



# **OpenCL**

## **Parallel Computing for Heterogeneous Devices**

# **Welcome to OpenCL**

- **With OpenCL you can...**
- **Leverage CPUs, GPUs, other processors such as Cell/B.E. processor and DSPs to accelerate parallel computation**
- **Get dramatic speedups for computationally intensive applications**
- **Write accelerated portable code across different devices and architectures**

# What You'll Learn

- **What is OpenCL?**
  - Design Goals
  - The OpenCL Platform, Execution and Memory Model
- **How to use OpenCL**
  - Setup
  - Resource Allocation
  - Execution and Synchronization
- **Programming with OpenCL C**
  - Language Features
  - Built-in Functions



# **What Is OpenCL?**

# Design Goals of OpenCL

- **Use all computational resources in system**
  - CPUs, GPUs, and other processors as peers
  - Data- and task- parallel compute model
- **Efficient parallel programming model**
  - Based on C99
  - Abstract the specifics of underlying hardware
- **Specify accuracy of floating-point computations**
- **Desktop and Handheld Profiles**

# OpenCL Platform Model

- A host connected to one or more OpenCL devices
- An OpenCL device is a collection of one or more compute units (**cores**)
  - A compute unit is composed of one or more processing elements
  - Processing elements execute code as SIMD or SPMD

# OpenCL Execution Model

- **Kernel**
  - Basic unit of executable code - similar to a C function
  - Data-parallel or task-parallel
- **Program**
  - Collection of kernels and other functions
  - Analogous to a dynamic library
- **Applications queue kernel execution instances**
  - Queued in-order
  - Executed in-order or out-of-order

# Expressing Data-Parallelism in OpenCL

- **Define N-dimensional computation domain (N = 1, 2 or 3)**
  - Each independent element of execution in N-D domain is called a work-item
  - The N-D domain defines the total number of work-items that execute in parallel
- **E.g., process a 1024 x 1024 image: Global problem dimensions: 1024 x 1024 = 1 kernel execution per pixel: 1,048,576 total kernel executions**

