23rd Summer School on PARALLEL COMPUTING

Introduction to OpenCL

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Heterogeneous High Performance Programming framework

- http://www.hpcwire.com/hpcwire/2012-02-28/opencl_gains_ground_on_cuda.html

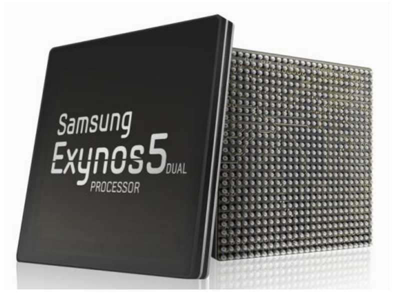
" As the two major programming frameworks for GPU computing, OpenCL and CUDA have been competing for mindshare in the developer community for the past few years. Until recently, CUDA has attracted most of the attention from developers, especially in the high performance computing realm. But OpenCL software has now matured to the point where HPC practitioners are taking a second look.

Both OpenCL and CUDA provide a general-purpose model for data parallelism as well as low-level access to hardware, but only OpenCL provides an open, industry-standard framework. As such, it has garnered support from nearly all processor manufacturers including AMD, Intel, and NVIDIA, as well as others that serve the mobile and embedded computing markets. As a result, applications developed in OpenCL are now portable across a variety of GPUs and CPUs."

Heterogeneous High Performance Programming framework (2)

A modern computing platform includes:

- One or more CPUs
- One of more GPUs
- DSP processors
- Accelerators
- … other?



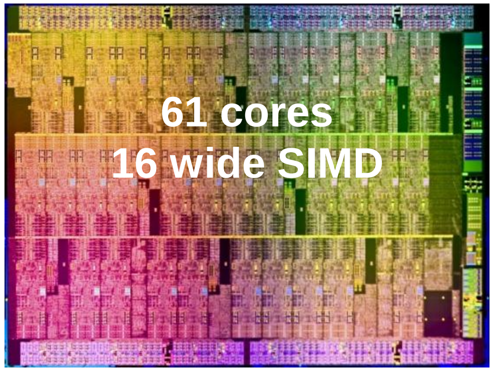
E.g. Samsung® Exynos 5:

- Dual core ARM A15 1.7GHz, Mali T604 GPU

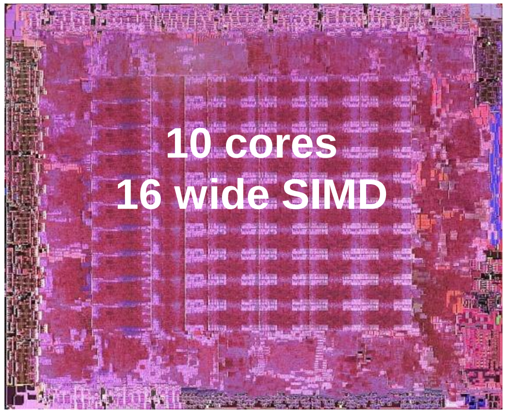
OpenCL lets Programmers write a single <u>portable</u> program that uses <u>ALL</u> resources in the heterogeneous platform

Microprocessor trends

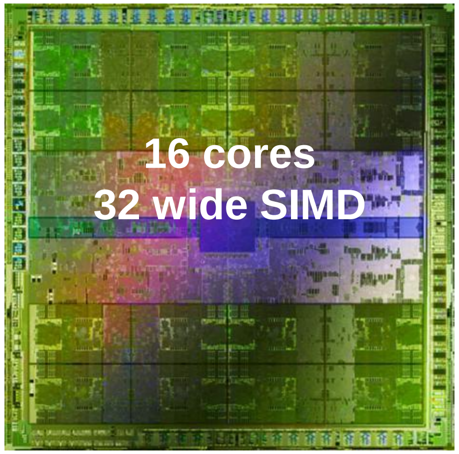
Individual processors have many (possibly heterogeneous) cores.



Intel® Xeon Phi™ coprocessor



ATI™ RV770

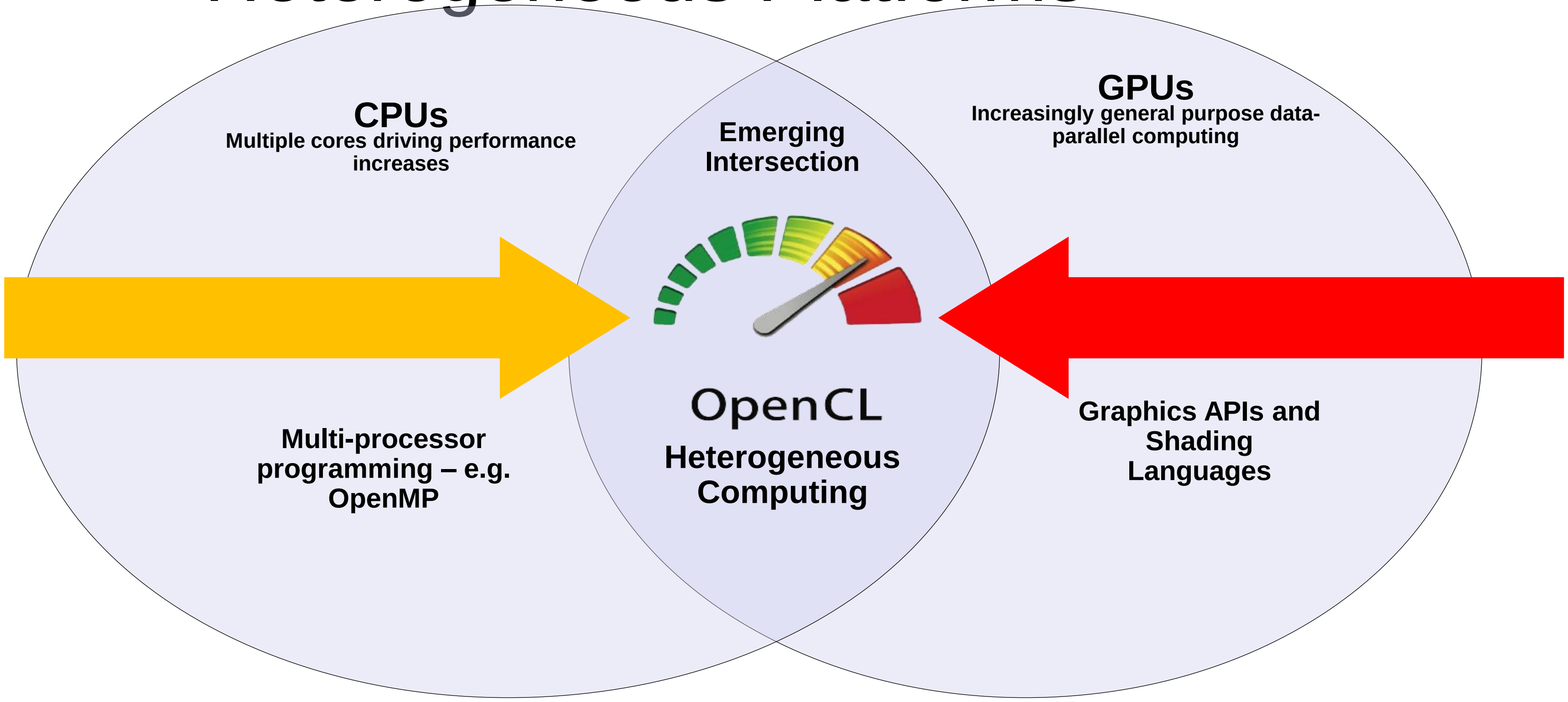


NVIDIA® Tesla® C2090

The Heterogeneous many-core challenge:

How are we to build a software ecosystem for the Heterogeneous many core platform?

Industry Standards for Programming Heterogeneous Platforms

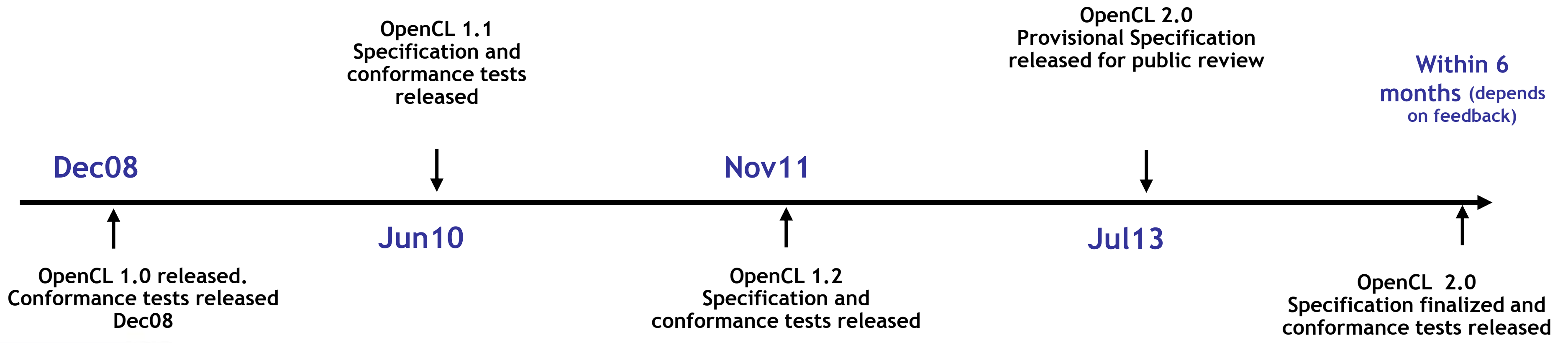

CPUs
Multiple cores driving performance increases
Emerging Intersection
GPUs
Increasingly general purpose data-parallel computing
Multi-processor programming – e.g. OpenMP
OpenCL
Heterogeneous Computing
Graphics APIs and Shading Languages

OpenCL – Open Computing Language

Open, royalty-free standard for portable, parallel programming of heterogeneous parallel computing CPUs, GPUs, and other processors

OpenCL Timeline

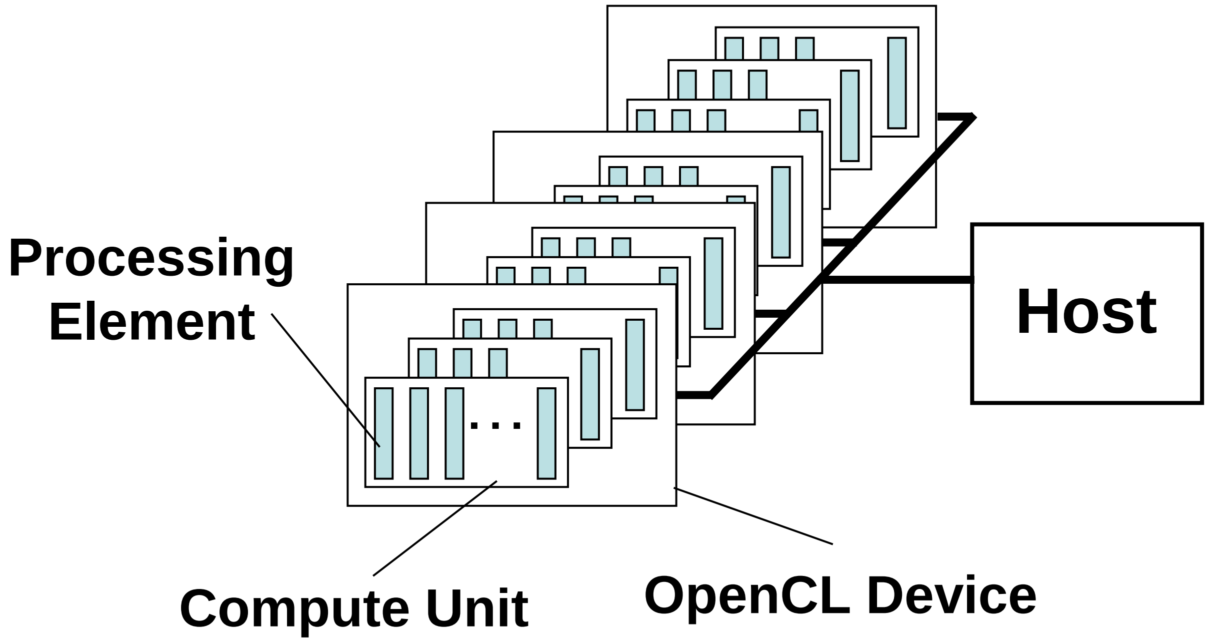
- Launched Jun'08 … 6 months from "strawman" to OpenCL 1.0
- Rapid innovation to match pace of hardware innovation
  - 18 months from 1.0 to 1.1 and from 1.1 to 1.2
  - Goal: a new OpenCL every 18-24 months
  - Committed to backwards compatibility to protect software investments


OpenCL 1.1 Specification and conformance tests released
OpenCL 2.0 Provisional Specification released for public review
Within 6 months (depends on feedback)
Dec08
Nov11
Jun10
Jul13
OpenCL 1.0 released. Conformance tests released Dec08
OpenCL 1.2 Specification and conformance tests released
OpenCL 2.0 Specification finalized and conformance tests released

OpenCL Working Group within Khronos

- Diverse industry participation
  - Processor vendors, system OEMs, middleware vendors, application developers.
- OpenCL became an important standard upon release by virtue of the market coverage of the companies behind it.

OpenCL Platform Model



- One ***Host*** and one or more ***OpenCL Devices***
  - Each OpenCL Device is composed of one or more ***Compute Units***
    - Each Compute Unit is divided into one or more ***Processing Elements***
- Memory divided into ***host memory*** and ***device memory***

OpenCL Platform Example (One node, two CPU sockets, two GPUs)

CPUs:

- Treated as one OpenCL device
  - One CU per core
  - 1 PE per CU, or if PEs mapped to SIMD lanes, *n* PEs per CU, where *n* matches the SIMD width
- Remember:
  - the CPU will also have to be its own host!

GPUs:

- Each GPU is a separate OpenCL device
- One CU per Streaming Multiprocessor
- Can use CPU and all GPU devices concurrently through OpenCL

CU = Compute Unit; PE = Processing Element

The BIG idea behind OpenCL

- Replace loops with functions (a kernel) executing at each point in a problem domain
  - E.g., process a 1024x1024 image with one kernel invocation per pixel or 1024x1024=1,048,576 kernel executions

Traditional loops

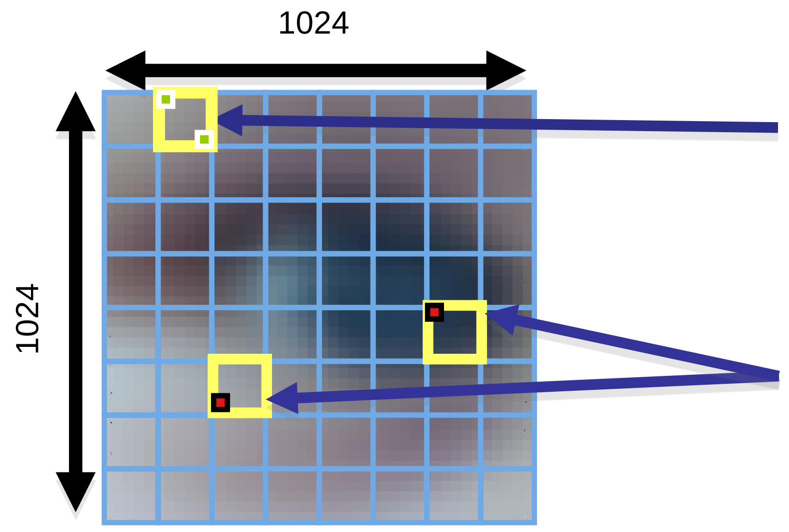
```
void
mul(const int n,
    const float *a,
    const float *b,
          float *c)
{
  int i;
  for (i = 0; i < n; i++)
    c[i] = a[i] * b[i];
}
```

Data Parallel OpenCL

```
__kernel void
mul(__global const float *a,
    __global const float *b,
    __global       float *c)
{
  int id = get_global_id(0);
  c[id] = a[id] * b[id];
}
// many instances of the kernel,
// called work-items, execute
// in parallel
```

An N-dimensional domain of work-items

- Global Dimensions:
  - 1024x1024 (whole problem space)
- Local Dimensions:
  - 128x128 (**work-group**, executes together)



