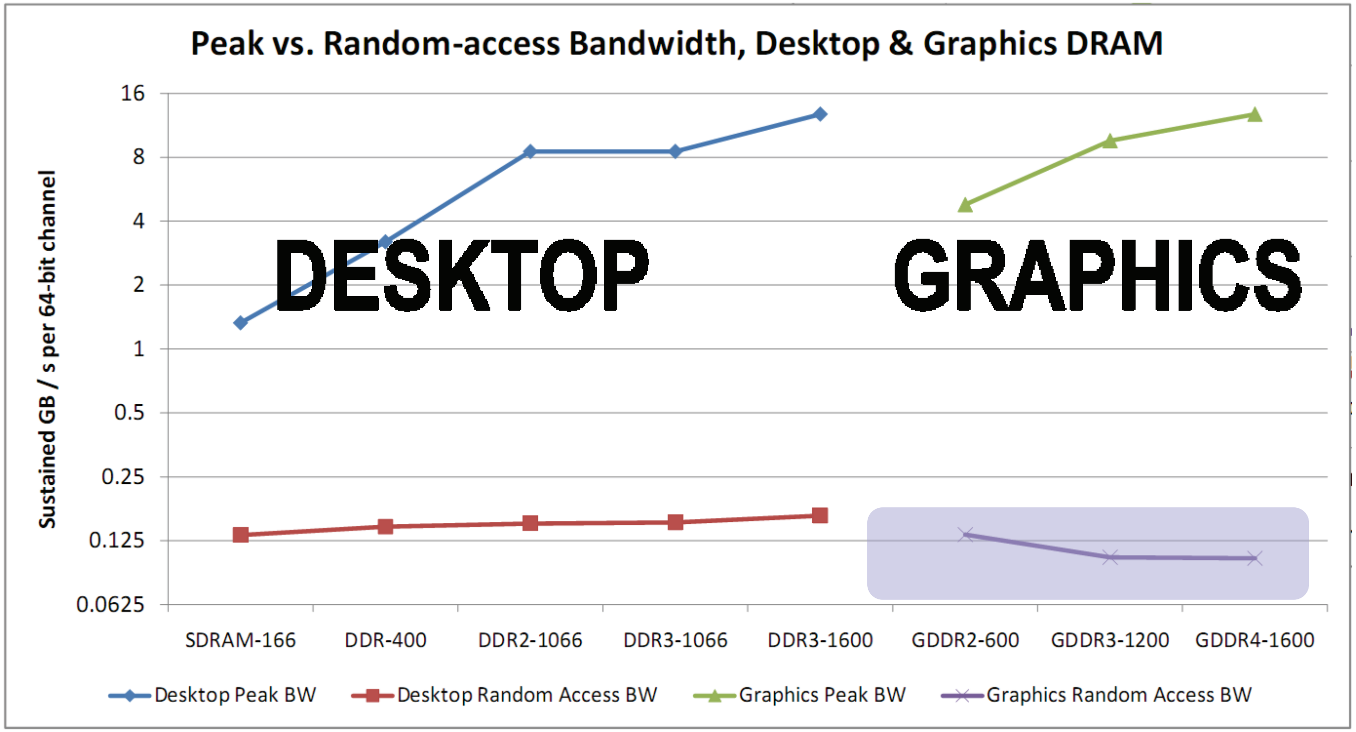
DRAM Bandwidth Trends Sets Programming Agenda



- **Random access BW** 1.2% **of peak for DDR3-1600,** 0.8% **for GDDR4-1600 (and falling)**
- **3D stacking and optical interconnects will unlikely help.**

Research Center

UIUC/NCSA AC Cluster

- 32 nodes
  - 4-GPU (GTX280, Tesla), 1-FPGA, quad-core Opteron node at NCSA
  - GPUs donated by NVIDIA
  - FPGA donated by Xilinx
  - 128 TFLOPS single precision, 10 TFLOPS double precision
- Coulomb Summation:
  - 1.78 TFLOPS/node
  - 271x speedup vs. Intel QX6700 CPU core w/ SSE

UIUC/NCSA AC Cluster

http://www.ncsa.uiuc.edu/Projects/GPUcluster/

A partnership between NCSA and academic departments.

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What is (Historical) GPGPU ?

- General Purpose computation using GPU and graphics API in applications other than 3D graphics
  - GPU accelerates critical path of application
- Data parallel algorithms leverage GPU attributes
  - Large data arrays, streaming throughput
  - Fine-grain SIMD parallelism
  - Low-latency floating point (FP) computation
- Applications – see //GPGPU.org
  - Game effects (FX) physics, image processing
  - Physical modeling, computational engineering, matrix algebra, convolution, correlation, sorting

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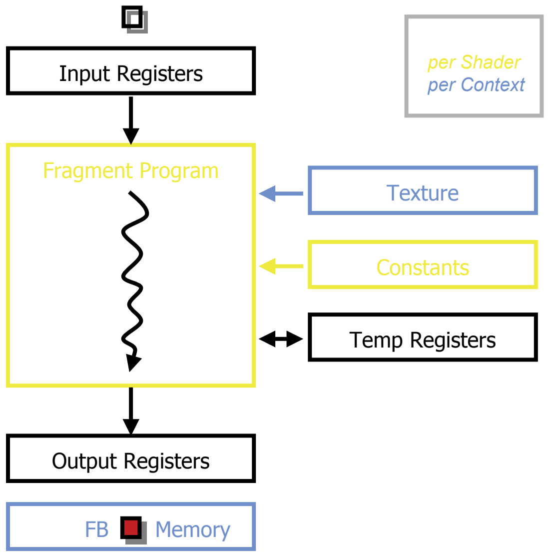
Previous GPGPU Constraints

- Dealing with graphics API
  - Working with the corner cases of the graphics API
- Addressing modes
  - Limited texture size/dimension
- Shader capabilities
  - Limited outputs
- Instruction sets
  - Lack of Integer & bit ops
- Communication limited
  - Between pixels
  - Scatter a[i] = p