## Scalar

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



## Data Parallel

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

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

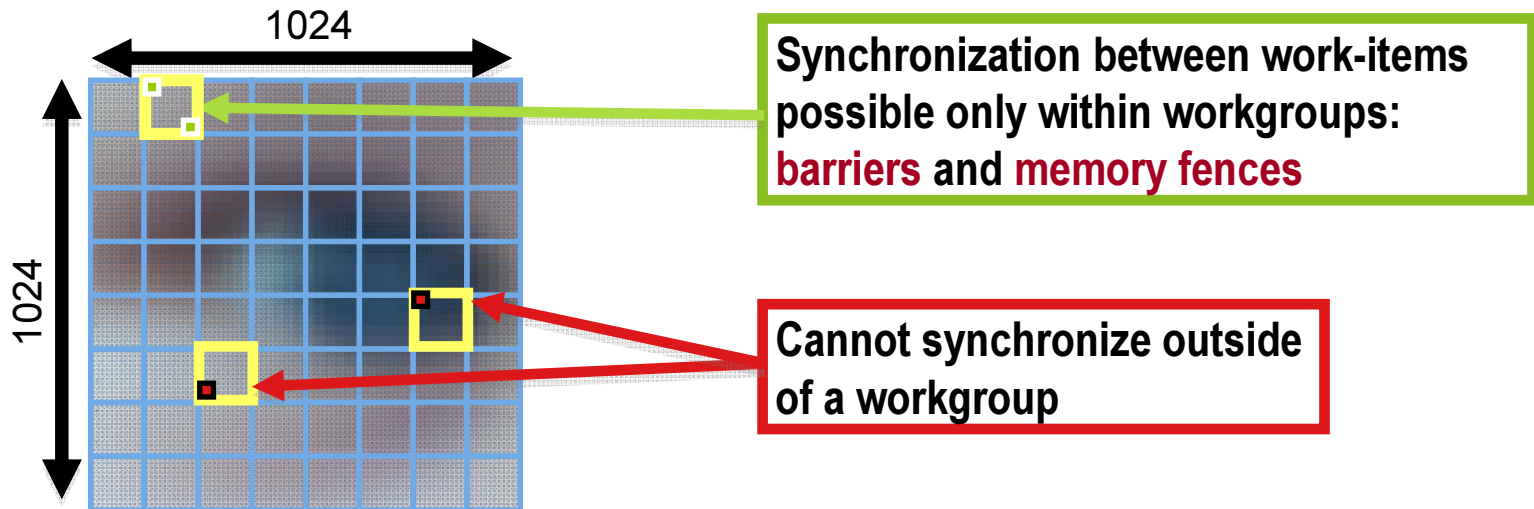


# Expressing Data-Parallelism in OpenCL

- **Kernels executed across a global domain of *work-items***
  - *Global dimensions* define the range of computation
  - One *work-item* per computation, executed in parallel
- **Work-items are grouped in local *workgroups***
  - *Local dimensions* define the size of the workgroups
  - Executed together on one device
  - Share local memory and synchronization
- **Caveats**
  - Global work-items must be independent: *no global synchronization*
  - Synchronization can be done within a workgroup

# Global and Local Dimensions

- Global Dimensions: 1024 x 1024 (whole problem space)
- Local Dimensions: 128 x 128 (executed together)



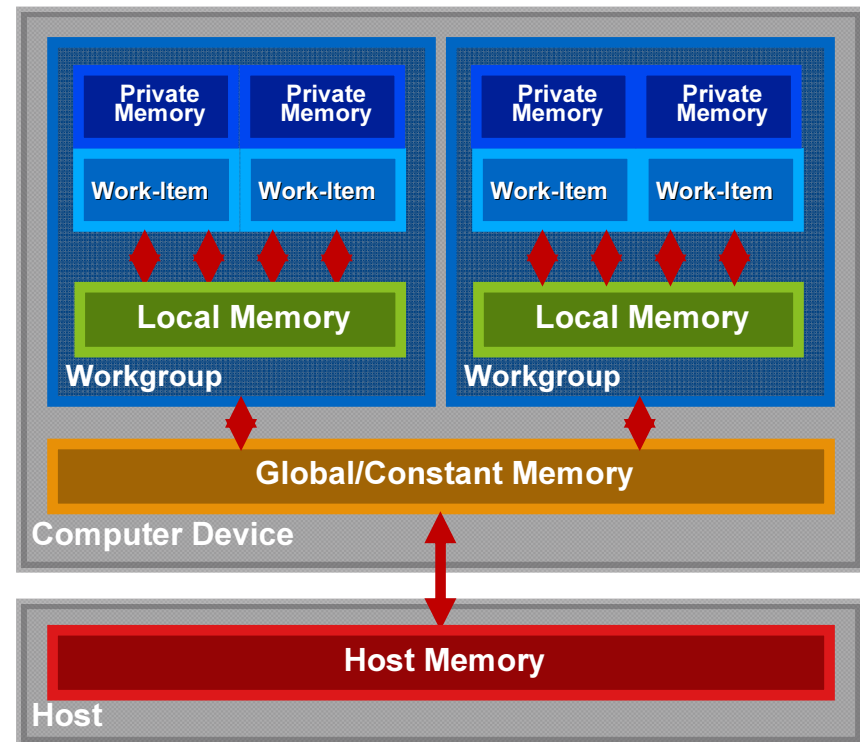
- Choose the dimensions that are “best” for your algorithm

# Expressing Task-Parallelism in OpenCL

- Executes as a single *work-item*
- A kernel written in OpenCL C
- A native C / C++ function

# OpenCL Memory Model

- **Private Memory**
  - Per work-item
- **Local Memory**
  - Shared within a workgroup (16Kb)
- **Local Global/Constant Memory**
  - Not synchronized
- **Host Memory**
  - On the CPU