Synchronization between work-items possible only within work-groups: and

Cannot synchronize between work-groups within a kernel

- Choose the dimensions that are "best" for your algorithm

OpenCL N Dimensional Range (NDRange)

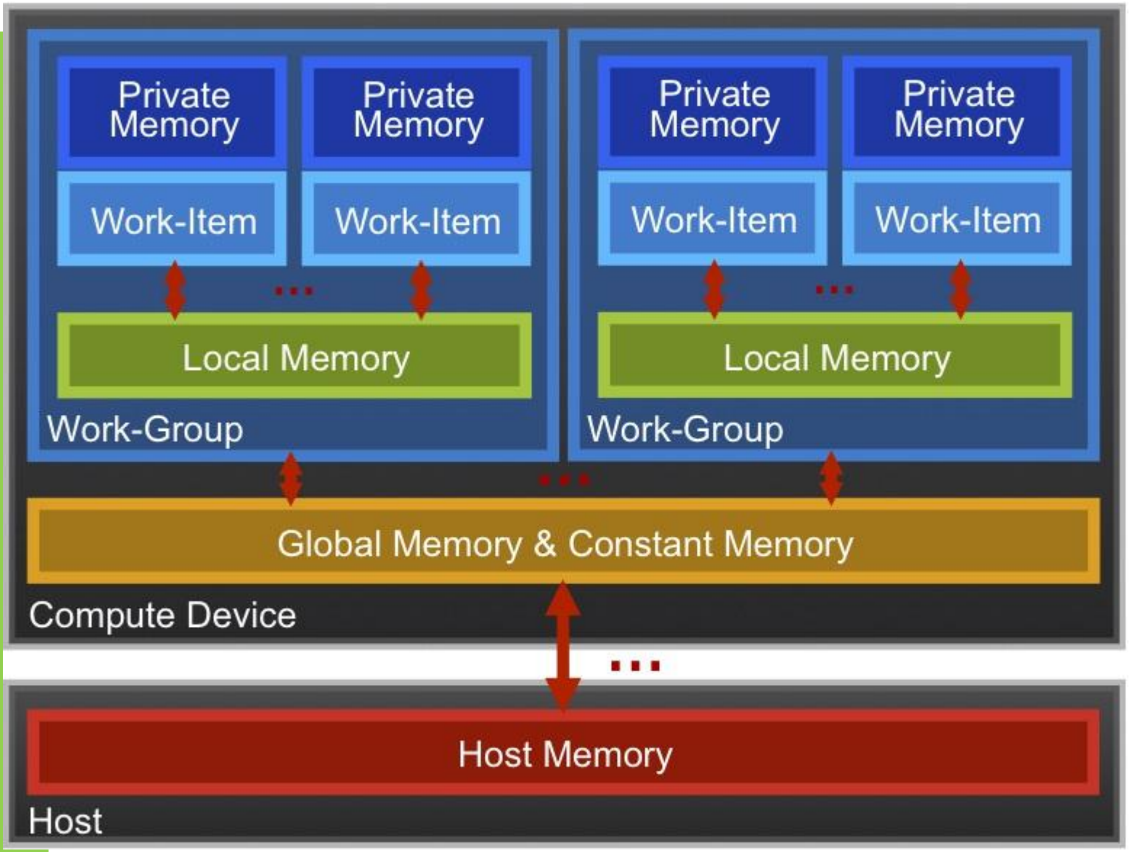
- The problem we want to compute should have some **dimensionality**;
  - For example, compute a kernel on all points in a cube
- When we execute the kernel we specify **up to 3 dimensions**
- We also **specify the total problem size** in each dimension – this is called the **global** size
- We associate each point in the iteration space with a **work-item**

OpenCL N Dimensional Range (NDRange)

- Work-items are grouped into **work-groups**; work-items within a work-group can share **local memory** and can **synchronize**
- We can specify the number of work-items in a work-group – this is called the **local** (work-group) size
- Or the OpenCL run-time can choose the work-group size for you (usually not optimally)

OpenCL Memory model

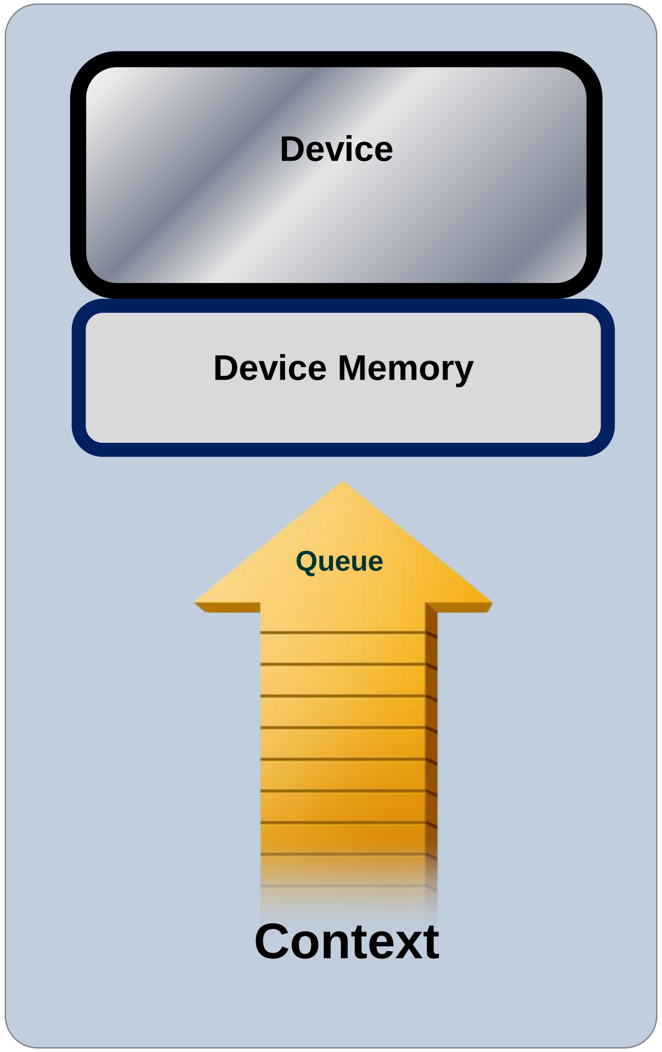
- ***Private Memory***
  - Per work-item
- ***Local Memory***
  - Shared within a work-group
- ***Global Memory /Constant Memory***
  - Visible to all work-groups
- ***Host memory***
  - On the CPU



Memory management is **explicit**:
You are responsible for moving data from host → global → local *and* back

Context and Command-Queues

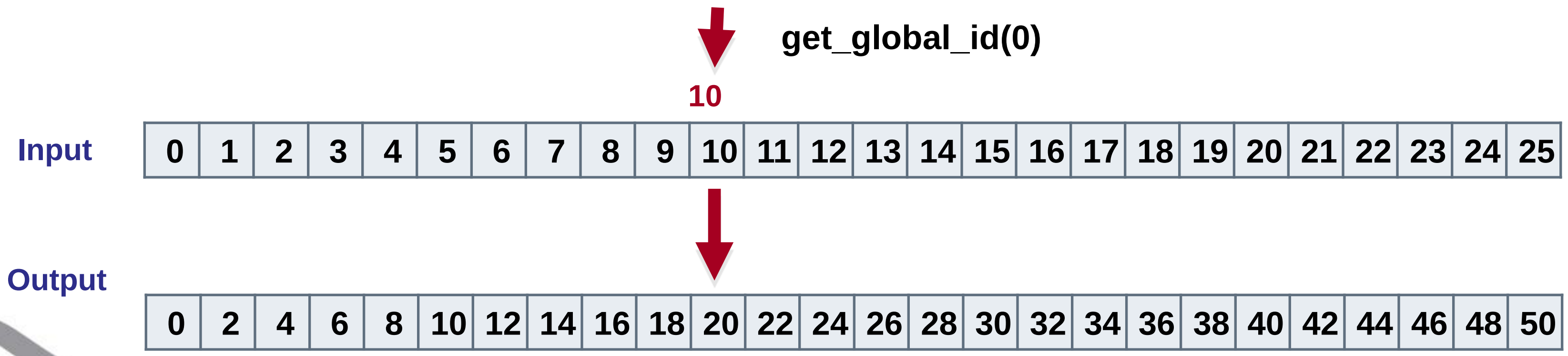
- ***Context***:
  - The environment within which kernels execute and in which synchronization and memory management is defined.
- The ***context*** includes:
  - One or more devices
  - Device memory
  - One or more command-queues
- All ***commands*** for a device (kernel execution, synchronization, and memory transfer operations) are submitted through a ***command-queue***.
- Each ***command-queue*** points to a single device within a context.



Execution model (kernels)

- OpenCL execution model … define a problem domain and execute an instance of a **kernel** for each point in the domain

```
__kernel void times_two(
    __global float* input,
    __global float* output)
{
   int i = get_global_id(0);
   output[i] = 2.0f * input[i];
}
```



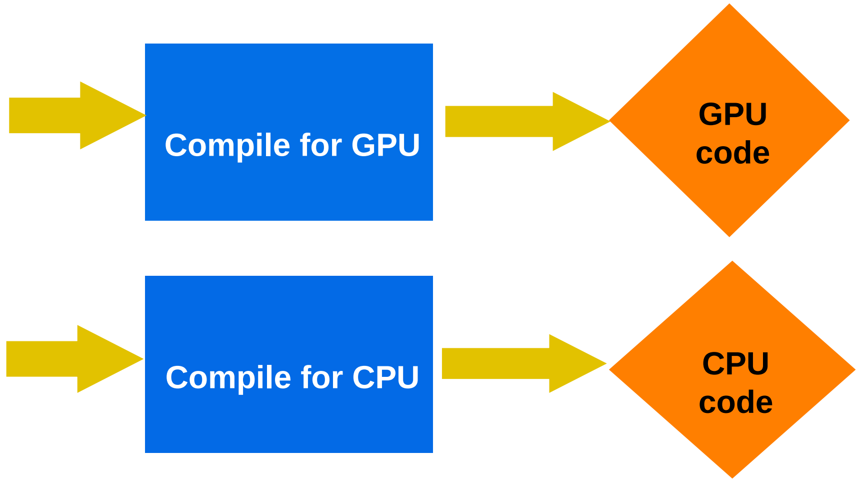
Input	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Output	0	2	4	6	8	10	12	14	16	18	20	22	24	26	28	30	32	34	36	38	40	42	44	46	48	50

Building Program Objects

- The program object encapsulates:
  - A context
  - The program kernel source or binary
  - List of target devices and build options
- The C API build process to create a program object:
  - clCreateProgramWithSource()
  - clCreateProgramWithBinary()

OpenCL uses runtime compilation … because in general you don't know the details of the target device when you ship the program

```
__kernel void
horizontal_reflect(read_only image2d_t src,
                   write_only image2d_t dst)
{
  int x = get_global_id(0);  // x-coord
  int y = get_global_id(1);  // y-coord
  int width = get_image_width(src);
  float4 src_val = read_imagef(src, sampler,
                       (int2)(width-1-x, y));
  write_imagef(dst, (int2)(x, y), src_val);
}
```



Example: vector addition

- The “hello world” program of data parallel programming is a program to add two vectors

C[i] = A[i] + B[i] for i=0 to N-1

- For the OpenCL solution, there are two parts
  - Kernel code
  - Host code

Vector Addition - Kernel

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

Vector Addition – Host

- The <u>host program</u> is the code that runs on the host to:
  - Setup the environment for the OpenCL program
  - Create and manage kernels
- 5 simple steps in a basic host program:
  1. Define the ***platform*** … platform = devices+context+queues
  2. Create and Build the ***program*** (dynamic library for kernels)
  3. Setup ***memory*** objects
  4. Define the ***kernel*** (attach arguments to kernel functions)
  5. Submit ***commands*** … transfer memory objects and execute kernels

Please, refer to he reference card. This will help you get used to the reference card and how to pull information from the card and express it in code.

1. Define the platform

- Grab the first available platform:

```
err = clGetPlatformIDs(1, &firstPlatformId,
                       &numPlatforms);
```

- Use the first CPU device the platform provides:

```
err = clGetDeviceIDs(firstPlatformId,
        CL_DEVICE_TYPE_CPU, 1, &device_id, NULL);
```

- Create a simple context with a single device:

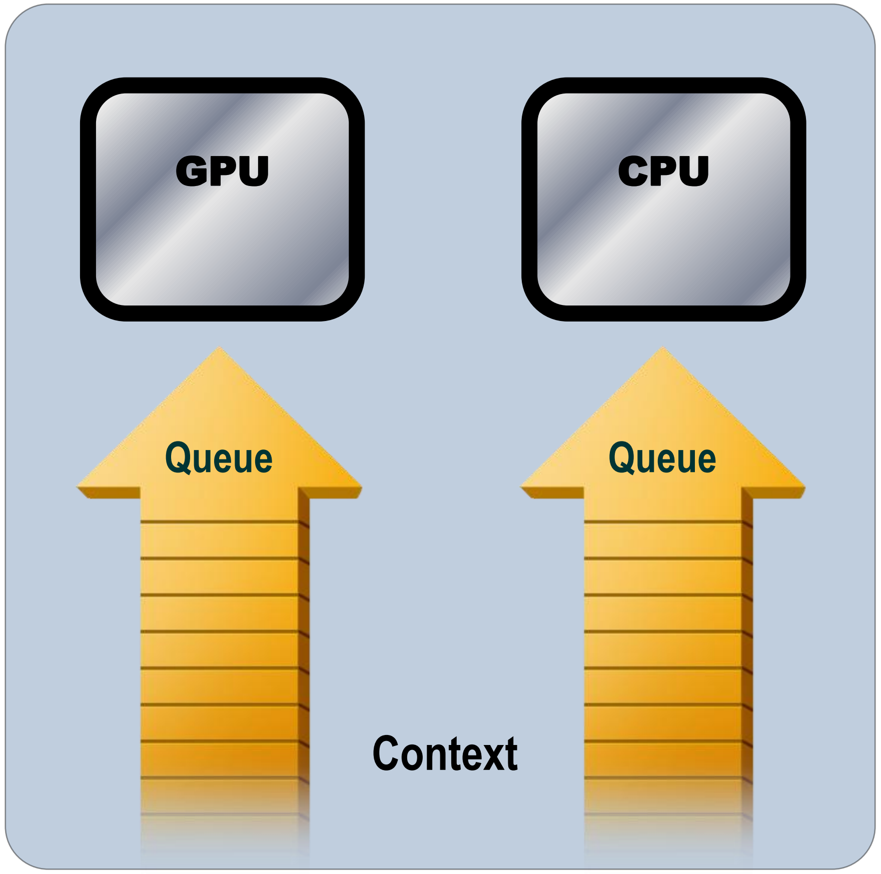
```
context = clCreateContext(firstPlatformId, 1,
                  &device_id, NULL, NULL, &err);
```

- Create a simple command-queue to feed our device:

```
commands = clCreateCommandQueue(context, device_id,
                                0, &err);
```

Command-Queues

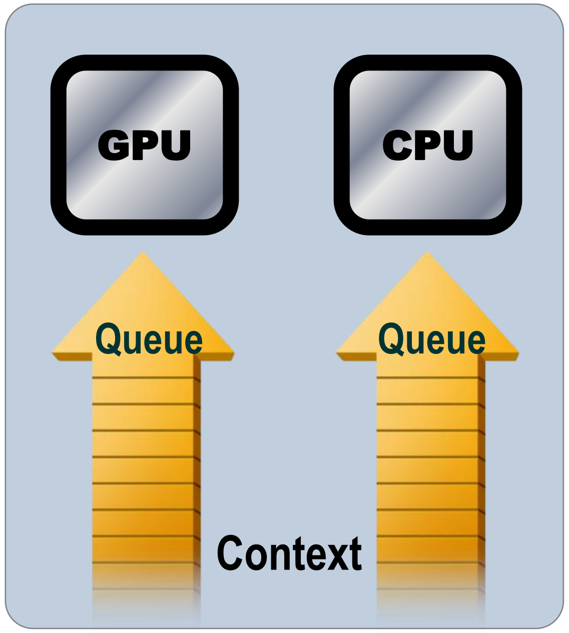
- Commands include:
  - Kernel executions
  - Memory object management
  - Synchronization
- The only way to submit commands to a device is through a command-queue.
- Each command-queue points to a single device within a context.
- Multiple command-queues can feed a single device.
  - Used to define independent streams of commands that don't require synchronization



Command-Queue execution details

Command queues can be configured in different ways to control how commands execute

- ***In-order queues***:
  - Commands are enqueued and complete in the order they appear in the program (program-order)
- ***Out-of-order queues***:
  - Commands are enqueued in program-order but can execute (and hence complete) in any order.
- Execution of commands in the command-queue are guaranteed to be completed at synchronization points



2. Create and Build the program

- Define source code for the kernel-program as a string literal (great for toy programs) or read from a file (for real applications).