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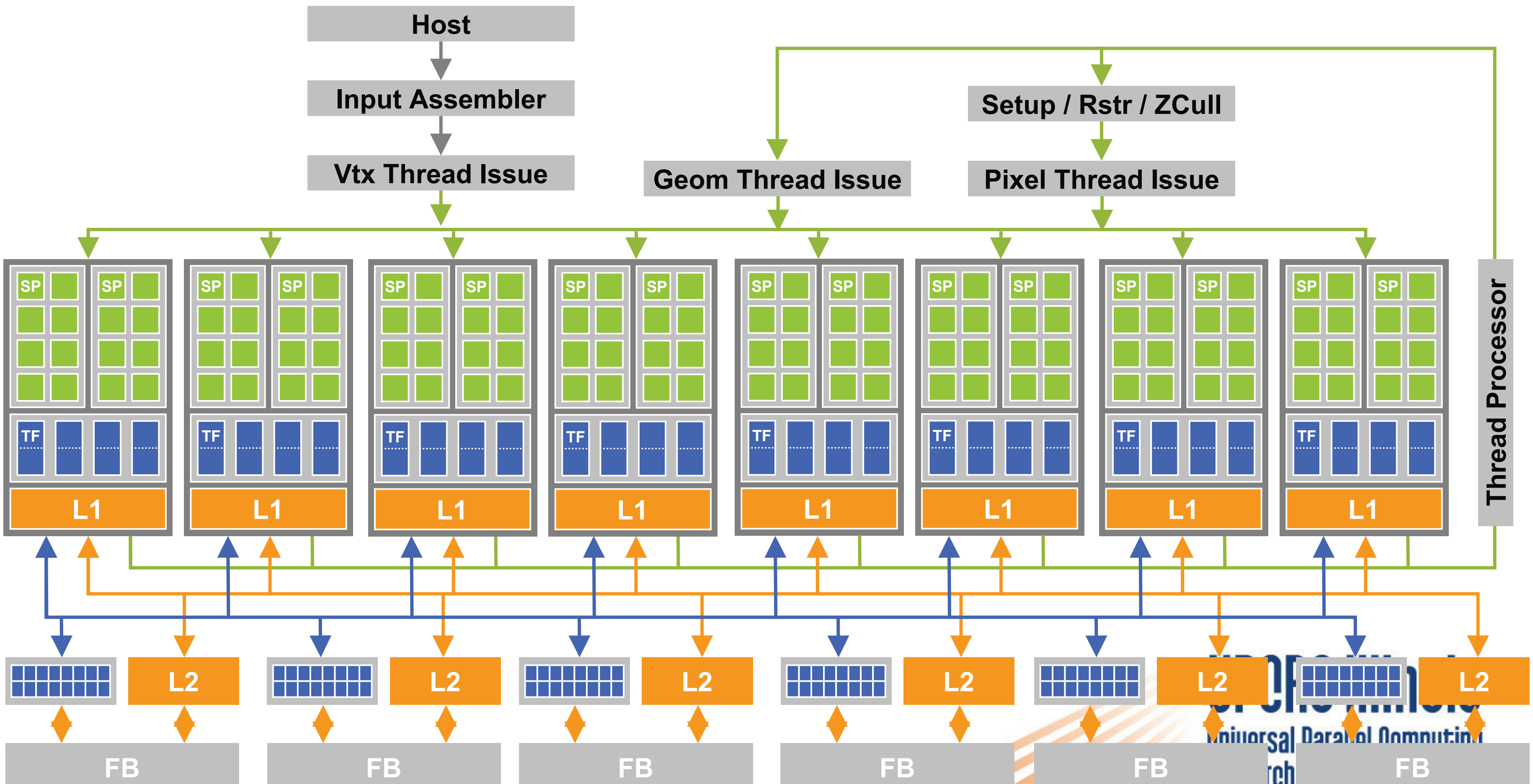
G80 – Graphics Mode

- The future of GPUs is programmable processing
- So – build the architecture around the processor

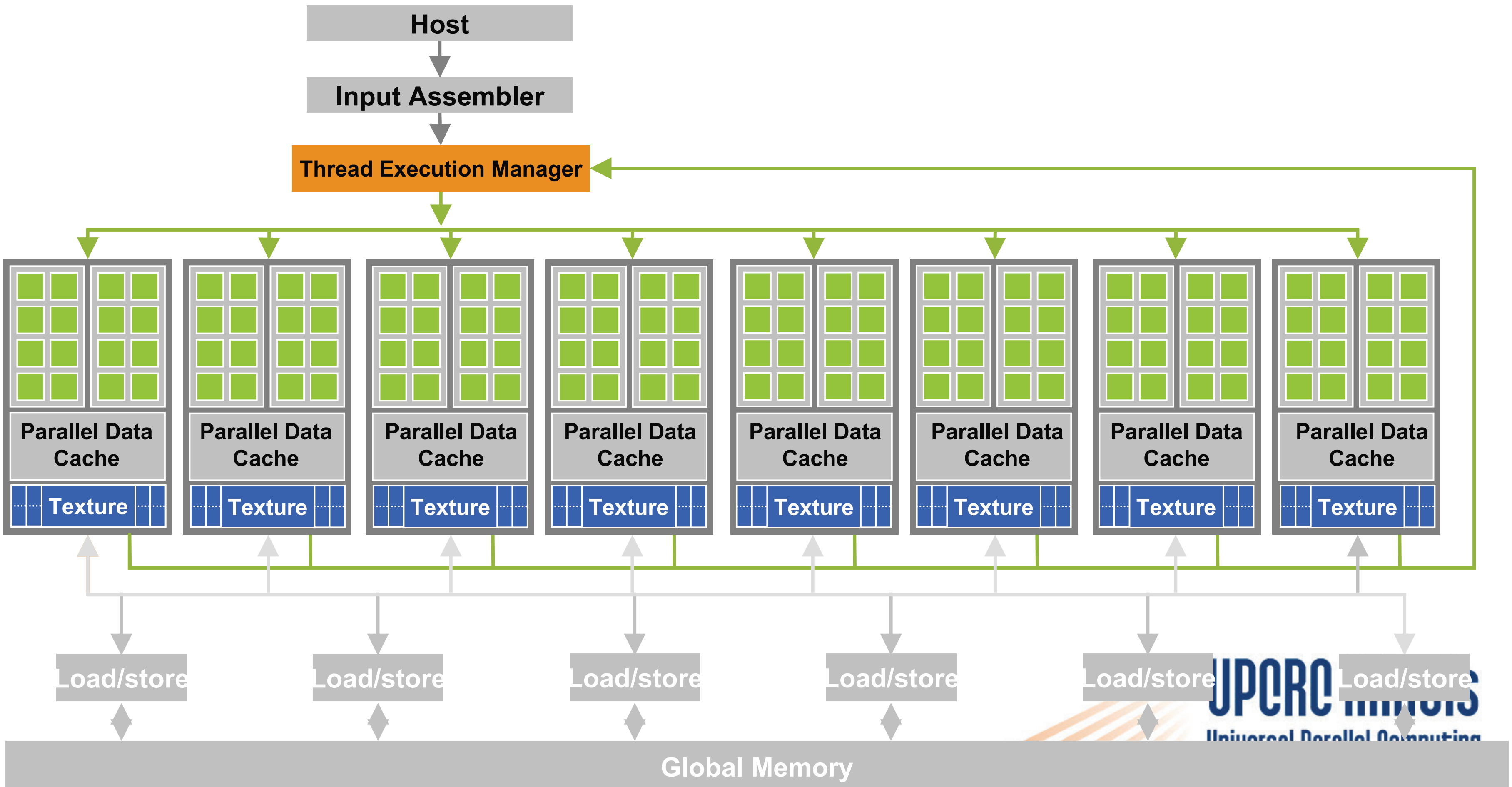


CUDA – Recent OpenCL Predecessor

- "Compute Unified Device Architecture"
- General purpose programming model
  - User kicks off batches of threads on the GPU
  - GPU = dedicated super-threaded, massively data parallel co-processor
- Targeted software stack
  - Compute oriented drivers, language, and tools
- Driver for loading computation programs into GPU
  - Standalone Driver - Optimized for computation
  - Interface designed for compute – graphics-free API
  - Data sharing with OpenGL buffer objects
  - Guaranteed maximum download & readback speeds
  - Explicit GPU memory management

G80 CUDA mode – A **Device** Example

- Processors execute computing threads
- New operating mode/HW interface for computing



What is OpenCL?