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



# Using OpenCL

# OpenCL Objects

- **Setup**

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

- **Memory**

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

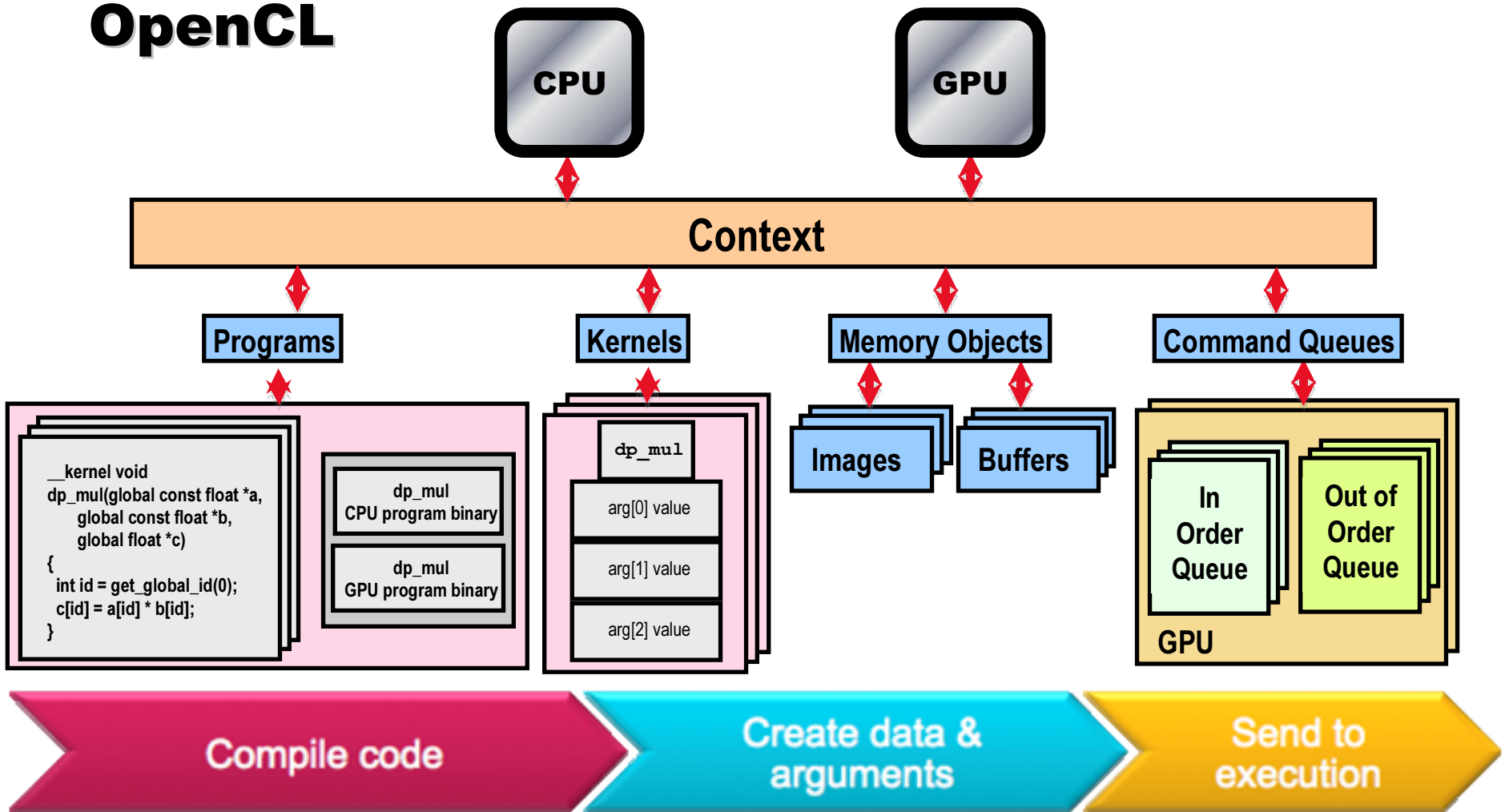
- **Execution**

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

- **Synchronization/profiling**

- **Events**

# OpenCL



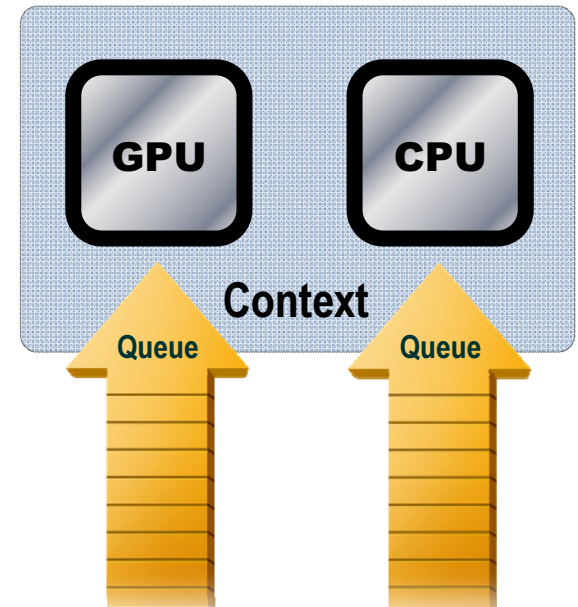
# Setup

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

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

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

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





# Setup: Notes

- **Devices**

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

- **Contexts**

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

- **Queues**

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

# Choosing Devices

- A system may have several devices—which is best?
- The “best” device is algorithm- and hardware-dependent
- Query device info with: `clGetDeviceInfo(device, param_name, *value)`
  - Number of compute units `CL_DEVICE_MAX_COMPUTE_UNITS`
  - Clock frequency `CL_DEVICE_MAX_CLOCK_FREQUENCY`
  - Memory size `CL_DEVICE_GLOBAL_MEM_SIZE`
  - Extensions (double precision, atomics, etc.)