- Build the program object:

```
program = clCreateProgramWithSource(context, 1
        (const char**) &KernelSource, NULL, &err);
```

- Compile the program to create a “dynamic library” from which specific kernels can be pulled:

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

Error messages

- Fetch and print error messages:

```
if (err != CL_SUCCESS) {
 size_t len;
 char buffer[2048];
 clGetProgramBuildInfo(program, device_id,
  CL_PROGRAM_BUILD_LOG, sizeof(buffer), buffer, &len);
 printf(“%s\n”, buffer);
}
```

- Important to do check all your OpenCL API error messages!
- Easier in C++ with try/catch

3. Setup Memory Objects

- For vector addition we need 3 memory objects, one each for input vectors A and B, and one for the output vector C.
- Create input vectors and assign values on the host:

```
float h_a[LENGTH], h_b[LENGTH], h_c[LENGTH];
for (i = 0; i < length; i++) {
    h_a[i] = rand() / (float)RAND_MAX;
    h_b[i] = rand() / (float)RAND_MAX;
}
```

- Define OpenCL memory objects:

```
d_a = clCreateBuffer(context, CL_MEM_READ_ONLY,
                     sizeof(float)*count, NULL, NULL);
d_b = clCreateBuffer(context, CL_MEM_READ_ONLY,
                     sizeof(float)*count, NULL, NULL);
d_c = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
                     sizeof(float)*count, NULL, NULL);
```

Memory Objects:

- A handle to a reference-counted region of global memory.

Creating and manipulating buffers

- Buffers are declared on the host as type: cl_mem
- Arrays in host memory hold your original host-side data:

```
float h_a[LENGTH], h_b[LENGTH];
```

- Create the buffer (d_a), assign sizeof(float)*count bytes from “h_a” to the buffer and copy it into device memory:

```
cl_mem d_a = clCreateBuffer(context,
  CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR,
   sizeof(float)*count, h_a, NULL);
```

Creating and manipulating buffers

- Other common memory flags include:
  CL_MEM_WRITE_ONLY, CL_MEM_READ_WRITE

- These are from the point of view of the **device**

- Submit command to copy the buffer back to host memory at “h_c”:
  - CL_TRUE = blocking, CL_FALSE = non-blocking

```
clEnqueueReadBuffer(queue, d_c, CL_TRUE,
                    sizeof(float)*count, h_c,
                    NULL, NULL, NULL);
```

4. Define the kernel

- Create kernel object from the kernel function “vadd”:

```
kernel = clCreateKernel(program, “vadd”, &err);
```

- Attach arguments of the kernel function “vadd” to memory objects:

```
err  = clSetKernelArg(kernel, 0, sizeof(cl_mem), &d_a);
err |= clSetKernelArg(kernel, 1, sizeof(cl_mem), &d_b);
err |= clSetKernelArg(kernel, 2, sizeof(cl_mem), &d_c);
err |= clSetKernelArg(kernel, 3, sizeof(unsigned int),
            &count);
```

5. Enqueue commands

- Write Buffers from host into global memory (as non-blocking operations):

```
err = clEnqueueWriteBuffer(commands, d_a, CL_FALSE,
          0, sizeof(float)*count, h_a, 0, NULL, NULL);
err = clEnqueueWriteBuffer(commands, d_b, CL_FALSE,
          0, sizeof(float)*count, h_b, 0, NULL, NULL
```

- Enqueue the kernel for execution (note: in-order so OK):

```
err = clEnqueueNDRangeKernel(commands, kernel, 1,
                NULL, &global, &local, 0, NULL, NULL);
```

5. Enqueue commands

- Read back result (as a blocking operation). We have an in-order queue which assures the previous commands are completed before the read can begin.

```
err = clEnqueueReadBuffer(commands, d_c, CL_TRUE,
            sizeof(float)*count, h_c, 0, NULL, NULL);
```

Vector Addition – Host Program

Define platform and queues

```
// create the OpenCL context on a GPU device
cl_context context = clCreateContextFromType(0,
                CL_DEVICE_TYPE_GPU, NULL, NULL, NULL);

// get the list of GPU devices associated with context
clGetC                                               ,cb);

cl_device_id[] devices = malloc(cb);
clGetContextInfo(context,CL_CONTEXT_DEVICES,cb,devices,NULL);

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

Define memory objects

```
// allocate the buffer memory objects
memobjs                                          Y |
    CL_I                                         LL);
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);
```

Create the program

```
// create the
program = c
            &program_source, NULL, NULL);
```

Build the program

```
// build the prog
err = clBuildPro                              LL,NULL);
```

Create and setup kernel

```
// create the kernel
kernel = clCreateKernel(program, "vec_add", NULL);

// set the args values
err  = clSetKernelArg(kernel, 0, (void *) &memobjs[0],

err |= clS
            sizeof(cl_mem));
err |= clSetKernelArg(kernel, 2, (void *) &memobjs[2],
            sizeof(cl_mem));
// set work-item dimensions
global_work_size[0] = n;
```

Execute the kernel

```
// execute ker
err = clEnque                                 el, 1, NULL,
        global_work_size, NULL,0,NULL,NULL);
```

Read results on the host