- Cross-platform parallel computing API and C-like language for heterogeneous computing devices
- Code is portable across various target devices:
  - Correctness is guaranteed
  - Performance of a given kernel is not guaranteed across differing target devices
- OpenCL implementations already exist for AMD and NVIDIA GPUs, x86 CPUs
- In principle, OpenCL could also target DSPs, Cell, and perhaps also FPGAs

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More on Multi-Platform Targeting

- Targets a broader range of CPU-like and GPU-like devices than CUDA
  - Targets devices produced by multiple vendors
  - Many features of OpenCL are optional and may not be supported on all devices
- OpenCL codes must be prepared to deal with much greater hardware diversity
- A single OpenCL kernel will likely not achieve peak performance on all device types

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Overview

- OpenCL programming model – basic concepts and data types
- OpenCL application programming interface - basic
- Simple examples to illustrate basic concepts and functionalities
- Case study to illustrate performance considerations

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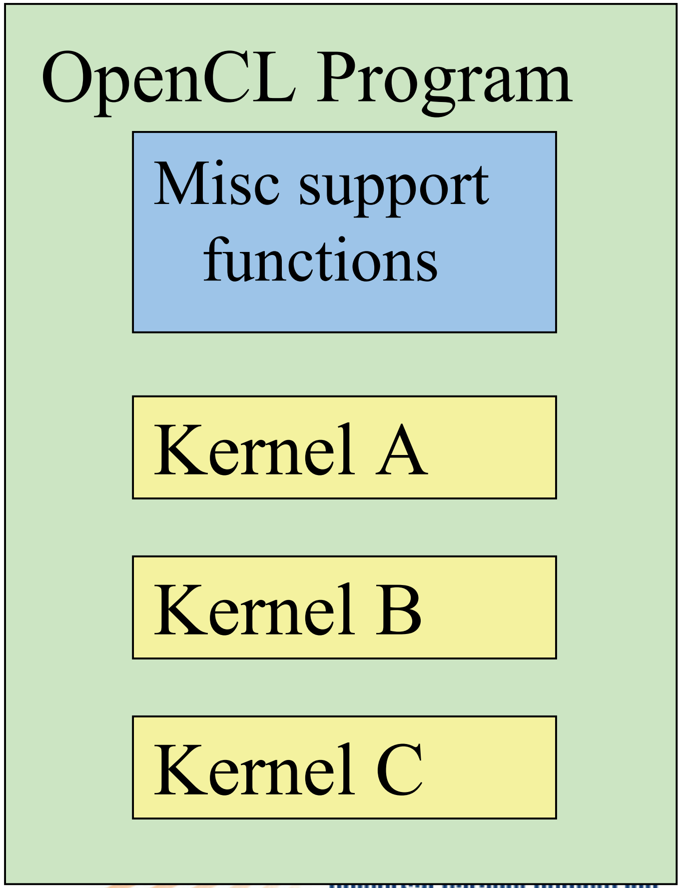
OpenCL Programs

- An OpenCL "program" contains one or more "kernels" and any supporting routines that run on a target device
- An OpenCL kernel is the basic unit of parallel code that can be executed on a target device



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OpenCL Execution Model

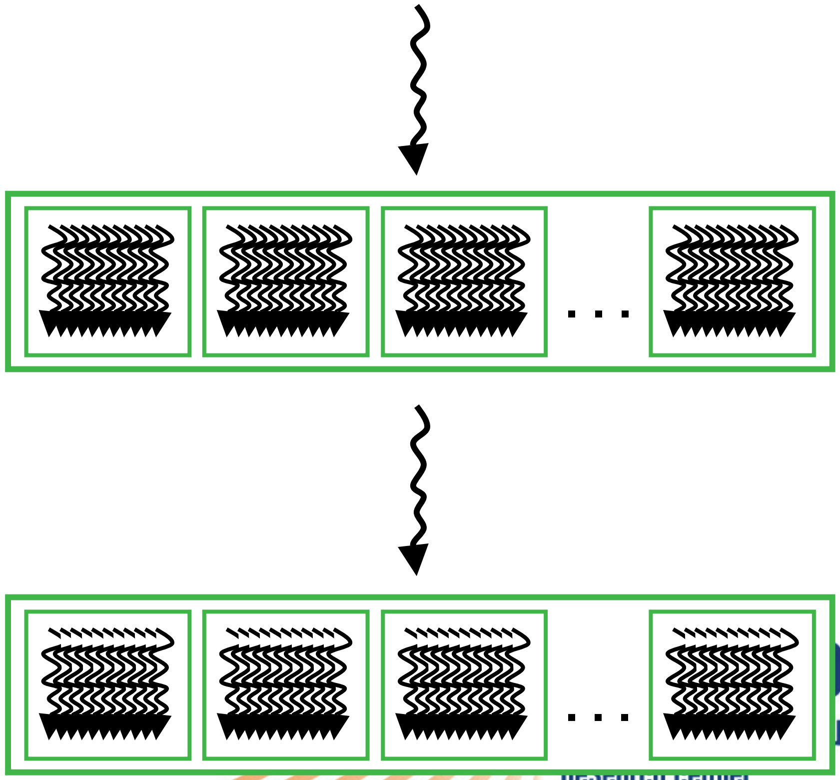
- Integrated host+device app C program
  - Serial or modestly parallel parts in **host** C code
  - Highly parallel parts in **device** SPMD kernel C code

Serial Code (host)

Parallel Kernel (device)
KernelA<<< nBlk, nTid >>>(args);

Serial Code (host)

Parallel Kernel (device)
KernelB<<< nBlk, nTid >>>(args);



OpenCL Kernels

- Code that actually executes on target devices
- Kernel body is instantiated once for each work item
  - An OpenCL work item is equivalent to a CUDA thread
- Each OpenCL work item gets a unique index

```
__kernel void
vadd(__global const float *a,
     __global const float *b,
     __global float *result) {
 int id = get_global_id(0);
 result[id] = a[id] + b[id];
}
```

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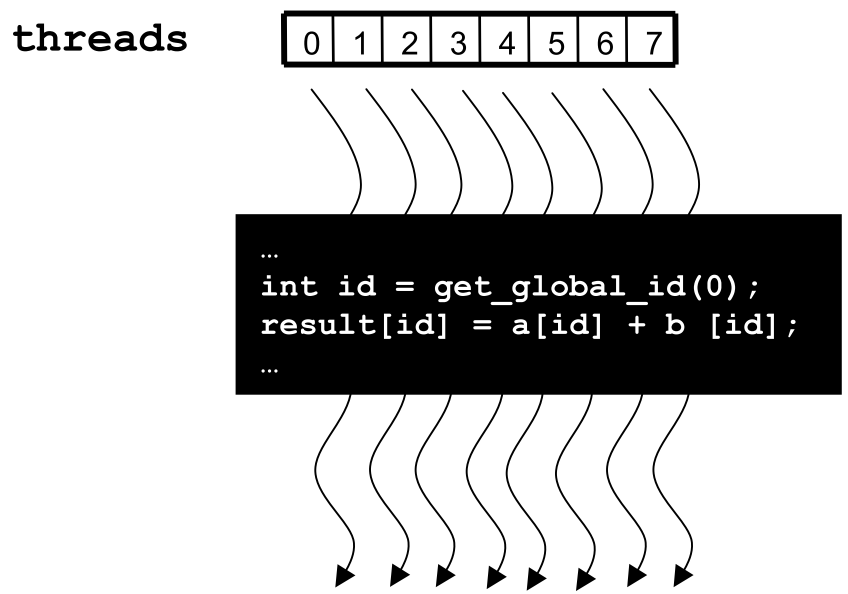
Array of Parallel Work Items