- Pick the best device for your algorithm

# Memory Resources

- **Buffers**

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

- **Images**

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

# Image Formats and Samplers

- **Formats**

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

- **Samplers (for reading images)**

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

- **Benefit from image access hardware on GPUs**

# Allocating Images and Buffers

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

cl_mem input_image;
input_image = clCreateImage2D(context, CL_MEM_READ_ONLY, &format,
                              image_width, image_height, 0, NULL, &err);

cl_mem output_image;
output_image = clCreateImage2D(context, CL_MEM_WRITE_ONLY, &format,
                               image_width, image_height, 0, NULL, &err);

cl_mem input_buffer;
input_buffer = clCreateBuffer(context, CL_MEM_READ_ONLY,
                              sizeof(cl_float)*4*image_width*image_height, NULL, &err);

cl_mem output_buffer;
output_buffer = clCreateBuffer(context, CL_MEM_WRITE_ONLY,
                               sizeof(cl_float)*4*image_width*image_height, NULL, &err);
```

# Reading / Writing Memory Object Data

- Explicit commands to access memory object data
- Read from a region in memory object to host memory
  - `clEnqueueReadBuffer(queue, object, blocking, offset, size, *ptr, ...)`
- Write to a region in memory object from host memory
  - `clEnqueueWriteBuffer(queue, object, blocking, offset, size, *ptr, ...)`
- Map a region in memory object to host address space
  - `clEnqueueMapBuffer(queue, object, blocking, flags, offset, size, ...)`
- Copy regions of memory objects
  - `clEnqueueCopyBuffer(queue, srcobj, dstobj, src_offset, dst_offset, ...)`
- Operate synchronously (`blocking = CL_TRUE`) or asynchronously



# **Compilation and Execution of Kernels**

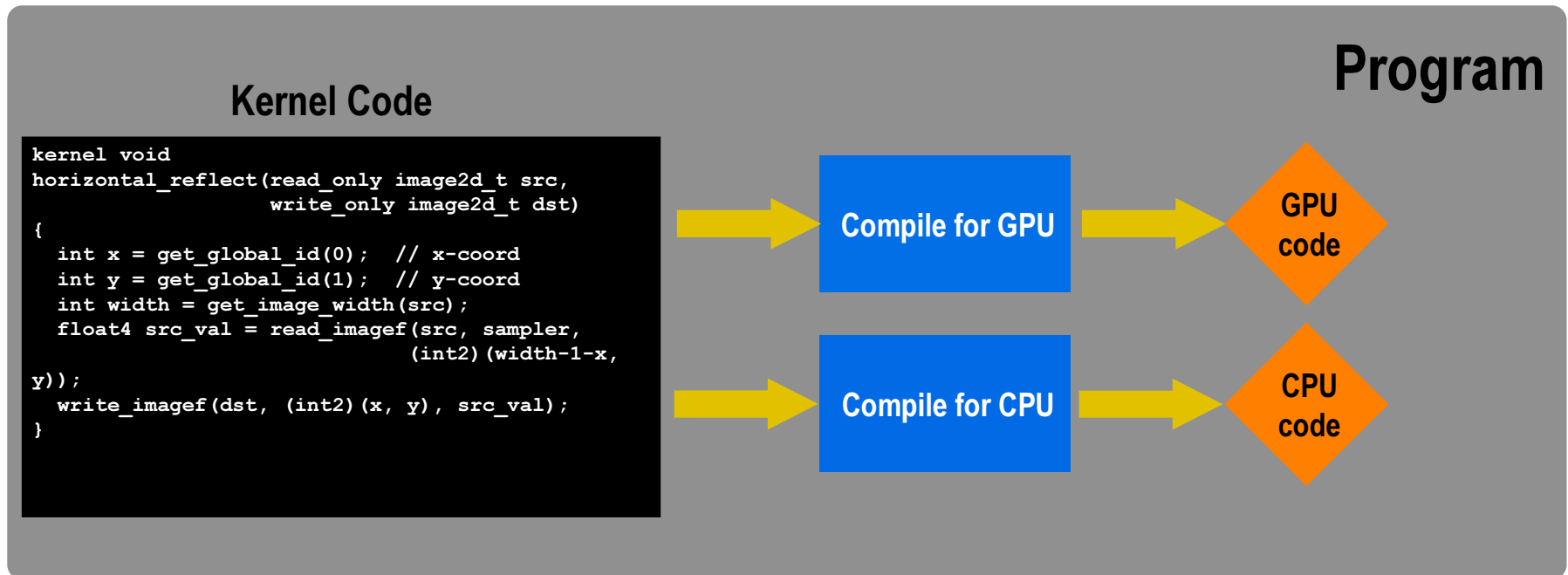
# Program and Kernel Objects

- **Program objects encapsulate ...**
  - a program source or binary
  - list of devices and latest successfully built executable for each device
  - a list of kernel objects
- **Kernel objects encapsulate ...**
  - a specific kernel function in a program - declared with the **kernel** qualifier
  - argument values
  - kernel objects created after the program executable has been built



# Executing Code

- Programs build executable code for multiple devices
- Execute the same code on different devices



# Executing Kernels

1. Set the kernel arguments
2. Enqueue the kernel