```
// read output array
err = clEn
            n*sizeof(cl_float), dst,
            0, NULL, NULL);
```

It's complicated, but most of this is "boilerplate" and not as bad as it looks.

OpenCL C for Compute Kernels

- Derived from **ISO C99**
  - A few ***restrictions***: no recursion, function pointers, functions in C99 standard headers ...
  - Preprocessing directives defined by C99 are supported (#include etc.)
- Built-in data types
  - Scalar and vector data types, pointers
  - Data-type conversion functions:
    - convert_type<_sat><_roundingmode>
  - Image types:
    - image2d_t, image3d_t and sampler_t

OpenCL C for Compute Kernels

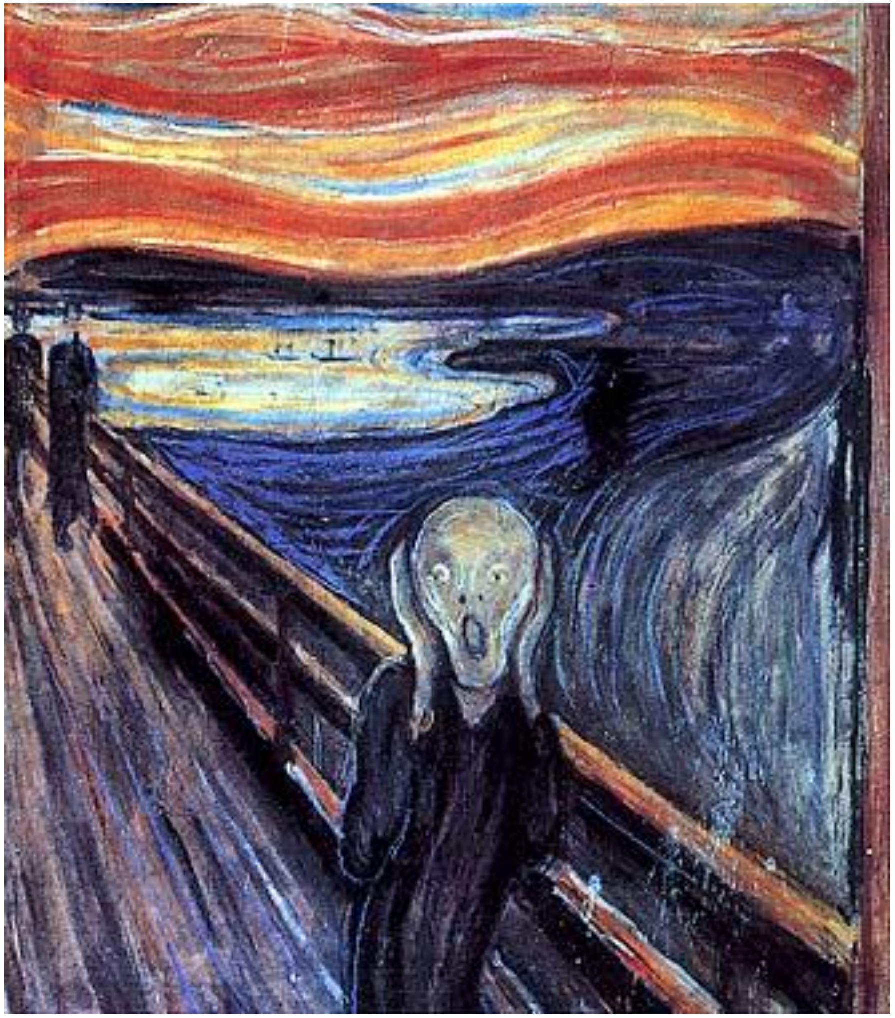
- Built-in functions — ***mandatory***
  - Work-Item functions, math.h, read and write image
  - Relational, geometric functions, synchronization functions
  - printf (v1.2 only, so not currently for NVIDIA GPUs)
- Built-in functions — ***optional*** (called “extensions”)
  - Double precision, atomics to global and local memory
  - Selection of rounding mode, writes to image3d_t surface

OpenCL C Language Highlights

- Function qualifiers
  - **__kernel** qualifier declares a function as a kernel
    - I.e. makes it visible to host code so it can be enqueued
  - Kernels can call other kernel-side functions
- Address space qualifiers
  - **__global, __local, __constant, __private**
  - Pointer kernel arguments must be declared with an address space qualifier
- Work-item functions
  - get_work_dim(), get_global_id(), get_local_id(), get_group_id()
- Synchronization functions
  - **Barriers** - all work-items within a work-group must execute the barrier function before any work-item can continue
  - **Memory fences** - provides ordering between memory operations

Host programs can be “ugly”

- OpenCL’s goal is extreme portability, so it exposes everything
  - (i.e. it is quite verbose!).
- But most of the host code is the same from one application to the next – the re-use makes the verbosity a non-issue.
- You can package common API combinations into functions or even C++ or Python classes to make the reuse more convenient.



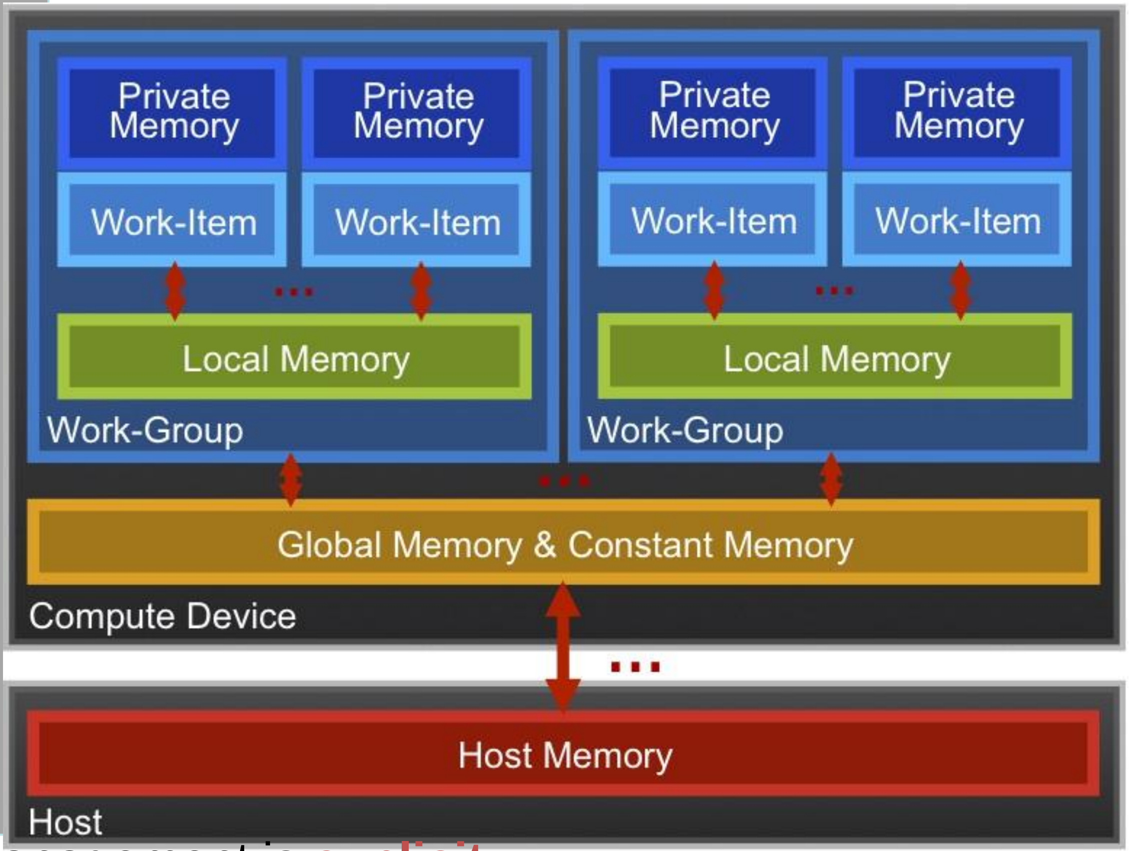
The C++ Interface

- Khronos has defined a common C++ header file containing a high level interface to OpenCL, cl.hpp
- This interface is dramatically easier to work with[1]
- Key features:
  - Uses common defaults for the platform and command-queue, saving the programmer from extra coding for the most common use cases
  - Simplifies the basic API by bundling key parameters with the objects rather than requiring verbose and repetitive argument lists
  - Ability to “call” a kernel from the host, like a regular function
  - Error checking can be performed with C++ exceptions

[1] especially for C++ programmers…

OpenCL Memory model

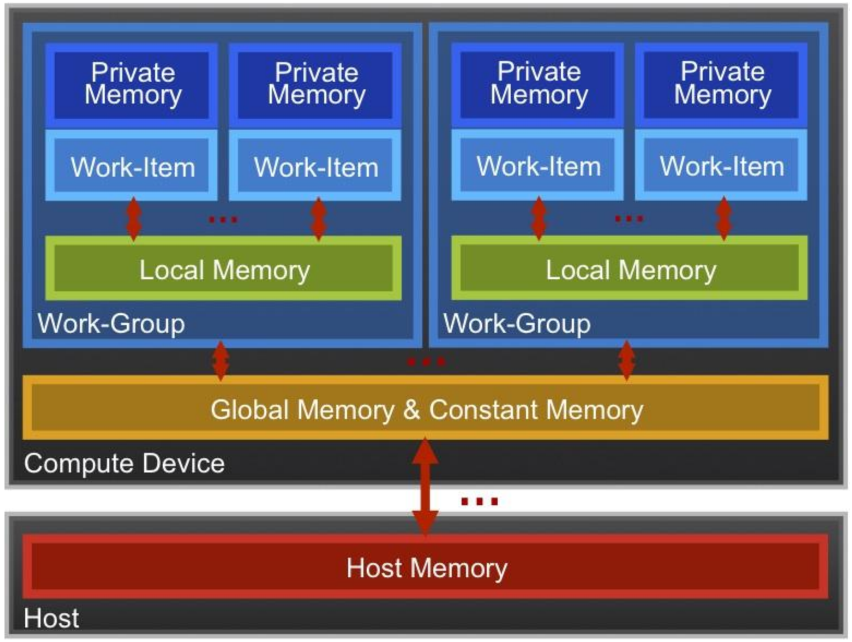
- Private Memory
  - Per work-item
- Local Memory
  - Shared within a work-group
- Global/Constant Memory
  - Visible to all work-groups
- Host memory
  - On the CPU



Memory management is **explicit**:
You are responsible for moving data from host → global → local *and* back

OpenCL Memory model

- Private Memory
  - Fastest & smallest: O(10) words/WI
- Local Memory
  - Shared by all WI's in a work-group
  - But not shared between work-groups!
  - O(1-10) Kbytes per work-group
- Global/Constant Memory
  - O(1-10) Gbytes of Global memory
  - O(10-100) Kbytes of Constant memory
- Host memory
  - On the CPU - GBytes



Memory management is **explicit**:
O(1-10) Gbytes/s bandwidth to discrete GPUs for
Host <-> Global transfers

Private Memory

- Managing the memory hierarchy is one of ***the*** most important things to get right to achieve good performance

- Private Memory:
  - A very scarce resource, only a few tens of 32-bit words per Work-Item at most
  - If you use too much it spills to global memory or reduces the number of Work-Items that can be run at the same time, potentially harming performance*
  - Think of these like registers on the CPU

* Occupancy on a GPU

Local Memory*

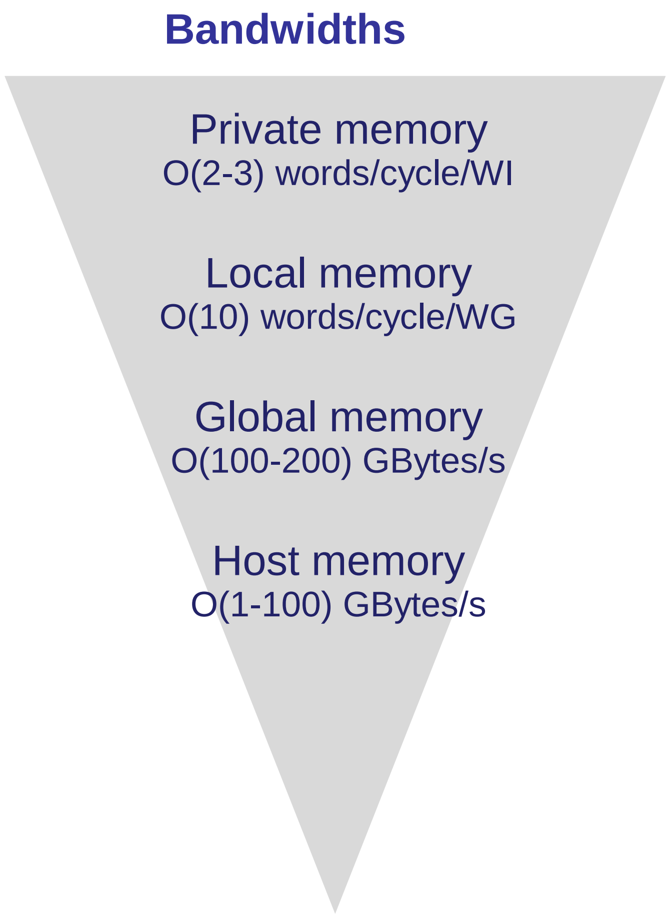
- Tens of KBytes per Compute Unit
  - As multiple Work-Groups will be running on each CU, this means only a fraction of the total Local Memory size is available to each Work-Group
- Assume O(1-10) KBytes of Local Memory per Work-Group
  - Your kernels are responsible for transferring data between Local and Global/Constant memories … there are optimized library functions to help
- Use Local Memory to hold data that can be reused by all the work-items in a work-group
- Access patterns to Local Memory affect performance in a similar way to accessing Global Memory
  - Have to think about things like coalescence & bank conflicts

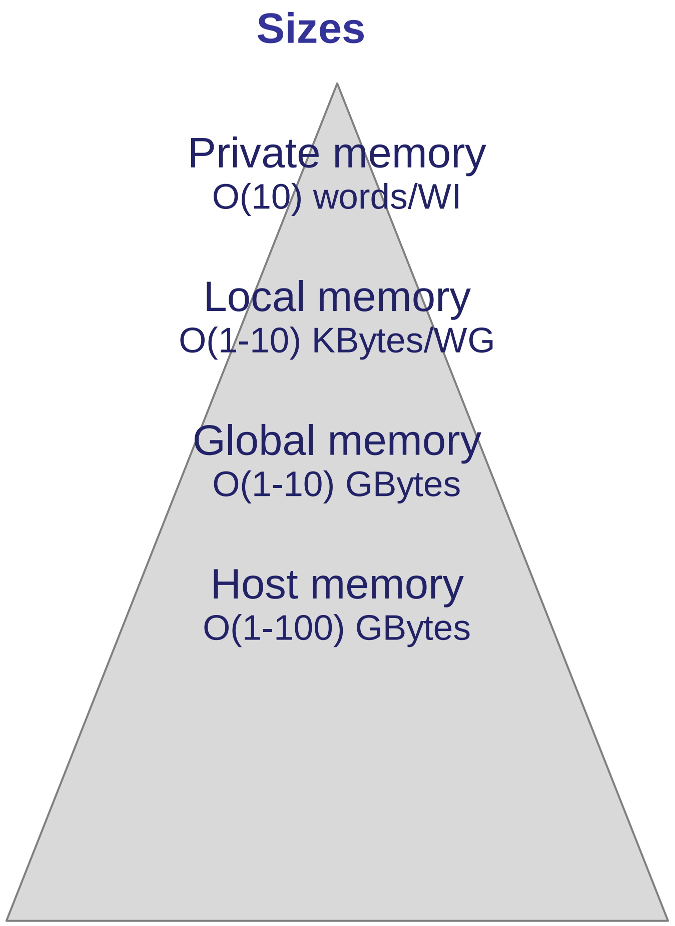
* Typical figures for a 2013 GPU

Local Memory

- Local Memory doesn’t always help…
  - CPUs don’t have special hardware for it
  - This can mean excessive use of Local Memory might slow down kernels on CPUs
  - GPUs now have effective on-chip caches which can provide much of the benefit of Local Memory but without programmer intervention
  - So, your mileage may vary!

The Memory Hierarchy





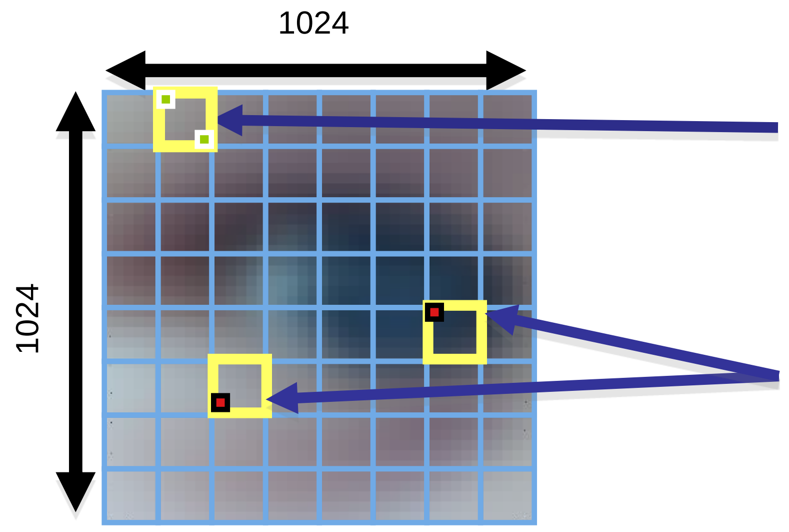
Speeds and feeds approx. for a high-end discrete GPU, circa 2011

Memory Consistency

- OpenCL uses a **relaxed consistency** memory model; i.e.
  - The state of memory visible to a work-item is not guaranteed to be consistent across the collection of work-items at all times.
- Within a work-item:
  - Memory has load/store consistency to the work-item's private view of memory, i.e. it sees its own reads and writes correctly
- Within a work-group:
  - Local memory is consistent between work-items at a barrier.
- Global memory is consistent within a work-group at a barrier, **but *not* guaranteed across different work-groups!!**
  - This is a common source of bugs!
- Consistency of memory shared between commands (e.g. kernel invocations) is enforced by synchronization (barriers, events, in-order queue)

Consider N-dimensional domain of work-items

- Global Dimensions:
  - 1024x1024 (whole problem space)
- Local Dimensions:
  - 128x128 (**work-group**, executes together)



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

Cannot synchronize between work-groups within a kernel

Synchronization: when multiple units of execution (e.g. work-items) are brought to a known point in their execution. Most common example is a barrier … i.e. all units of execution "in scope" arrive at the barrier before any proceed.

Work-Item Synchronization

Ensure correct order of memory operations to local memory (with flushes or queuing a memory fence)l or global

- Within a work-group

  void barrier()

  – Takes optional flags

    CLK_LOCAL_MEM_FENCE and/or CLK_GLOBAL_MEM_FENCE

  – A work-item that encounters a barrier() will wait until ALL work-items in its work-group reach the barrier()

  – Corollary: If a barrier() is inside a branch, then the branch must be taken by either:

    - ALL work-items in the work-group, OR
    - NO work-item in the work-group

- Across work-groups

  – No guarantees as to where and when a particular work-group will be executed relative to another work-group

  – Cannot exchange data, or have barrier-like synchronization between two different work-groups! (Critical issue!)

  – Only solution: finish the kernel and start another

- Targets a broader rang of CPU-l and GPU-like devices th n CUDA
  - Targets endors