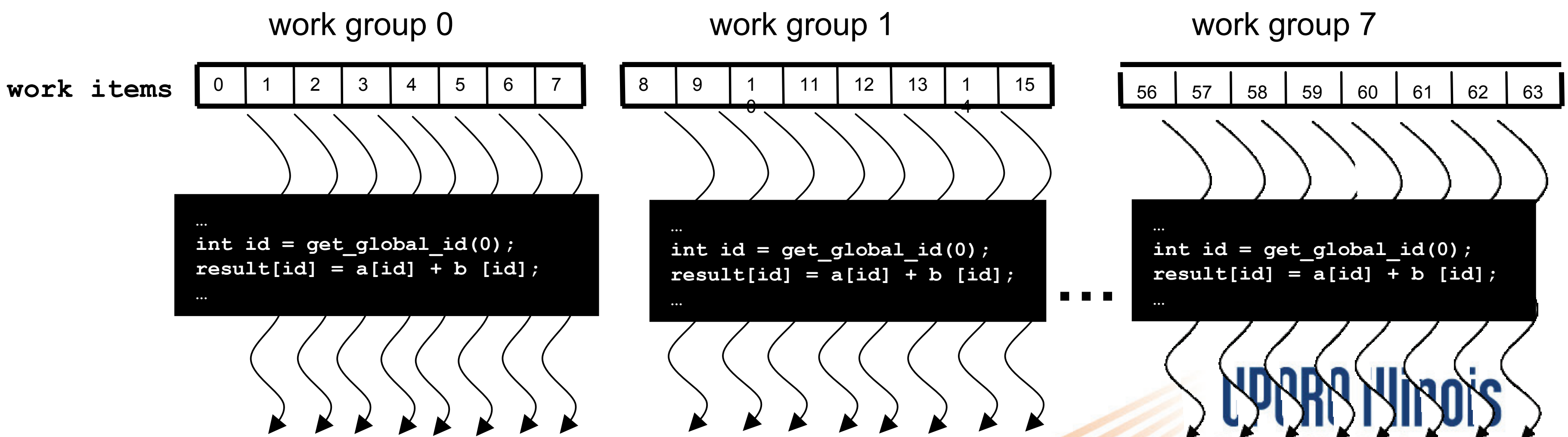
- An OpenCL kernel is executed by an array of work items
  - All work items run the same code (SPMD)
  - Each work item has an index that it uses to compute memory addresses and make control decisions




```
…
int id = get_global_id(0);
result[id] = a[id] + b [id];
…
```

Work Groups: Scalable Cooperation

- Divide monolithic work item array into work groups
  - Work items within a work group cooperate via **shared memory, atomic operations** and **barrier synchronization**
  - Work items in different work groups cannot cooperate



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OpenCL Data Parallel Model Summary

- Parallel work is submitted to devices by launching kernels
- Kernels run over global dimension index ranges (NDRange), broken up into “work groups”, and “work items”
- Work items executing within the same work group can synchronize with each other with barriers or memory fences
- Work items in different work groups can’t sync with each other, except by launching a new kernel

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OpenCL Host Code

- Prepare and trigger device code execution
  - Create and manage device context(s) and associate work queue(s), etc…
  - Memory allocations, memory copies, etc
  - Kernel launch

- OpenCL programs are normally compiled entirely at runtime, which must be managed by host code

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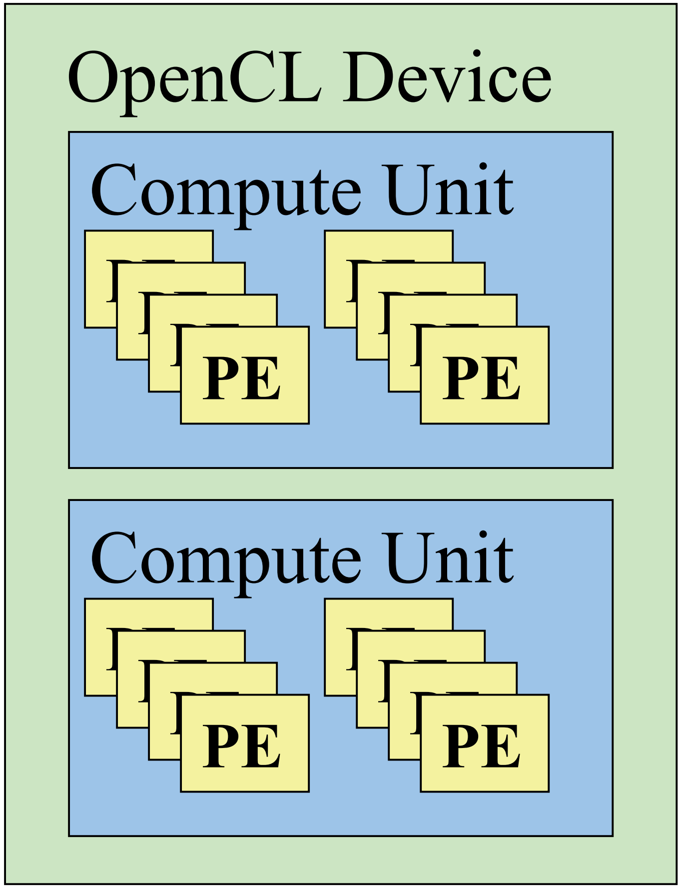
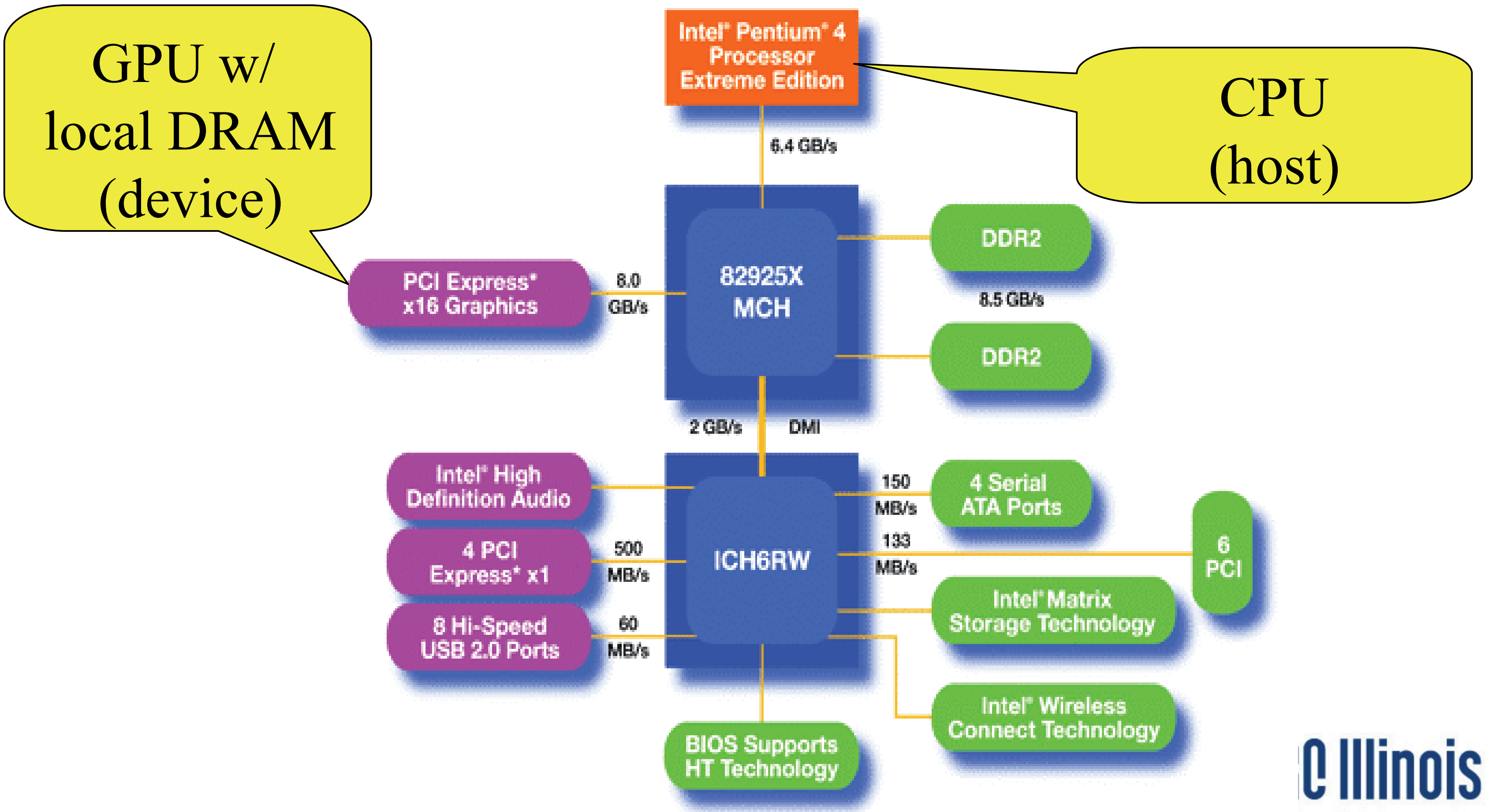
OpenCL Hardware Abstraction