```
err = clSetKernelArg(kernel, 0, sizeof(input), &input);  
err = clSetKernelArg(kernel, 1, sizeof(output), &output);
```

```
size_t global[3] = {image_width, image_height, 0};  
err = clEnqueueNDRangeKernel(queue, kernel, 2, NULL, global, NULL, 0, NULL, NULL);
```

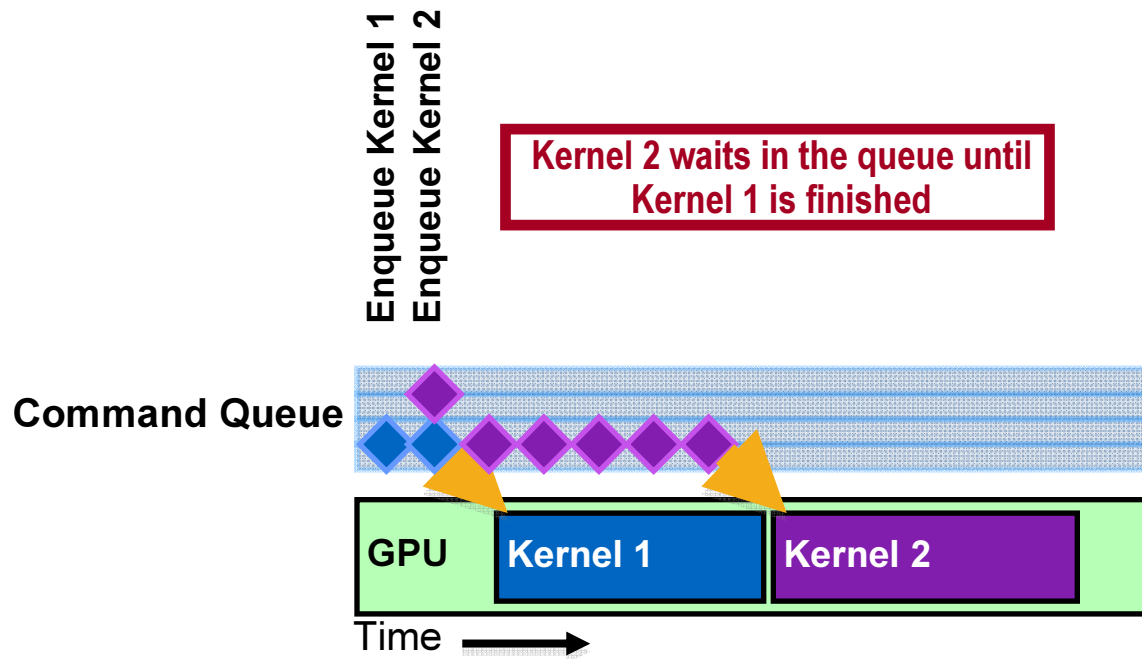
- **Note: Your kernel is executed asynchronously**
  - Nothing may happen — you have just enqueued your kernel
  - Use a blocking read `clEnqueueRead* (... CL_TRUE ...)`
  - Use events to track the execution status

# Synchronization Between Commands

- Each *individual* queue can execute in order or out of order
  - For in-order queue, all commands execute in order
  - Behaves as expected (as long as you're enqueueing from one thread)
- You must *explicitly synchronize between queues*
  - Multiple devices each have their own queue
  - Use events to synchronize
- Events
  - Commands *return events and obey waitlists*
  - `clEnqueue* (... , num_events_in_waitlist, *event_waitlist, *event_out)`