  - Man f ay not
    be
- OpenCl th much
  s
- **A sin ot achieve peak p pes**

Performance????

Portable performance in OpenCL

- Portable performance is always a challenge, more so when OpenCL devices can be so varied (CPUs, GPUs, …)
- But OpenCL provides a powerful framework for writing performance portable code
- The following slides are general advice on writing code that should work well on most OpenCL devices

- Tremendous amount of computing power available

__1170 GFLOPs peak__

__1070 GFLOPs peak__

Optimization issues

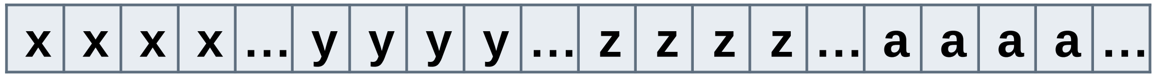
- Efficient access to memory
  - Memory coalescing
    - Ideally get work-item i to access data[i] and work-item j to access data[j] at the same time etc.
  - Memory alignment
    - Padding arrays to keep everything aligned to multiples of 16, 32 or 64 bytes
- Number of work-items and work-group sizes
  - Ideally want at least 4 work-items per PE in a Compute Unit on GPUs
  - More is better, but diminishing returns, and there is an upper limit
    - Each work item consumes PE finite resources (registers etc)
- Work-item divergence
  - What happens when work-items branch?
  - Actually a SIMD data parallel model
  - Both paths (if-else) may need to be executed (*branch divergence*), avoid where possible (non-divergent branches are termed *uniform*)

Memory layout is critical to performance

- "Structure of Arrays vs. Array of Structures" problem:

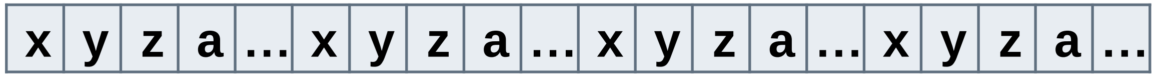
```
struct { float x, y, z, a; } Point;
```

- Structure of Arrays (SoA) suits memory coalescence on GPUs



Adjacent work-items like to access adjacent memory

- Array of Structures (AoS) may suit cache hierarchies on CPUs



Individual work-items like to access adjacent memory

Advice for performance portability

- Optimal Work-Group sizes will differ between devices
  - E.g. CPUs tend to prefer 1 Work-Item per Work-Group, while GPUs prefer lots of Work-Items per Work-Group (usually a multiple of the number of PEs per Compute Unit, i.e. 32, 64 etc.)
- From OpenCL v1.1 you can discover the preferred Work-Group size multiple for a kernel once it's been built for a specific device
  - Important to pad the total number of Work-Items to an exact multiple of this
  - Again, will be different per device
- The OpenCL run-time will have a go at choosing good EnqueueNDRangeKernel dimensions for you
  - With very variable results

- **Your mileage will vary**, the best strategy is to write ***adaptive*** code that makes decisions at run-time

Tuning Knobs some general issues

- Tiling size (work-group sizes, dimensionality etc.)
  - For block-based algorithms (e.g. matrix multiplication)
  - Different devices might run faster on different block sizes
- Data layout
  - Array of Structures or Structure of Arrays (AoS vs. SoA)
  - Column or Row major
- Caching and prefetching
  - Use of local memory or not
  - Extra loads and stores assist hardware cache?
- Work-item / work-group data mapping
  - Related to data layout
  - Also how you parallelize the work
- Operation-specific tuning
  - Specific hardware differences
  - Built-in trig / special function hardware
  - Double vs. float (vs. half)

Auto tuning

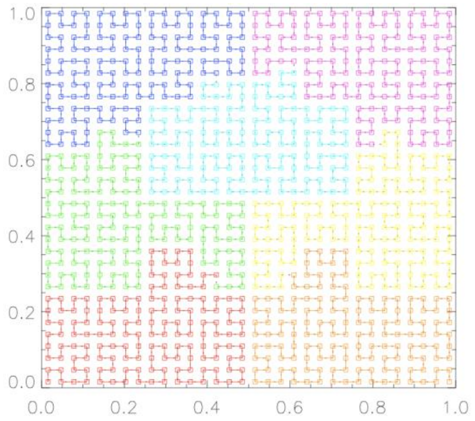
- Q: How do you know what the ***best*** parameter values for your program are?
  - What is the best work-group size, for example

- A: Try them all! (Or a well chosen subset)

- This is where auto tuning comes in
  - Run through different combinations of parameter values and optimize the runtime (or another measure) of your program.

How much fast? The Hydro benchmark

Hydro is a simplified version of RAMSES (CEA, France astrophysics code to study large scale structure and galaxy formation)



Hydro main features:

- regular cartesian mesh (no AMR)
- solves compressible Euler equations of hydrodynamics
- finite volume method, second order Godunov scheme
- it uses a Riemann solver numerical flux at the interfaces

The Hydro benchmark

Hydro is about 1K lines of code and has been ported to different programming environment and architectures, including accelerators. In particular:

- ❑ initial Fortran branch including OpenMP, MPI, hybrid MPI+OpenMP
- ❑ C branch for CUDA, **OpenCL**, OpenACC, UPC

Hydro run comparison

performances of OpenCL code are very good (better than CUDA!)

More than 16 Intel Xeon SandyBridge cores are needed to compare OpenCL 1 K20 device

Intel MIC preliminary run on CINECA prototype. 240 threads, vectorized code,KMP_AFFINITY=balanced

Device/version	Elapsed time (sec.) without initialization	EfficiencyLoss (with respect to the best timing)
CUDA K20C	52.37	0.24
OpenCL K20C	42.09	0
MPI (1 process)	780.8	17.5
MPI+OpenMP (16 OpenMP threads)	109.7	1.60
MPI+OpenMP MIC (240 threads)	147.5	2.50
OpenACC (Pgi)	N.A.	N.A.

OpenAcc run it fails using Pgi compiler

Hydro OpenCL scaling

performances are good. Scalability is limited by domain size

OpenCL+MPI run, varying the number of NVIDIA Tesla K20 device,4091x4091 domain,100 iterations

Number of K20 devices	Elapsed time (sec.) without initialization	Speed-Up
1	42.0	1.0
2	23.5	1.7
4	12.2	3.4
8	8.56	4.9
16	5.70	7.3

How much fast? The EuroBen Benchmark

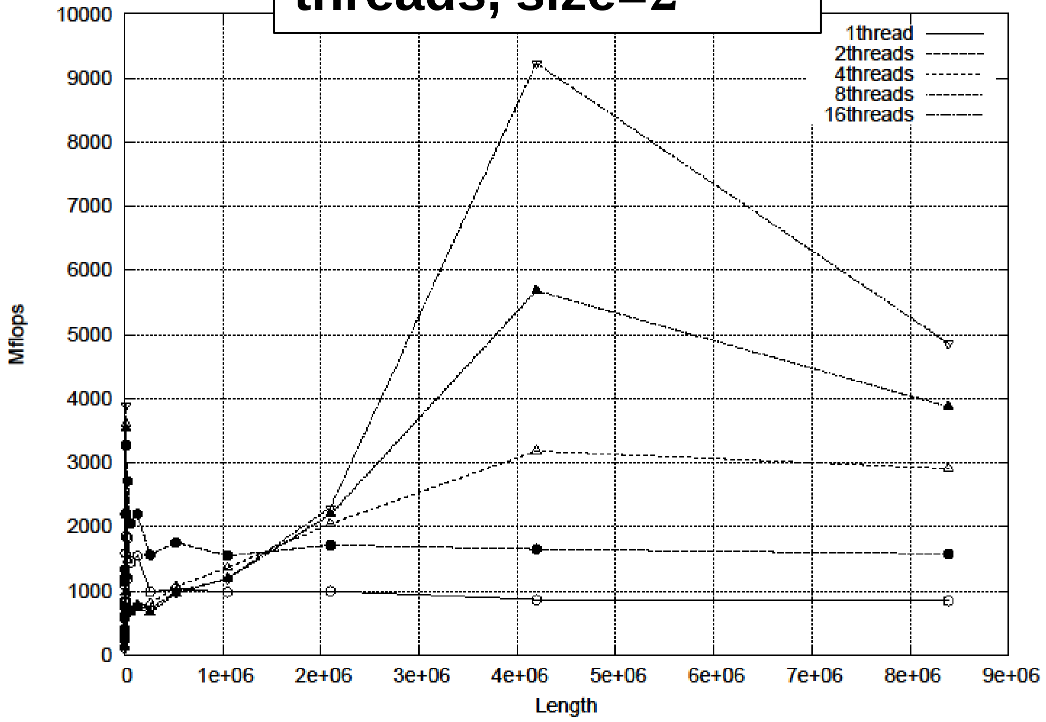
The EuroBen Benchmark Group provides benchmarks for the evaluation of the performance for scientific and technical computing on single processor cores and on parallel computers systems using standard parallel tool (OpenMP, MPI, ….) but also emerging standard (OpenCL, Cilk, …)

- Programs are available in Fortran and C
- The benchmark codes range from measuring the performance of basic operations and mathematical functions to skeleton applications.
- **Cineca started a new activity in the official PRACE framework to test and validate EuroBen benchmarks on Intel MIC architecture (V. Ruggiero-C.Cavazzoni).**

MOD2F benchmark

16 OpenMP threads, size=2^{22}

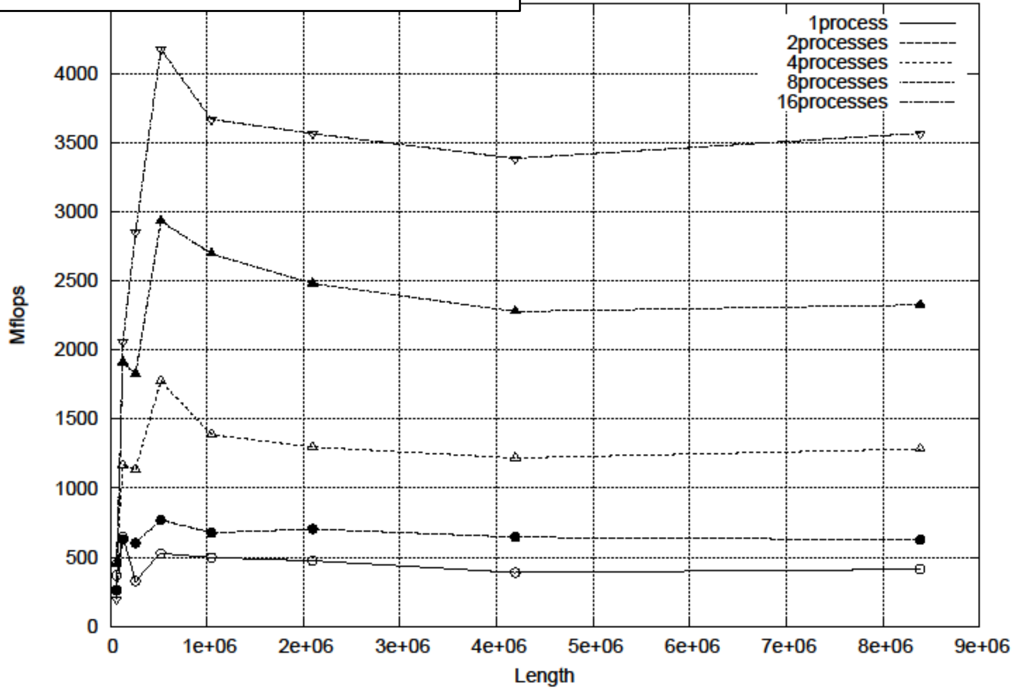
Host: Intel Xeon SandyBridge cores



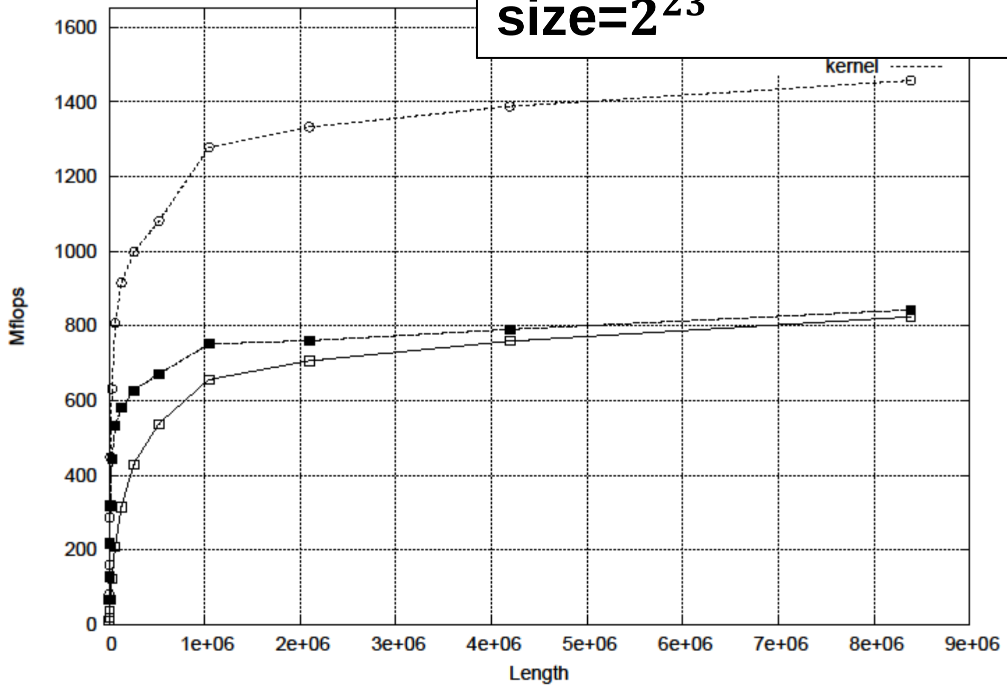
MOD2F benchmark

16 MPI process, size=2^{19}

Host: Intel Xeon SandyBridge cores



MOD2F benchmark



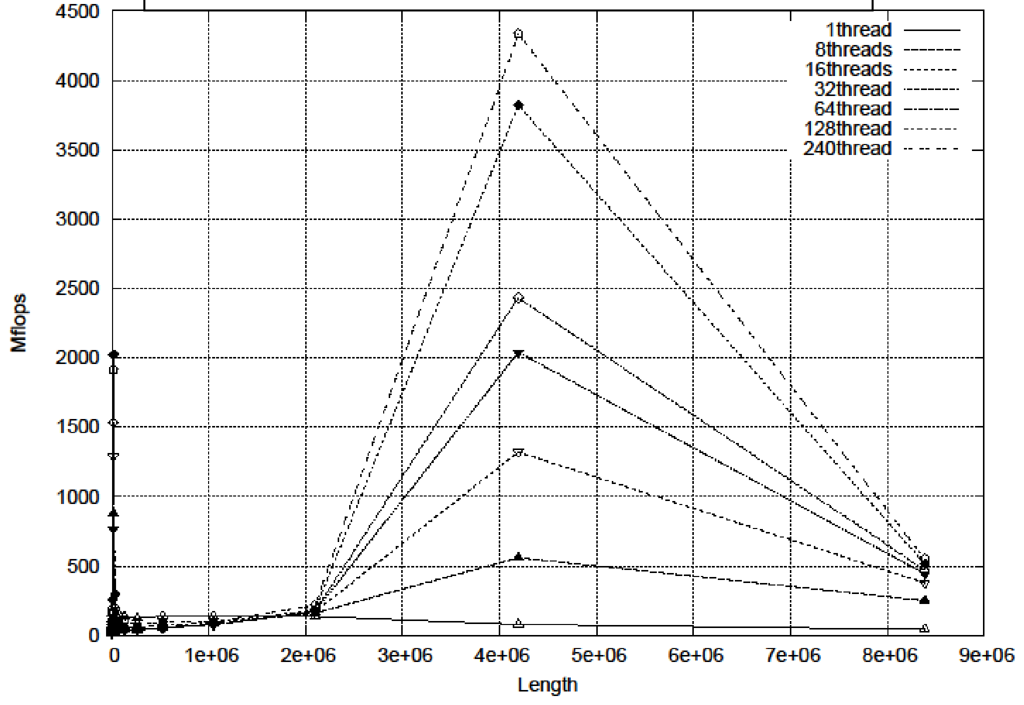
OpenCL, kernel only, size=2^{23}

Host: Intel Xeon SandyBridge cores

MOD2F benchmark

240 OpenMP threads, size=2^{22}

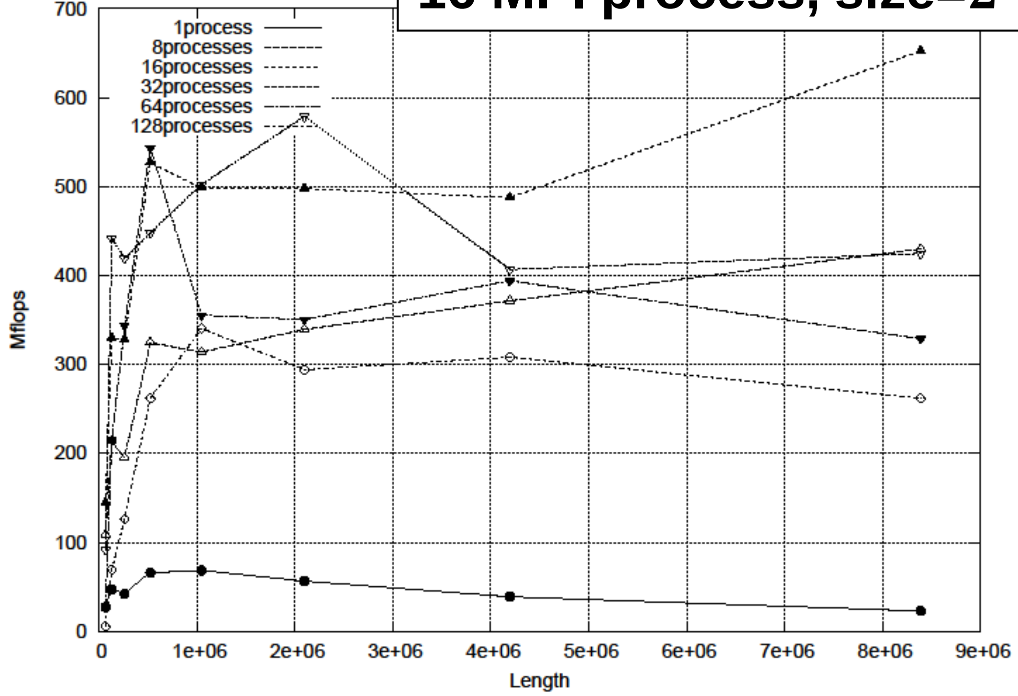
Native: Intel MIC, up to 240 hw threads



MOD2F benchmark

16 MPI process, size=2^{23}

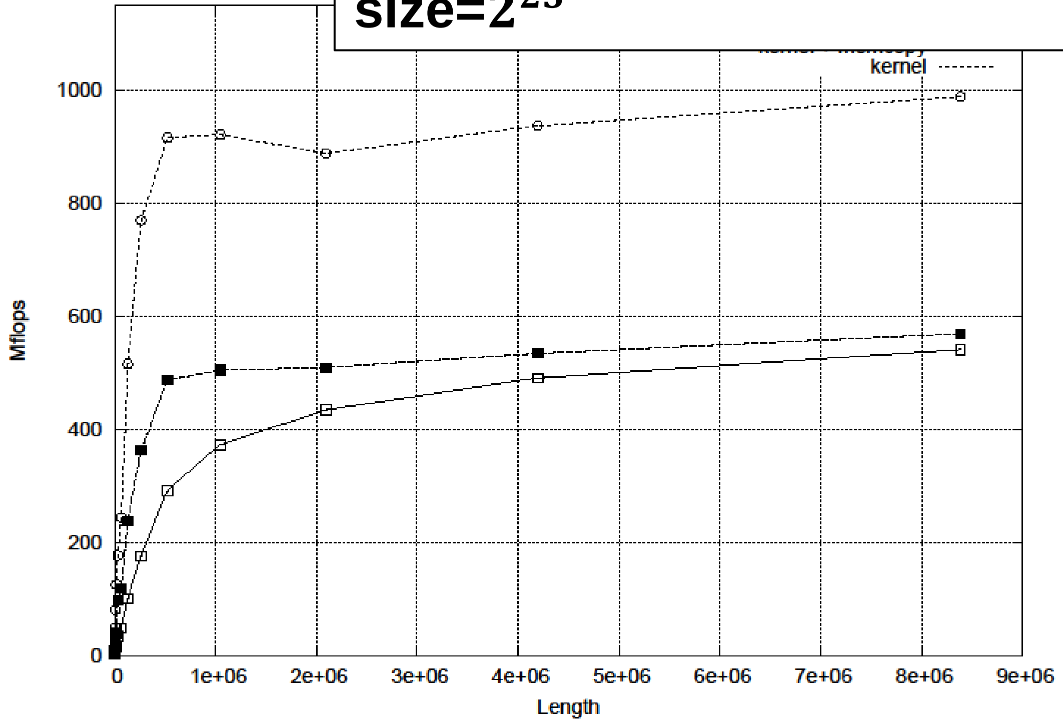
Native: Intel MIC, up to 240 hw threads



MOD2F benchmark

OpenCL, kernel only, size=2^{23}

Native: Intel MIC, up to 240 hw threads



How much fast? The EuroBen Benchmark results

- OpenCL performances are quite good (better than expected) both on host and device. OpenCL test is faster than MPI for native runs.
- Host<->device memory transfers are a potential bottlenecks for OpenCL.
- There is room for improvement…..OpenCL performance portability is always a challenge.

OpenCL live@Eurora

Eurora

- Eurora CINECA-Eurotech prototype
- 1 rack
- Two Intel SandyBridge and
- two NVIDIA K20 cards per node or:
- **Two Intel MIC card per node**
- Hot water cooling
- Energy efficiency record (up to 3210 MFLOPs/w)
- 100 TFLOPs sustained

Running environment

NVIDIA Tesla K20

- 13 Multiprocessors
- 2496 CUDA Cores
- 5 GB of global memory
- GPU clock rate 760MHz

Intel MIC Xeon Phi

- 236 compute units
- 8 GB of global memory
- CPU clock rate 1052 MHz

Setting up OpenCL on Eurora

- Login on front-end.

Then:

```
>module load profile/advanced
> module load intel_opencl/none--intel--cs-xe-2013--binary
```

It defines:

INTEL_OPENCL_INCLUDE

and

INTEL_OPENCL_LIB

environmental variables that can be used:

```
>cc –I$INTEL_OPENCL_INCLUDE -L$INTEL_OPENCL_LIB –lOpenCL vadd.c –o vadd
```

Running on Intel

```
PROFILE=FULL_PROFILE
VERSION=OpenCL 1.2 LINUX
NAME=Intel(R) OpenCL
VENDOR=Intel(R) Corporation
EXTENSIONS=cl_khr_fp64 cl_khr_global_int32_base_atomics
cl_khr_global_int32_extended_atomics cl_khr_local_int32_base_atomics
cl_khr_local_int32_extended_atomics cl_khr_byte_addressable_store
--0--
DEVICE NAME=       Intel(R) Xeon(R) CPU E5-2660 0 @ 2.20GHz
DEVICE VENDOR=Intel(R) Corporation
DEVICE VERSION=OpenCL 1.2 (Build 67279)
DEVICE_MAX_COMPUTE_UNITS=16
DEVICE_MAX_WORK_GROUP_SIZE=1024
DEVICE_MAX_WORK_ITEM_DIMENSIONS=3
DEVICE_MAX_WORK_ITEM_SIZES=1024 1024 1024
DEVICE_GLOBAL_MEM_SIZE=16685436928
--1--
DEVICE NAME=Intel(R) Many Integrated Core Acceleration Card
DEVICE VENDOR=Intel(R) Corporation
DEVICE VERSION=OpenCL 1.2 (Build 67279)
DEVICE_MAX_COMPUTE_UNITS=236
DEVICE_MAX_WORK_GROUP_SIZE=1024
DEVICE_MAX_WORK_ITEM_DIMENSIONS=3
DEVICE_MAX_WORK_ITEM_SIZES=1024 1024 1024
DEVICE_GLOBAL_MEM_SIZE=6053646336
--2--
DEVICE NAME=Intel(R) Many Integrated Core Acceleration Card
DEVICE VENDOR=Intel(R) Corporation
DEVICE VERSION=OpenCL 1.2 (Build 67279)
DEVICE_MAX_COMPUTE_UNITS=236
DEVICE_MAX_WORK_GROUP_SIZE=1024
DEVICE_MAX_WORK_ITEM_DIMENSIONS=3
DEVICE_MAX_WORK_ITEM_SIZES=1024 1024 1024
DEVICE_GLOBAL_MEM_SIZE=6053646336
Computed sum = 549754961920.0.
Check passed.
```

Intel OpenCL platform found and 3 devices (cpu and Intel MIC card)

Intel MIC device was selected

Results are OK no matter what performances

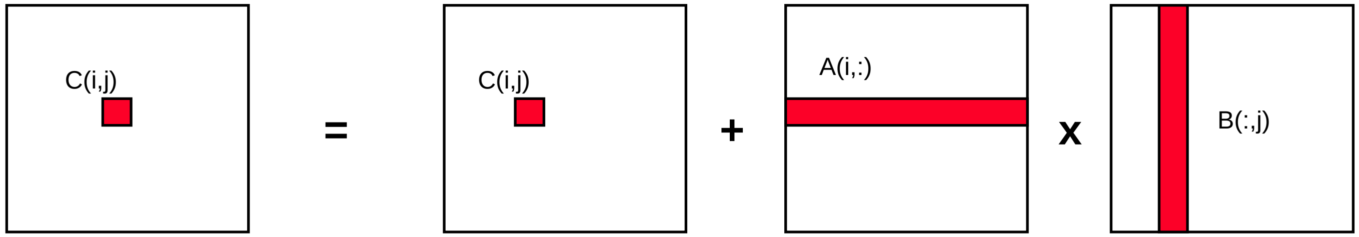
Exercise 1

- Goal:
  - To inspect and verify that you can run an OpenCL kernel on Eurora machines
- Procedure:
  - Take the provided C ***vadd.c*** and ***vadd.cl*** source programs from VADD directory
  - Compile and link ***vadd.c***
  - Run on NVIDIA or Intel platform.
- Expected output:
  - A message verifying that the vector addition completed successfully
  - Some useful info about OpenCL environment (Intel and NVIDIA)

Matrix multiplication: sequential code

```
void mat_mul(int Mdim, int Ndim, int Pdim,
                   float *A, float *B, float *C)
{
   int i, j, k;
   for (i = 0; i < Ndim; i++) {
      for (j = 0; j < Mdim; j++) {
         for (k = 0; k < Pdim; k++) {
            // C(i, j) = sum(over k) A(i,k) * B(k,j)
            C[i*Ndim+j] += A[i*Ndim+k] * B[k*Pdim+j];
         }
      }
   }
}
```

We calculate C=AB, dimA = (N x P), dimB=(P x M), dimC=(N x M)



Dot product of a row of A and a column of B for each element of C

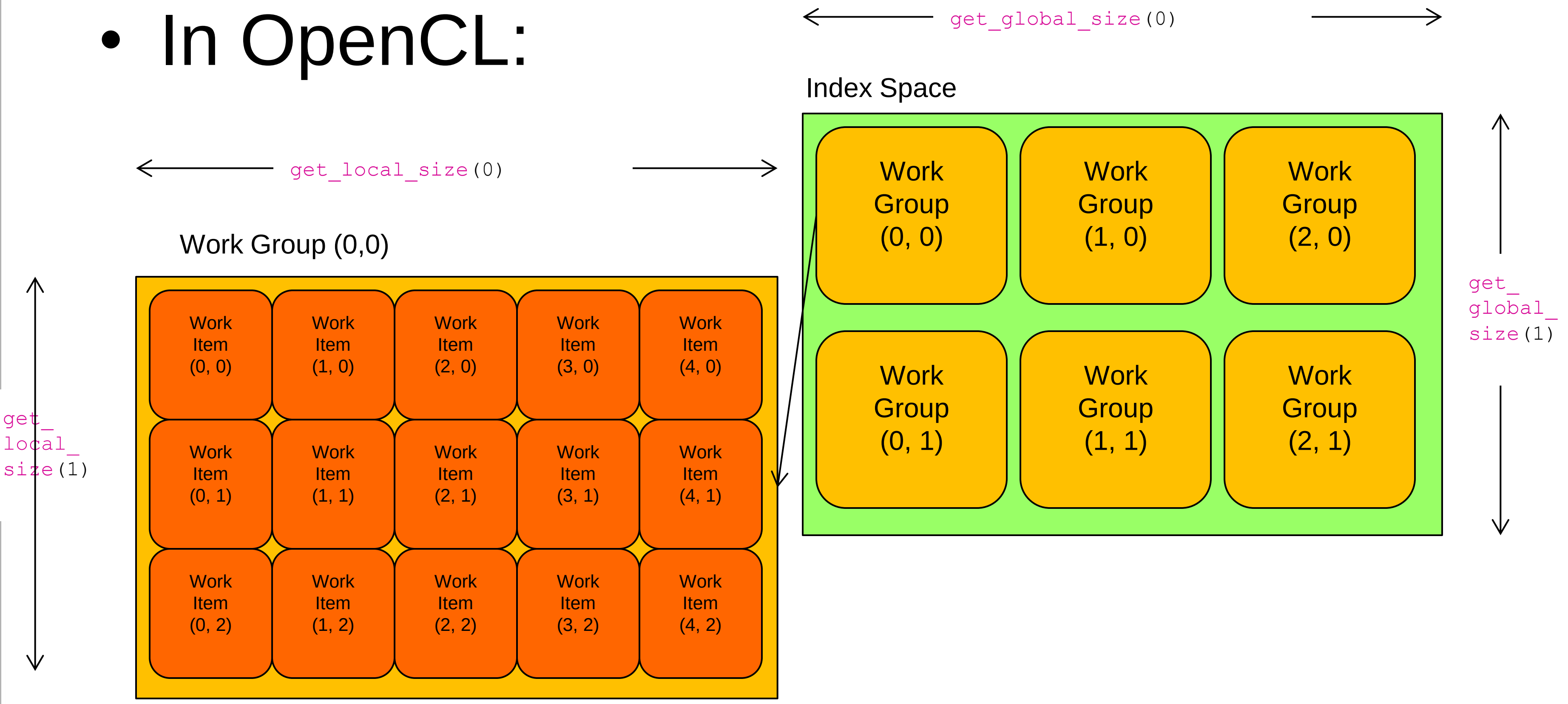
Matrix multiplication: sequential code

```
void mat_mul(int Mdim, int Ndim, int Pdim,
                   float *A, float *B, float *C)
{
   int i, j, k;
   for (i = 0; i < Ndim; i++) {
      for (j = 0; j < Mdim; j++) {
         for (k = 0; k < Pdim; k++) {
            // C(i, j) = sum(over k) A(i,k) * B(k,j)
            C[i*Ndim+j] += A[i*Ndim+k] * B[k*Pdim+j];
         }
      }
   }
}
```

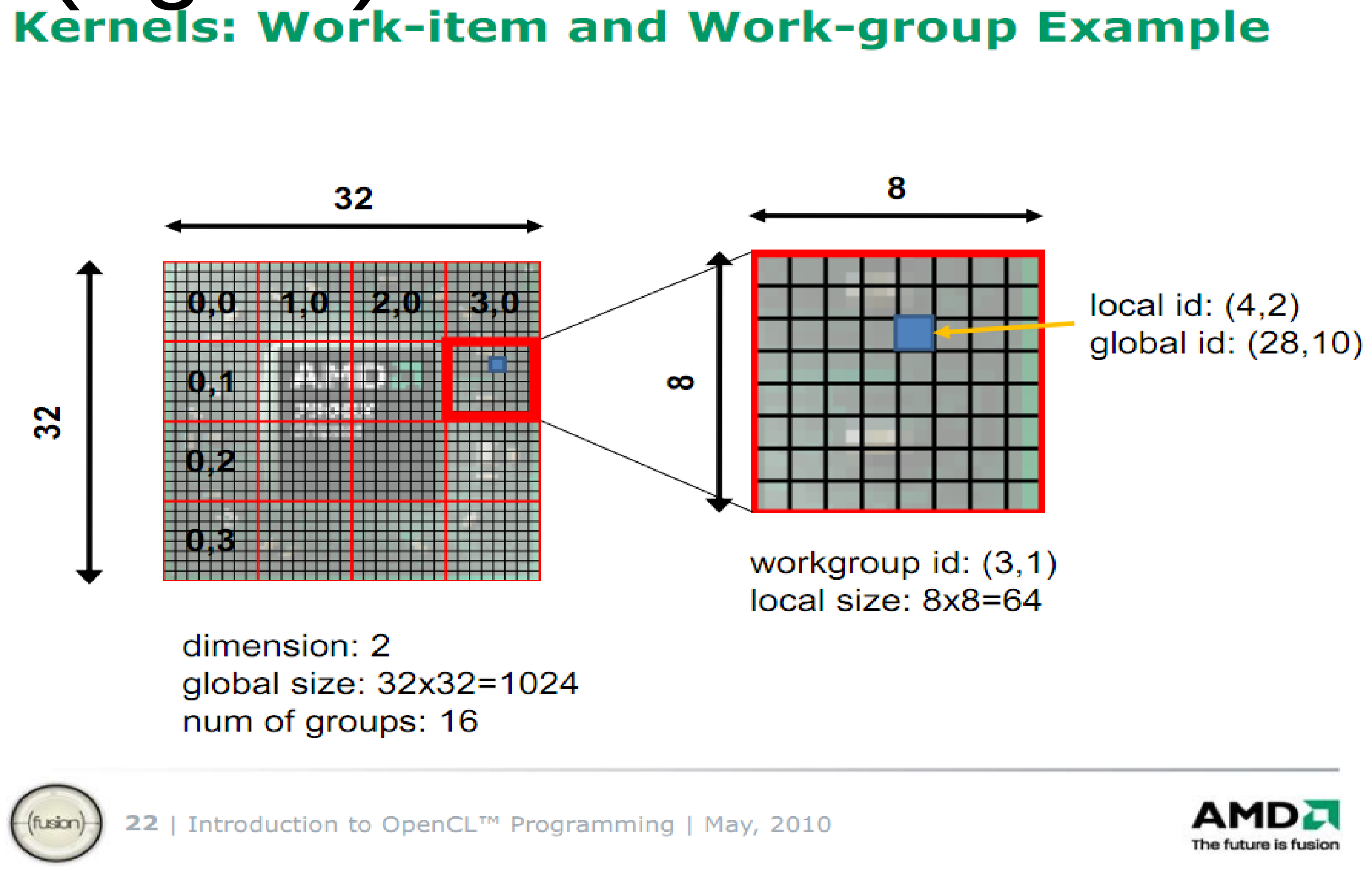
We turn this into an OpenCL kernel!

OpenCL mapping

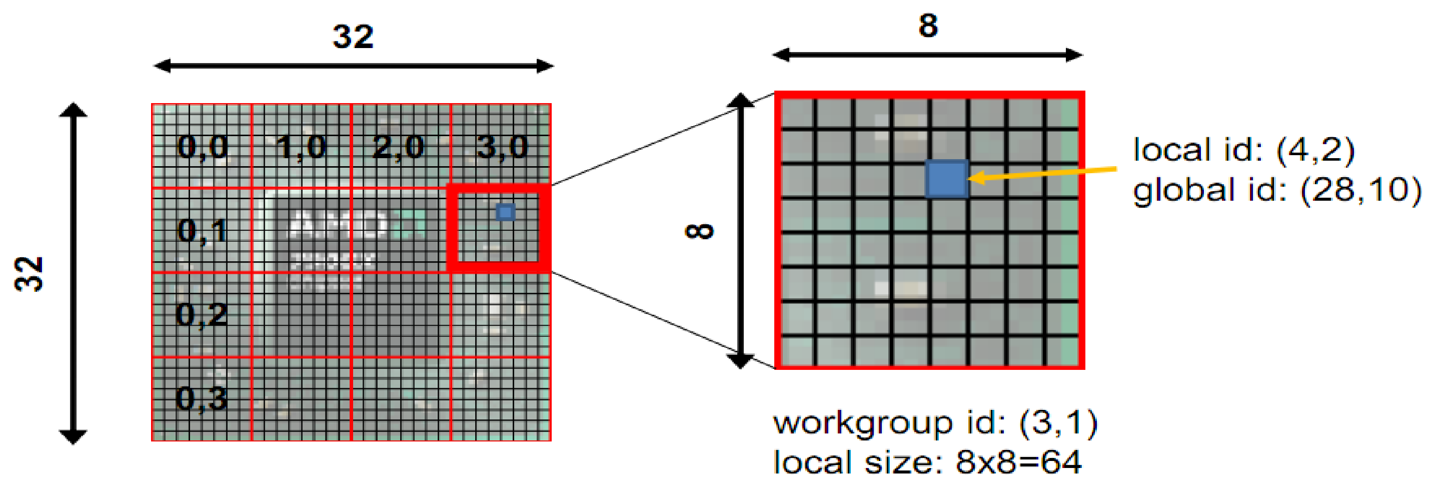
- In OpenCL:



OpenCL mapping (again)



Kernels: Work-item and Work-group Example



dimension: 2
global size: 32x32=1024
num of groups: 16

22 | Introduction to OpenCL™ Programming | May, 2010

AMD The future is fusion

Matrix multiplication: OpenCL kernel (1/2)

```
__kernel void mat_mul(
 const int Mdim, const int Ndim, const int Pdim,
 __global float *A, __global float *B, __global float *C)

{
    int i, j, k;
    for (i = 0; i < Ndim; i++) {
      for (j = 0; j < Mdim; j++) {
        // C(i, j) = sum(over k) A(i,k) * B(k,j)
        for (k = 0; k < Pdim; k++) {
          C[i*Ndim+j] += A[i*Ndim+k] * B[k*Pdim+j];
        }
      }
    }
}
```

Mark as a kernel function and specify memory qualifiers

Matrix multiplication: OpenCL kernel (2/2)

```
__kernel void mat_mul(
  const int Mdim, const int Ndim, const int Pdim,
  __global float *A, __global float *B, __global float *C)
{
   int i, j, k;
     i = get_global_id(0);
     j = get_global_id(1);
         for (k = 0; k < Pdim; k++) {
            // C(i, j) = sum(over k) A(i,k) * B(k,j)
            C[i*Ndim+j] += A[i*Ndim+k] * B[k*Pdim+j];
         }

   }
}
```

Remove outer loops and set work-item co-ordinates

Matrix multiplication: OpenCL kernel