- OpenCL exposes CPUs, GPUs, and other Accelerators as “devices”
- Each “device” contains one or more “compute units”, i.e. cores, SMs, etc...
- Each “compute unit” contains one or more SIMD “processing elements”



An Example of Physical Reality Behind OpenCL Abstraction



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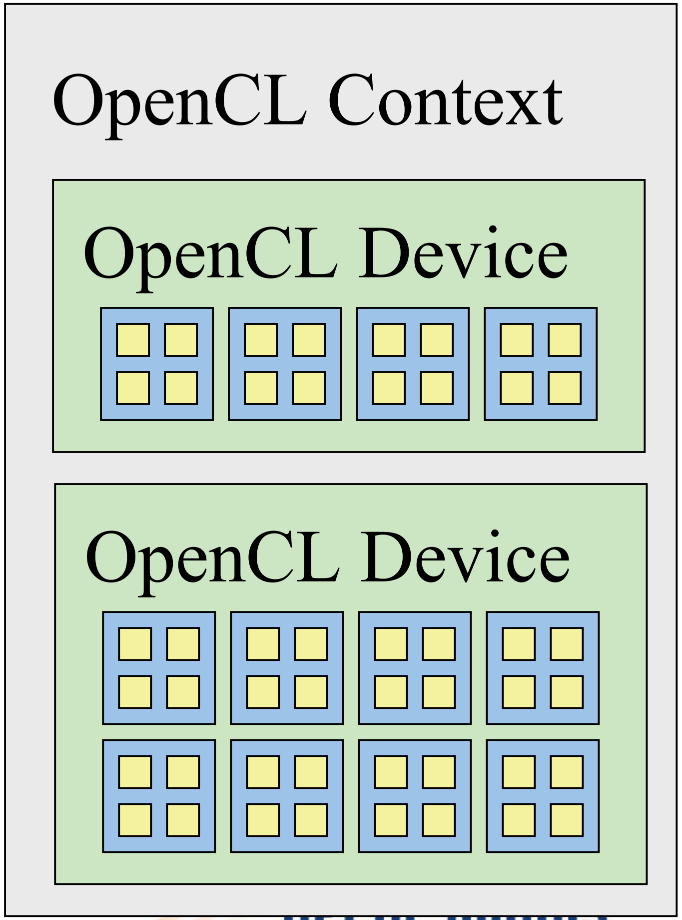
OpenCL Context

- Contains one or more devices
- OpenCL memory objects are associated with a context, not a specific device
- clCreateBuffer() is the main data object allocation function
  - error if an allocation is too large for any device in the context
- Each device needs its own work queue(s)
- Memory transfers are associated with a command queue (thus a specific device)



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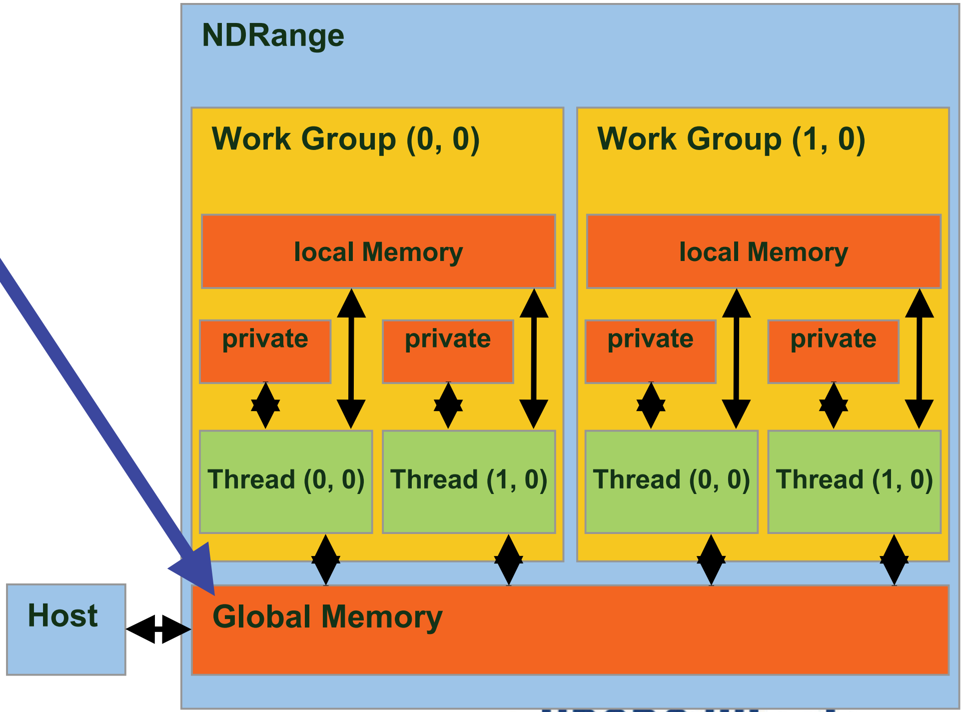
OpenCL Context Setup Code (simple)

```
cl_int clerr = CL_SUCCESS;
cl_context clctx = clCreateContextFromType(0, CL_DEVICE_TYPE_ALL, NULL,
    NULL, &clerr);

size_t parmsz;
clerr = clGetContextInfo(clctx, CL_CONTEXT_DEVICES, 0, NULL, &parmsz);

cl_device_id* cldevs = (cl_device_id *) malloc(parmsz);
clerr = clGetContextInfo(clctx, CL_CONTEXT_DEVICES, parmsz, cldevs,
    NULL);

cl_command_queue clcmdq = clCreateCommandQueue(clctx, cldevs[0], 0,
    &clerr);
```

OpenCL Memory Model Overview

- Global memory
  - Main means of communicating R/W Data between host and device
  - Contents visible to all threads
  - Long latency access
- We will focus on global memory for now



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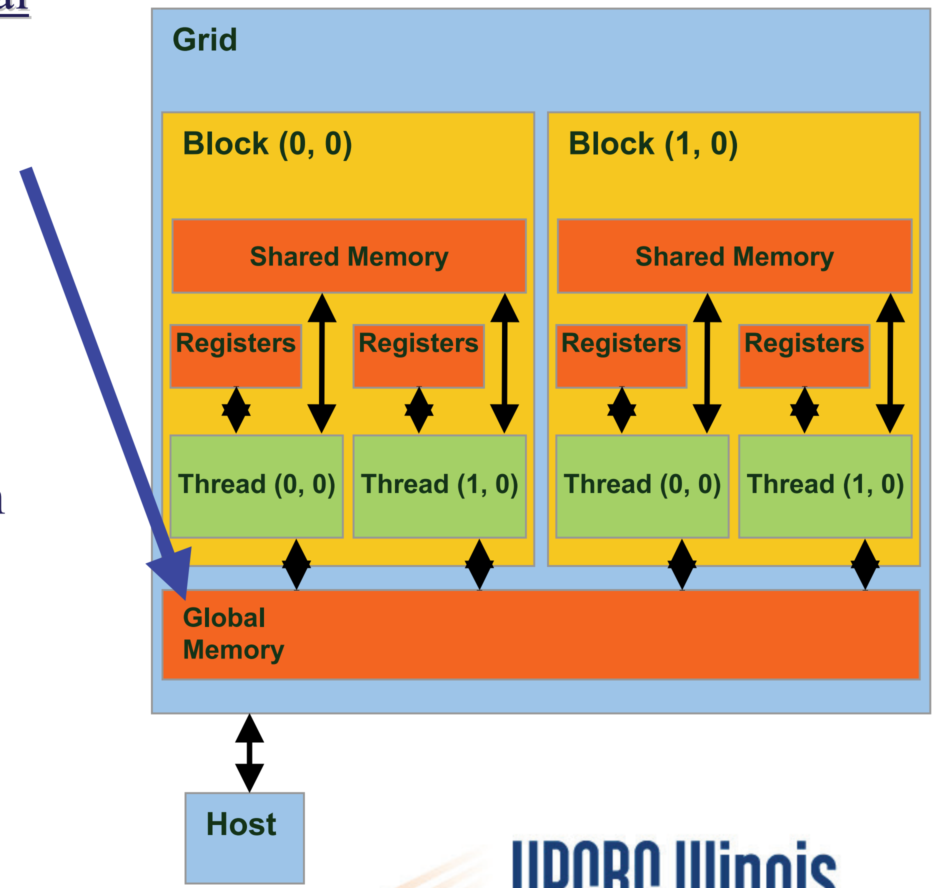
OpenCL Device Memory Allocation

- **clCreateBuffer();**
  - Allocates object in the device Global Memory
  - Returns a pointer to the object
  - Requires five parameters
    - OpenCL context pointer
    - Flags for access type by device
    - Size of allocated object
    - Host memory pointer, if used in copy-from-host mode
    - Error code
- **clReleaseMemObject()**
  - Frees object
    - Pointer to freed object



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OpenCL Device Memory Allocation (cont.)

- Code example:
  - Allocate a 1024 single precision float array
  - Attach the allocated storage to d_a
  - “d” is often used to indicate a device data structure

```
VECTOR_SIZE = 1024;
cl_mem d_a;
int size = VECTOR_SIZE* sizeof(float);

d_a = clCreateBuffer(clctx, CL_MEM_READ_ONLY, size,
NULL, NULL);
clReleaseMemObject(d_a);
```