```
__kernel void mat_mul(
 const int Mdim, const int Ndim, const int Pdim,
 __global float *A, __global float *B, __global float *C)
{
    int i, j, k;
    i = get_global_id(0);
    j = get_global_id(1);
    // C(i, j) = sum(over k) A(i,k) * B(k,j)
    for (k = 0; k < Pdim; k++) {
      C[i*Ndim+j] += A[i*Ndim+k] * B[k*Pdim+j];
    }
}
```

Matrix multiplication: OpenCL kernel improved

Rearrange and use a local scalar for intermediate C element values (a common optimization in Matrix Multiplication functions)

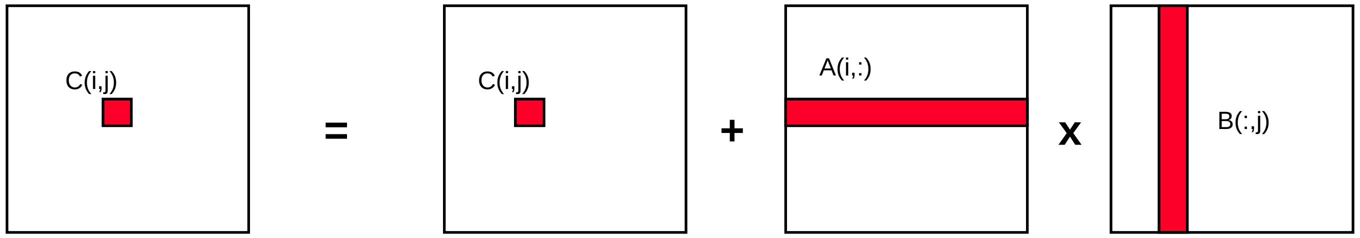
```
__kernel void mat_mul(
   const int Mdim,
   const int Ndim,
   const int Pdim,
   __global float *A,
   __global float *B,
   __global float *C)
{
  int k;
  int i = get_global_id(0);
  int j = get_global_id(1);
  float tmp = 0.0f;
  for (k = 0; k < Pdim; k++)
   tmp += A[i*Ndim+k]*B[k*Pdim+j];
  }
  C[i*Ndim+j] += tmp;
}
```

Exercise 2

- Goal:
  - To inspect and verify that you can run the first mat_mul OpenCL kernels
- Procedure:
  - Take the provided C ***mat_mul.c.1*** source program.
  - Look at the host code and identify the API calls in the host code. Compare them against the vadd source code.
  - Try to understand regions where timing the execution, profiling and error checks.
  - Compile and link ***mat_mul.c*** on front-end.
  - Run ***both mat_mul.cl.1 and mat_mul.cl.1.1*** kernels.
  - Compare results
- Expected output:
  - A message verifying that the matrix multiply succeeded, GFLOPS and time results (if activated)

Optimizing matrix multiplication

- MM cost determined by FLOPS and memory movement:
  - $2*n^3 = O(n^3)$ FLOPS
  - Operates on $3*n^2 = O(n^2)$ numbers
- To optimize matrix multiplication, we must ensure that for every memory access we execute as many FLOPS as possible.
- Outer product algorithms are faster, but for pedagogical reasons, let's stick to the simple dot-product algorithm.

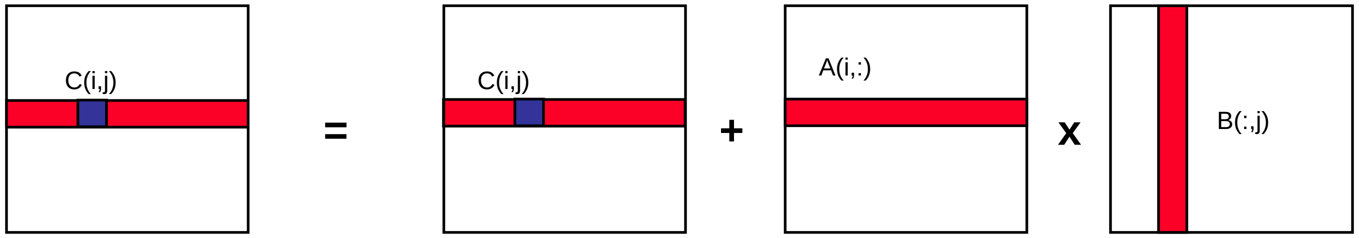


Dot product of a row of A and a column of B for each element of C

- **We will work with work-item/work-group sizes and the memory model to optimize matrix multiplication**

Optimizing matrix multiplication

- There may be significant overhead to manage work-items and work-groups.
- So let’s have each work-item compute a full row of C



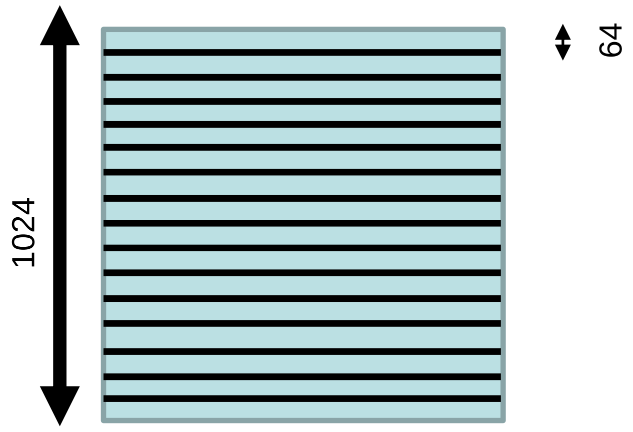
Dot product of a row of A and a column of B for each element of C

An N-dimension domain of work-items

- Global Dimensions: 1024 (1D)

  Whole problem space (index space)
- Local Dimensions: 16 (work-items per work-group)

  1024/64 = 64 work-groups in total



Reduce work-item overhead

```
__kernel void mmul(
 const int Mdim, const int Ndim, const int Pdim,
 __global float *A, __global float *B, __global float *C)
{
    int k, j;
     int i = get_global_id(0);
    float tmp;
    for (j = 0; j < Mdim; j++) {
        // Mdim is width of rows in C
        tmp = 0.0f;
        for (k = 0; k < Pdim; k++)
            tmp += A[i*Ndim+k] * B[k*Pdim+j];
        C[i*Ndim+j]  += tmp;
    }
}
```

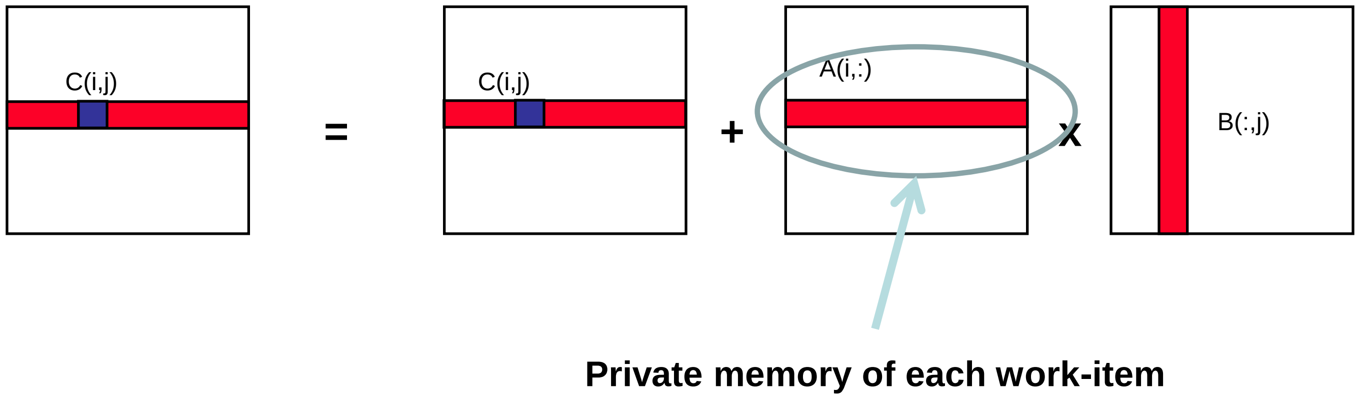
Do a whole row of C per work-item

Exercise 3

- Goal:
  - To inspect and verify that you can run the second mat_mul OpenCL kernel
- Procedure:
  - Take the provided *C* ***mat_mul.c.0*** host program and compare against the previous mat_mul source code.
  - Take the ***mat_mul.cl.0*** kernel from SKEL directory.
  - Insert the correct call, compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - A message verifying that the mat_mul completed successfully

Optimizing matrix multiplication

- Notice that, in one row of C, each element reuses the same row of A.
- Let’s copy that row of A into private memory of the work-item that’s (exclusively) using it to avoid the overhead of loading it from global memory for each C(i,j) computation.



Matrix multiplication: OpenCL kernel (3/3)

```
__kernel void mat_mul(
    const int Mdim,
    const int Ndim,
    const int Pdim,
    __global float *A,
    __global float *B,
    __global float *C)
{
  int k, j;
  int i = get_global_id(0);
  float Awrk[1024];
  float tmp;
  for (k = 0; k < Pdim; k++)
      Awrk[k] = A[i*Ndim+k];
  for (j = 0; j < Mdim; j++) {
     tmp = 0.0f;
     for (k = 0; k < Pdim; k++)
        tmp += Awrk[k]*B[k*Pdim+j];
     C[i*Ndim+j] += tmp;
  }
}
```

Setup a work array for A in private memory and copy into it from global memory before we start with the matrix multiplications.

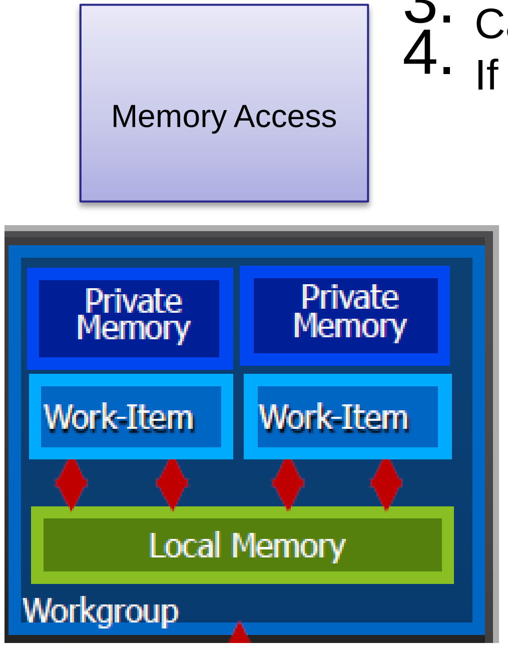
(Actually, this is using ***far*** more private memory than we'll have and so Awrk[] will be spilled to global memory)

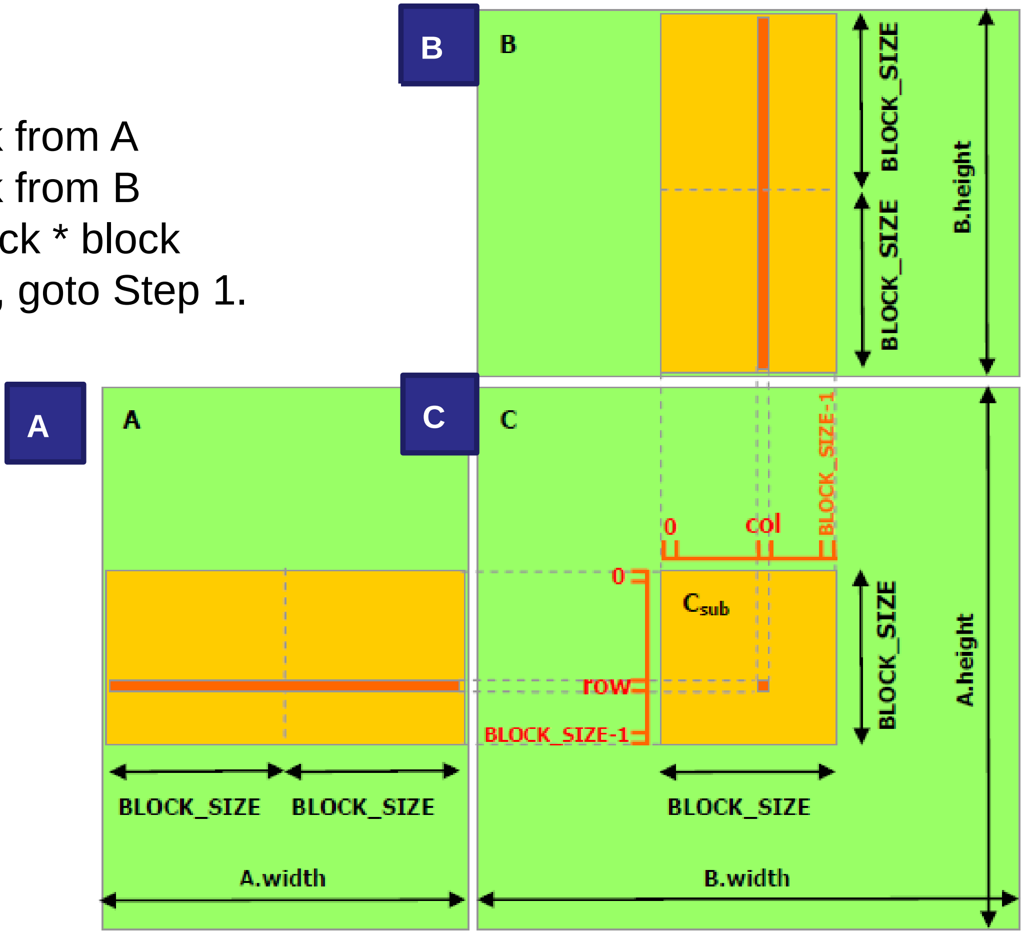
Exercise 4

- Goal:
  - To inspect and verify that you can run the third mat_mul OpenCL kernel
- Procedure:
  - Take the provided C ***mat_mul.c.00*** host program.
  - Take ***the mat_mul.cl.00*** kernel from SKEL directory.
  - Insert the correct calls, compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - A message verifying that the mat_mul completed successfully

Matrix Multiplication: using Local Memory

1. Move a block from A
2. Move a block from B
3. Calculate block * block
4. If no finished, goto Step 1.





MM using Local Memory (2)

```
#define BLOCK_SIZE 16
__kernel void mat_mul(
 const int wA, const int wB, const int hA,
 __global float *A, __global float *B, __global float *C)
{
    // Block index
    int tx = get_local_id(0);
    int ty = get_local_id(1);
    int bx = get_group_id(0);
    int by = get_group_id(1);

    // Index of the first sub-matrix of A processed
    // by the block
//Coalesced
    int indexA=by*BLOCK_SIZE*wA+ty*wA+tx;
    int indexB=bx*BLOCK_SIZE+ty*wB+tx;
    float Csub=0.0f;
```

1. Move a block from A.

2. Move a block from B.

```
// Loop over all the sub-matrices of A and B
    // required to compute the block sub-matrix
    for (int m =0;m<wA/BLOCK_SIZE;m++)
    {
        // Declaration of the local memory array As
        // used to store the sub-matrix of A
        __local float As[BLOCK_SIZE][BLOCK_SIZE];
        // Declaration of the local memory array Bs
        // used to store the sub-matrix of B
        __local float Bs[BLOCK_SIZE][BLOCK_SIZE];
        // Load the matrices from global memory
        // to local memory; each thread loads
        // one element of each matrix
         As[ty][tx] = A[indexA];
         Bs[ty][tx] = B[indexB];
            indexA+=BLOCK_SIZE;
            indexB+=wB*BLOCK_SIZE;
        // Synchronize to make sure the matrices
        // are loaded
        barrier(CLK_LOCAL_MEM_FENCE);
```

Matrix Multiplication: using Local Memory (3)

```
// Multiply the two matrices together;
        // each thread computes one element
        // of the block sub-matrix
        for (int k = 0; k < BLOCK_SIZE; ++k)
            Csub += As[ty][k] * Bs[k][tx];
        // Synchronize to make sure that the preceding
        // computation is done before loading two new
        // sub-matrices of A and B in the next iteration
        barrier(CLK_LOCAL_MEM_FENCE);
    }
    // Write the block sub-matrix to device memory;
    // each thread writes one element
    int
       indexC=wB*BLOCK_SIZE*by+BLOCK_SIZE*bx+wB*ty+tx;
    C[indexC] = Csub;
}
```

3. Calculate block * block.

Exercise 5

- Goal:
  - To inspect and verify that you can run the fourth mat_mul OpenCL kernel
- Procedure:
  - Take the provided C ***mat_mul.c.3*** host program.
  - Take the ***mat_mul.cl.3*** kernel from SKEL directory.
  - Insert the correct calls, compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - A message verifying that the mat_mul completed successfully

Exercise 5 (again)

- Additional Goal:
  - To inspect and verify the performances of this mat_mul OpenCL kernel
- Procedure:
  - Take the ***mat_mul.cl.3uncoalesced*** kernel from SOURCE directory.
  - Compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - You should verify performance degradation. Why?

From work-group to hw threads

- OpenCL kernels are structured into work groups that map to device compute units.
- Compute units on GPUs consist of SIMT processing elements.
- Hw creates ***wavefronts (warps)*** grouping threads of a WG (dimension zero first).
- All threads in a wavefront execute the same instruction.
- Thead mapping determine which thread access which data!
  - ❑ Proper mapping can align to hw (greater performances)
  - ❑ Improper mapping can be disastrous

Thread mapping

- To ensure coalesced accesses consecutive threads in a warp should be mapped to columns of B and C.

```
__kernel void mat_mul(
 const int Mdim, const int Ndim, const int Pdim,
 __global float *A, __global float *B, __global float *C)
{
    int i, j, k;
    i = get_global_id(0);
    j = get_global_id(1);
    for (k = 0; k < Pdim; k++) {
      C[i][j] += A[i][k] * B[k][j];
    }
}
```

Consecutive threads (i) are mapped to different rows of matrix C

Highly inefficient memory access

Thread mapping

- To ensure coalesced accesses consecutive threads in a warp should be mapped to columns of B and C.

```
__kernel void mat_mul(
 const int Mdim, const int Ndim, const int Pdim,
 __global float *A, __global float *B, __global float *C)
{
   int i, j, k;
   i = get_global_id(0);
   j = get_global_id(1);
   for (k = 0; k < Pdim; k++) {
     C[j][i] += A[j][k] * B[k][i];
   }
}
```

Consecutive threads (i) are mapped to consecutive rows of matrices B and C

Highly efficient memory access

Making matrix multiplication really fast

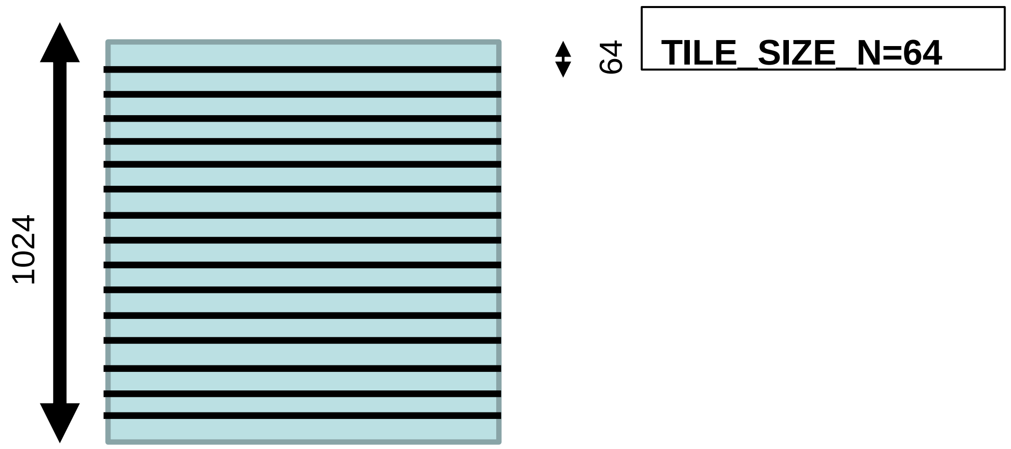
- Tiled (or blocked) algorithm can improves data reuse on architectures where at least two memory hierarchies exist:

1. **Slow and big memory**
2. **Fast but small memory**

- To utilize it, try to maximize data reuse, so instead of producing one element of C, compute a block.

An 2-dimension domain of tiles

- **For example:total number of tiles in N direction: 1024**
- This number is equal to 16 (work-items per work-group size in one dimension) * 64 (TILE_SIZE_N parameter)



TILE_GROUP_N=16

Blocked (Tiled) Matrix Multiply

Consider A,B,C to be divided into blocks (tilings) along the two dimensions.

```
          for i = 0 to NUM_OF_TILES_M-1
             for j = 1 to NUM_OF_TILES_N-1
       C_BLOCK=ZERO_MATRIX(TILE_SIZE_M,TILE_SIZE_N);
       for k = 0 to size-1
                  for ib = 0 to TILE_SIZE_M-1
                         for jb = 0 to TILE_SIZE_N-1
       C_BLOCK(jb,ib)=C_BLOCK(jb,ib)+A(k,i*TILE_SIZE_M+ib)*B(j*TILE_SIZE_N+jb,k)
                         end for
                     end for
       end for
               for ib = 0 to TILE_SIZE_M -1
                     for jb = 0 to TILE_SIZE_N -1
                           C(j*TILE_SIZE_M+jb,i*TILE_SIZE_N+ib) = C_BLOCK(jb,ib)
                           end for
                end for
           end for
        end for
```

TILE_SIZE_N*TILE_SIZE_M being the number of elements of matrix C computed by one work-item

Blocked (Tiled) Matrix Multiply

Consid (tilings) along the tw

```
int Aind = …
int Bind = …

Int Cind = …
```

```
C_BLOCK=ZERO_MATRIX(TILE_SIZE_M,TILE_SIZE_N);
for k = 0 to size-1
        for ib = 0 to TILE_SIZE_M-1
             for jb = 0 to TILE_SIZE_N-1
C_BLOCK(jb,ib)=C_BLOCK(jb,ib)+A(k,i*TILE_SIZE_M+ib)*B(j*TILE_SIZE_N+jb,k)
             end for
          end for
end for
      for ib = 0 to TILE_SIZE_M -1
          for jb = 0 to TILE_SIZE_N -1
              C(j*TILE_SIZE_M+jb,i*TILE_SIZE_N+ib) = C_BLOCK(jb,ib)
              end for
       end for
```

TILE_GROUP_N and TILE_GROUP_M being the zero and one dimension of local work-group size

size/TILE_SIZE_N and size/TILE_SIZE_M being the zero and one dimension of NDRange

Exercise 6

- Goal:
  - To inspect and verify that you can run the fifth mat_mul OpenCL kernel
- Procedure:
  - Take the provided C ***mat_mul.c.4*** host program.
  - Take the ***mat_mul.cl.4*** kernel from SKEL directory.
  - Insert the correct calls, compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - A message verifying that the mat_mul completed successfully

Exercise 6 (again)

- Additional Goal:
  - To inspect and verify the performances of this mat_mul OpenCL kernel
- Procedure:
  - Play with TILE* parameters and matrix size.
  - Compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - You should verify very exciting performance on Intel MIC. Why?

Summer School on PARALLEL COMPUTING

OpenCL on Intel MIC

- Tremendous computing power available (236 compute units…)
- More than 1 TFLOPs peak for double precision computation
- You should understand how to optimize OpenCL code in order to reach peak performances

Is Intel MIC, not a Pentium 4

Intel MIC architecture

- Intel MIC architecture targets highly parallel and computationally intensive applications. Three basic factors:

1. **Threading scalability (60+ Intel CPU cores in a single chip)**
2. **Vectorization (wide vector registers and associated SIMD operations)**
3. **Memory bandwidth utilization**

OpenCL on Intel MIC

- Intel MIC combines many core onto a single chip. Each core runs exactly **4 hardware threads**. In particular:

1. **All cores/threads are a single OpenCL device**
2. **Separate hardware threads are OpenCL CU.**

- In the end, you'll have parallelism at the work-group level (vectorization) and parallelism between work-groups (threading).

OpenCL on Intel MIC

- To reach performances, the number of work-groups should be not less than ***CL_DEVICE_MAX_COMPUTE_UNITS*** parameter (more is better)
- Again, automatic vectorization module should be fully utilized. This module:
  - ❑ packs adiacent work-items (from dimension 0 of NDRange)
  - ❑ executes them with SIMD instructions
- Use the recommended work-group size as multiple of 16 (SIMD width for float, int, …data type).

OpenCL on Intel MIC

- Memory bandwidth should be saturated. Use
  - ❑ Prefetching
  - ❑ Blocking (tiling)
  - ❑ Data structures layout optimized
- All aforementioned techniques have already been applied to matrix multiply kernel, resulting in extreme performances on Intel MIC device.

More than 400 GFLOPs for SGEMM

Himeno Benchmark

- Dr. Ryutaro Himeno, Director of the Advanced Center for Computing and Communication, has developed this benchmark to evaluate performance of incompressible fluid analysis code.
- This benchmark takes measurements to proceed major loops in solving the Poisson's equation solution using the Jacobi iteration method.
- Being the code very simple and easy to compile and to execute, users can measure actual speed (in MFLOPS) immediately on different machines and languages/tools (C, Fortran, OpenMP, MPI, …).
- The most computational part of Himeno Benchmark is restricted to **Jacobi** routine.
- **A simple OpenCL version of Himeno Benchmark was realized in order to test performances on NVIDIA and Intel Platforms.**

Jacobi routine: sequential code

```
Float jacobi(int nn,int MIMX,int MJMX,int MKMX,int imax,int
jmax,int kmax,float* a1,float* a2,float* a3,float* a4,float* b1,float*
b2,float* b3,float* c1,float* c2,float* c3,float* p,float* wrk1,float*
bnd,float* wrk2)
{
#define idxz(i,j,k) ((k)+MKMX*((j)+MJMX*(i)))
  int i,j,k,n;
  float gosa, s0, ss;
  for(n=0 ; n<nn ; ++n){
    gosa = 0.0;
for(i=1 ; i<imax-1 ; i++)
      for(j=1 ; j<jmax-1 ; j++)
        for(k=1 ; k<kmax-1 ; k++){
          s0 = a1[idxz(i,j,k)] * p[idxz(i+1,j,k)]
             + a2[idxz(i,j,k)] * p[idxz(i,j+1,k)]
             + a3[idxz(i,j,k)] * p[idxz(i,j,k+1)]
             + b1[idxz(i,j,k)] * ( p[idxz(i+1,j+1,k)] - p[idxz(i+1,j-1,k)]
                              - p[idxz(i-1,j+1,k)  ] + p[idxz(i-1,j-1,k)  ] )
             + b2[idxz(i,j,k)] * ( p[idxz(i,j+1,k+1)] - p[idxz(i,j-1,k+1)]
                               - p[idxz(i,j+1,k-1)] + p[idxz(i,j-1,k-1)] )
             + b3[idxz(i,j,k)] * ( p[idxz(i+1,j,k+1)] - p[idxz(i-1,j,k+1)]
                               - p[idxz(i+1,j,k-1)] + p[idxz(i-1,j,k-1)] )
             + c1[idxz(i,j,k)] * p[idxz(i-1,j,k)  ]
             + c2[idxz(i,j,k)] * p[idxz(i,j-1,k)  ]
             + c3[idxz(i,j,k)] * p[idxz(i,j,k-1)]
             + wrk1[idxz(i,j,k)];
          ss = ( s0 * a4[idxz(i,j,k)] - p[idxz(i,j,k)] ) * bnd[idxz(i,j,k)];
          gosa+= ss*ss;

   wrk2[idxz(i,j,k)] = p[idxz(i,j,k)] + omega * ss;

      }
    for(i=1 ; i<imax-1 ; ++i)
      for(j=1 ; j<jmax-1 ; ++j)
        for(k=1 ; k<kmax-1 ; ++k)
          p[idxz(i,j,k)] = wrk2[idxz(i,j,k)];


     } /* end n loop */


  return(0);
}
```

Jacobi routine: OpenCL kernel

```
Float jacobi(int nn,int MIMX,int MJMX,int MKMX,int imax,int
jmax,int kmax,float* a1,float* a2,float* a3,float* a4,float* b1,float*
b2,float* b3,float* c1,float* c2,float* c3,float* p,float* wrk1,float*
bnd,float* wrk2)
{
#define idxz(i,j,k) ((k)+MKMX*((j)+MJMX*(i)))
  int i,j,k,n;
  float gosa, s0, ss;
  for(n=0 ; n<nn ; ++n){
```

```
int I=get_global_id(0);
int J=get_global_id(1);
int K=get_global_id(2);
```

```
           + a2[idxz(i,j,k)] * p[idxz(i,j+1,k)]
           + a3[idxz(i,j,k)] * p[idxz(i,j,k+1)]
           + b1[idxz(i,j,k)] * ( p[idxz(i+1,j+1,k)] - p[idxz(i+1,j-1,k)]
                         - p[idxz(i-1,j+1,k)  ] + p[idxz(i-1,j-1,k)  ] )
           + b2[idxz(i,j,k)] * ( p[idxz(i,j+1,k+1)] - p[idxz(i,j-1,k+1)]
                          - p[idxz(i,j+1,k-1)] + p[idxz(i,j-1,k-1)] )
           + b3[idxz(i,j,k)] * ( p[idxz(i+1,j,k+1)] - p[idxz(i-1,j,k+1)]
                          - p[idxz(i+1,j,k-1)] + p[idxz(i-1,j,k-1)] )
           + c1[idxz(i,j,k)] * p[idxz(i-1,j,k)  ]
           + c2[idxz(i,j,k)] * p[idxz(i,j-1,k)  ]
           + c3[idxz(i,j,k)] * p[idxz(i,j,k-1)]
           + wrk1[idxz(i,j,k)];
         ss = ( s0 * a4[idxz(i,j,k)] - p[idxz(i,j,k)] ) * bnd[idxz(i,j,k)];
         gosa+= ss*ss;
```

```
  wrk2[idxz(i,j,k)] = p[idxz(i,j,k)] + omega * ss;
```

```
int I=get_global_id(0);
int J=get_global_id(1);
int K=get_global_id(2);
```

```
      p[idxz(i,j,k)] = wrk2[idxz(i,j,k)];

    }
```

Swap kernel

```
  return(0);
}
```

Exercise 7

- Goal:
  - To inspect and verify that you can run the Himeno Benchmark (OpenCL version)
- Procedure:
  - Take the provided C ***himenoBMTxps.c*** host program.
  - Take the provided OpenCL ***initmt.cl*** kernel from SOURCES directory
  - Take the ***swap.cl*** and ***update.cl*** kernels from SKEL directory.
  - Insert the correct calls, compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - A message verifying that the Himeno Benchmark completed successfully

Exercise 7 (again)

- Additional Goal:
  - To inspect and verify the performances of Himeno Benchmark OpenCL
- Procedure:
  - Play with LOCAL WORK-GROUPS parameter and input size.
  - Compile and link.
  - Run on NVIDIA and Intel plaform.
- Expected output:
  - You should verify correctness and performances on NVIDIA and Intel MIC.

Himeno Benchmark on Intel MIC

- Hardware prefetching is enabled by default on Intel MIC (from GDDR to L2 cache).
- Compiler insert prefetch instructions into assembly based on kernel code analysis (automatic prefetching).
  - ❑ Variables in global and constant address spaces.
  - ❑ Well detected memory access pattern
- **Auto Prefetching level is enabled by default. Can be changed using *"-auto-prefetch-level=0/1/2/3"* option argument of *clBuildProgram()* API call.**

Exercise 7 (again)

- Additional Goal:
  - To inspect and verify the performances of Himeno Benchmark OpenCL using different manual and auto-prefetching levels.
- Procedure:
  - Play with different auto-prefetching levels.
  - Try to insert prefetch built-in into update.cl source code.
  - Compile and link.
  - Run on Intel plaform.
- Expected output:
  - You should verify correctness and performances Intel MIC.

Conclusions

- Nine (9) things we missed during this presentation….
  - **Vector data types, …**
  - **Events, …**
  - **C++ interface, Python interface, Fortran interface** (via Ompss runtime)
  - **Profiling**
  - **Debugging**
  - **Porting CUDA code to OpenCL**
  - **OpenCL 2.0 and beyond**

Conclusions

And Six (6) things we won't miss to say….

- OpenCL is an **open** standard, which is targeted for **portability** on **heterogeneous** devices (GPUs, AMD, Intel MIC,…)
- OpenCL has widespread **industrial support**
- OpenCL is the **only** parallel programming standard that enables mixing **task parallel** and **data parallel** code in a single program while load balancing across ALL of the platform's available resources
- To reach its full potential, however, OpenCL needs to deliver **Performance portability**.
- OpenCL gives users the chance to efficiently use native **SIMD engines** (like vector units) of CPUs, accelerators, ….
- OpenCL will help you use **existing and future devices** increasingly provide tremendous computing power at a **reduced energy-requirement and price**

References

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