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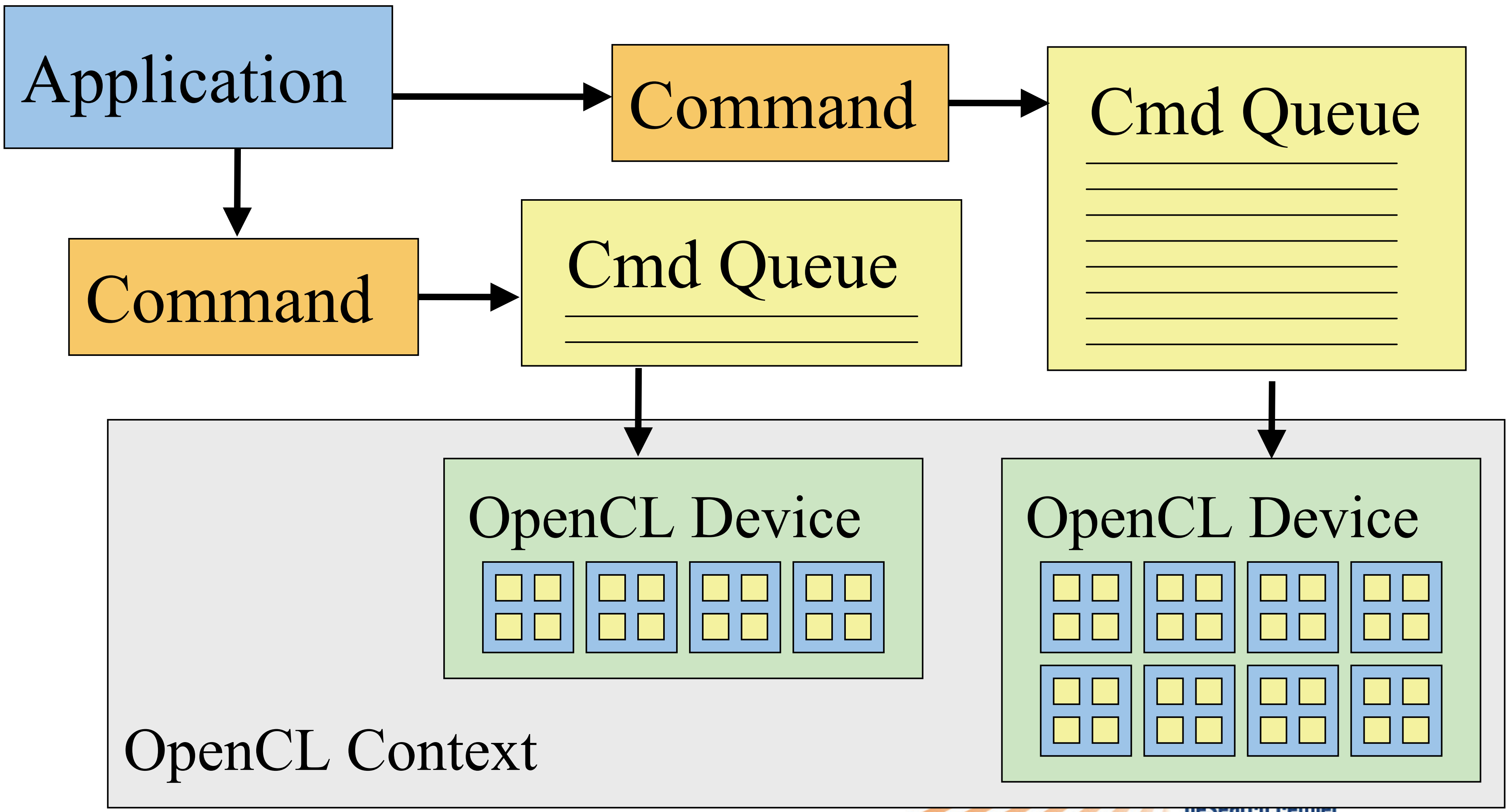
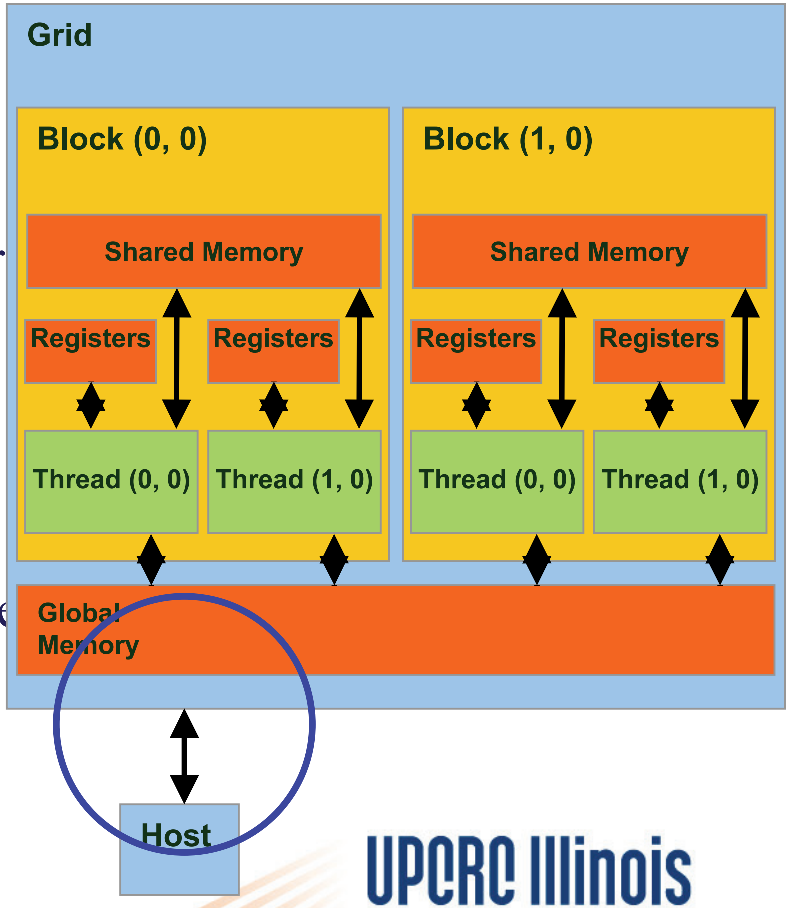
OpenCL Device Command Execution



OpenCL Host-to-Device Data Transfer

- clEnqueueWriteBuffer();
  - memory data transfer to device
  - Requires nine parameters
    - OpenCL command queue pointer
    - Destination OpenCL memory buffer
    - Blocking flag
    - Offset in bytes
    - Size of bytes of written data
    - Host memory pointer
    - List of events to be completed before execution of this command
    - Event object tied to this command
- Asynchronous transfer later



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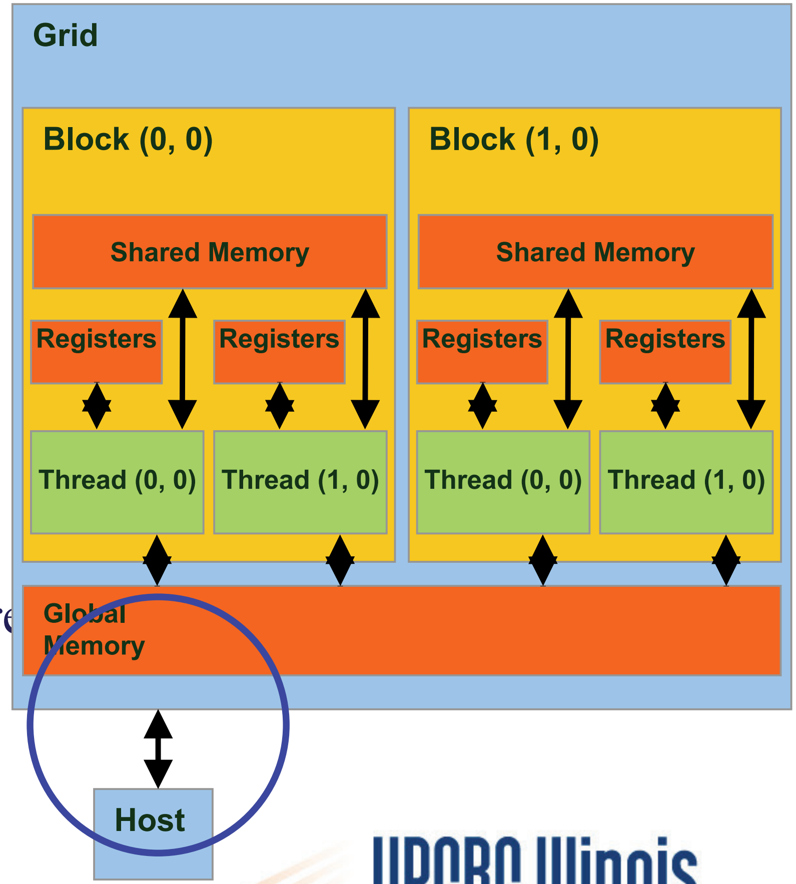
OpenCL Device-to-Host Data Transfer

- clEnqueueReadBuffer();
  - memory data transfer to host
  - Requires nine parameters
    - OpenCL command queue pointer
    - Source OpenCL memory buffer
    - Blocking flag
    - Offset in bytes
    - Size of bytes of read data
    - Destination host memory pointer
    - List of events to be completed before execution of this command
    - Event object tied to this command
- Asynchronous transfer later



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OpenCL Host-Device Data Transfer (cont.)

- Code example:
  - Transfer a 64 * 64 single precision float array
  - a is in host memory and d_a is in device memory

```
clEnqueueWriteBuffer(clcmdq, d_a, CL_FALSE, 0,
    mem_size, (const void * )a, 0, 0, NULL);

clEnqueueReadBuffer(clcmdq, d_result, CL_FALSE, 0,
    mem_size, (void * ) host_result, 0, 0, NULL);
```

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OpenCL Host-Device Data Transfer (cont.)

- clCreateBuffer and clEnqueueWriteBuffer can be combined into a single command using special flags.
- Eg:

```
d_A=clCreateBuffer(clctxt, CL_MEM_READ_ONLY |
  CL_MEM_COPY_HOST_PTR, mem_size, h_A, NULL);
```

  - Combination of 2 flags here. CL_MEM_COPY_HOST_PTR to be used only if a valid host pointer is specified.
  - This creates a memory buffer on the device, and copies data from h_A into d_A.
  - Includes an implicit clEnqueueWriteBuffer operation, for all devices/command queues tied to the context clctxt.

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OpenCL Memory Systems

- __global – large, long latency
- __private – on-chip device registers
- __local – memory accessible from multiple PEs or work items. May be SRAM or DRAM, must query…
- __constant – read-only constant cache
- Device memory is managed explicitly by the programmer, as with CUDA

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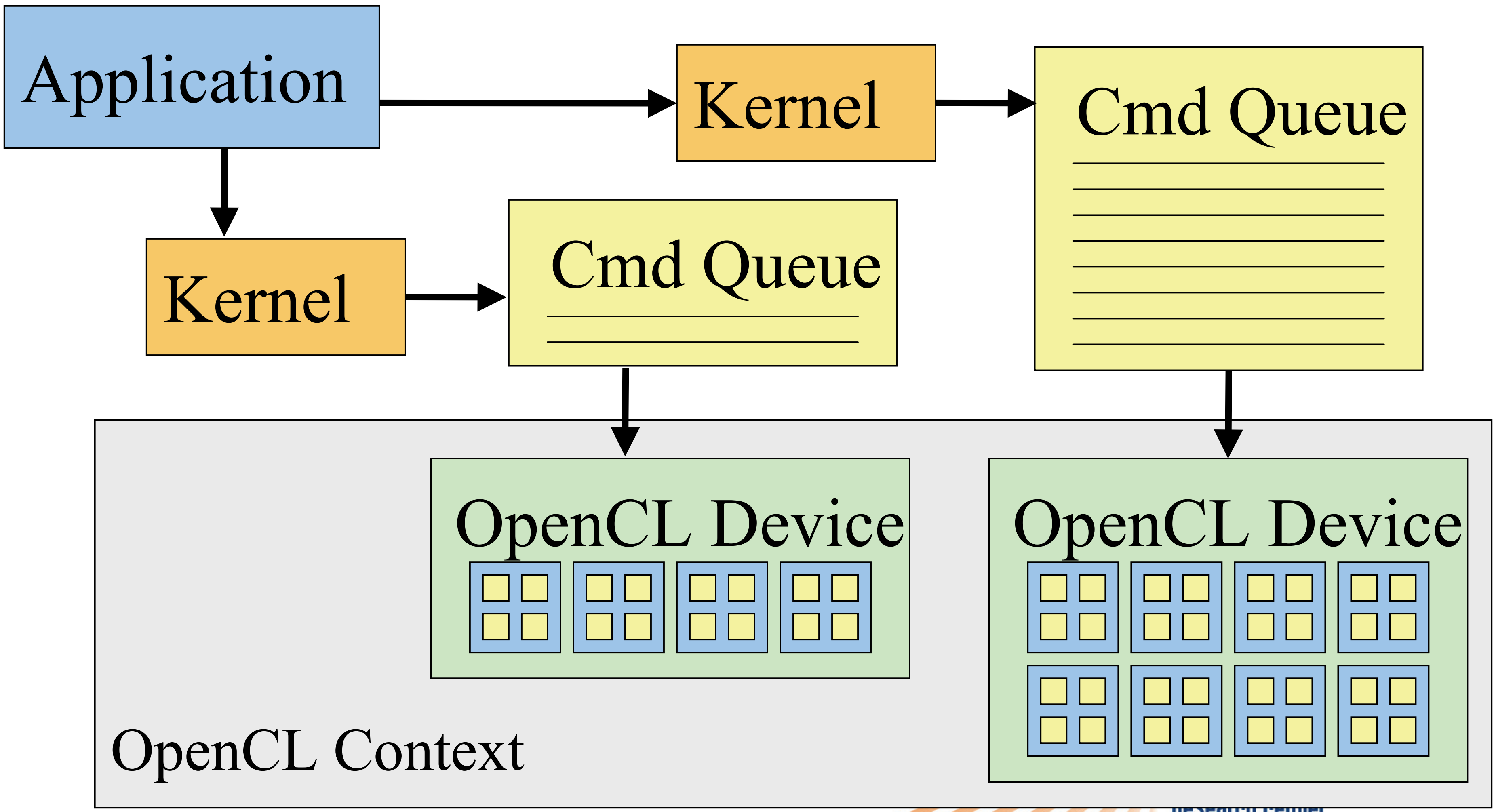
OpenCL Kernel Execution Launch



OpenCL Kernel Compilation Example

OpenCL kernel source code as a big string

```
const char* vaddsrc =
  "__kernel void vadd(__global float *d_A, __global float *d_B, __global float *d_C, int N) {
  \n"   […etc and so forth…]
cl_program clpgm;
clpgm = clCreateProgramWithSource(clctx, 1, &vaddsrc, NULL, &clerr);
char clcompileflags[4096];
sprintf(clcompileflags, "-cl-mad-enable");
clerr = clBuildProgram(clpgm, 0, NULL, clcompileflags, NULL, NULL);
cl_kernel clkern = clCreateKernel(clpgm, "vadd", &clerr);
```

Gives raw source code string(s) to OpenCL

Set compiler flags, compile source, and retreive a handle to the "vadd" kernel

Summary: Host code for `vadd`

```
int main()
{    // allocate and initialize host (CPU) memory
     float *h_A = …,    *h_B = …;
     // allocate device (GPU) memory
    cl_mem d_A, d_B, d_C;
    d_A = clCreateBuffer(clctx, CL_MEM_READ_ONLY |
           CL_MEM_COPY_HOST_PTR, N *sizeof(float), h_A, NULL);
    d_B = clCreateBuffer(clctx, CL_MEM_READ_ONLY |
           CL_MEM_COPY_HOST_PTR, N *sizeof(float), h_B, NULL);
    d_C = clCreateBuffer(clctx, CL_MEM_WRITE_ONLY, N *sizeof(float), NULL, NULL);
    clkern=clCreateKernel(clpgm, "vadd", NULL);
    clerr= clSetKernelArg(clkern, 0,sizeof(cl_mem), (void *) &d_A);
    clerr= clSetKernelArg(clkern, 1,sizeof(cl_mem), (void *) &d_B);
    clerr= clSetKernelArg(clkern, 2,sizeof(cl_mem), (void *) &d_C);
    clerr= clSetKernelArg(clkern, 3,sizeof(int), &N);
    cl_event event=NULL;
    clerr= clEnqueueNDRangeKernel(clcmdq,clkern, 2, NULL, Gsz,Bsz,
          0, NULL, &event);
    clerr= clWaitForEvents(1, &event);
    clEnqueueReadBuffer(clcmdq, d_C, CL_TRUE, 0, N*sizeof(float), h_C, 0,
                   NULL, NULL);
    clReleaseMemObject(d_A);
    clReleaseMemObject(d_B);
    clReleaseMemObject(d_C);
}
```

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Let's take a break!

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