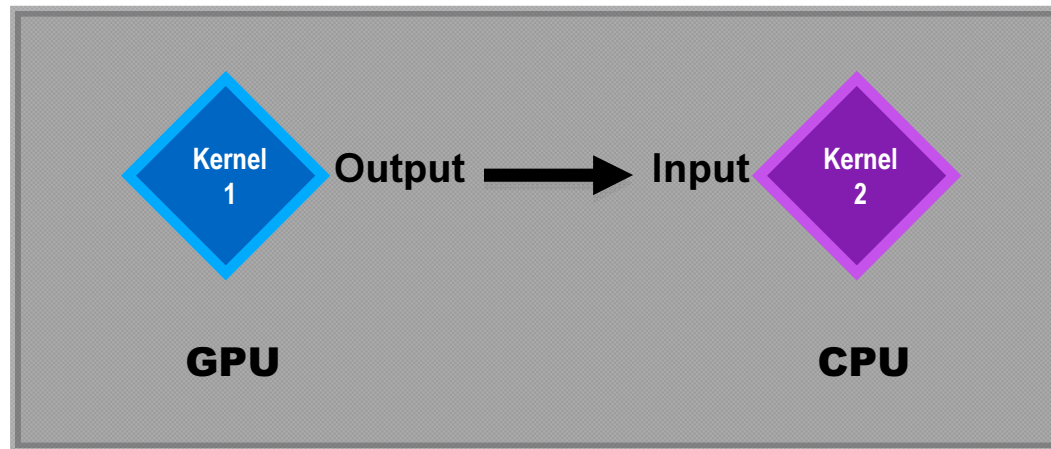
# Synchronization: One Device/Queue

- Example: Kernel 2 uses the results of Kernel 1

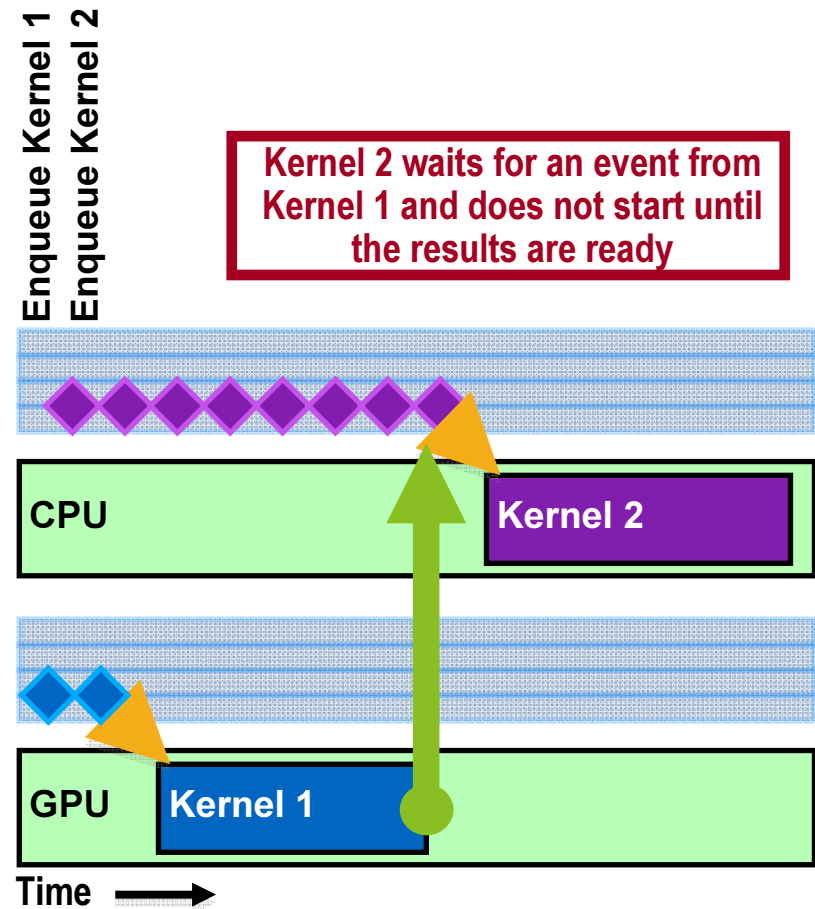
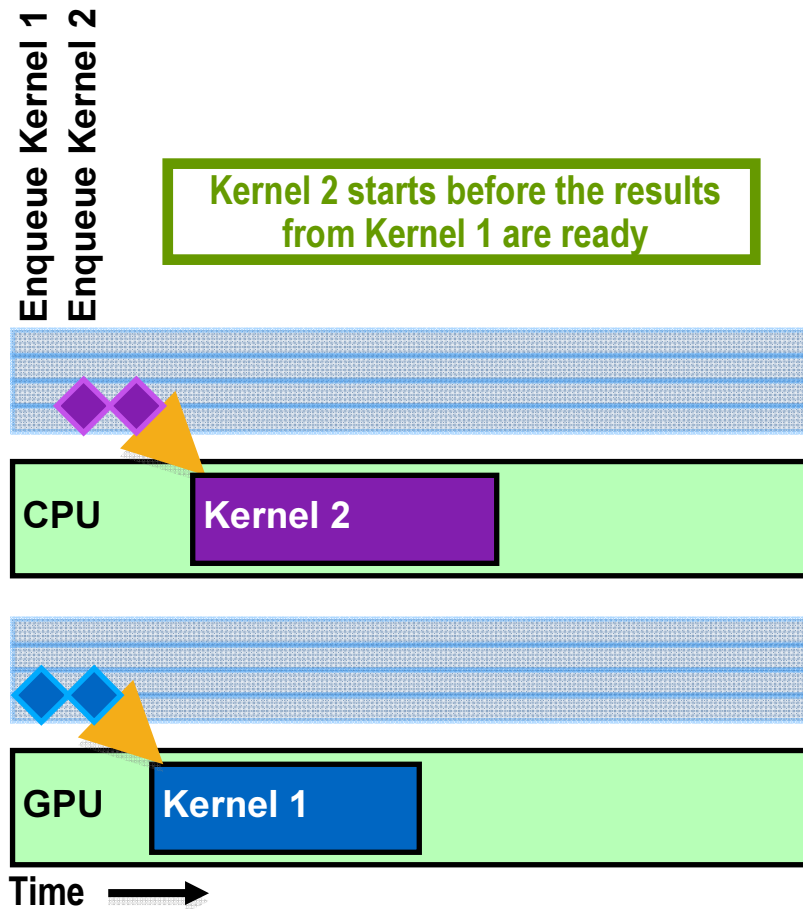


# Synchronization: Two Devices/Queues

- Explicit dependency: Kernel 1 must finish before Kernel 2 starts



# Synchronization: Two Devices/Queues



# Using Events on the Host

- **clWaitForEvents(num\_events, \*event\_list)**
  - Blocks until events are complete
- **clEnqueueMarker(queue, \*event)**
  - Returns an event for a marker that moves through the queue
- **clEnqueueWaitForEvents(queue, num\_events, \*event\_list)**
  - Inserts a “WaitForEvents” into the queue
- **clGetEventInfo()**
  - Command type and status  
`CL_QUEUED`, `CL_SUBMITTED`, `CL_RUNNING`, `CL_COMPLETE`, or error code
- **clGetEventProfilingInfo()**
  - Command queue, submit, start, and end times



# **Programming Advice**

## **Performance and Debugging**



# Performance: Overhead

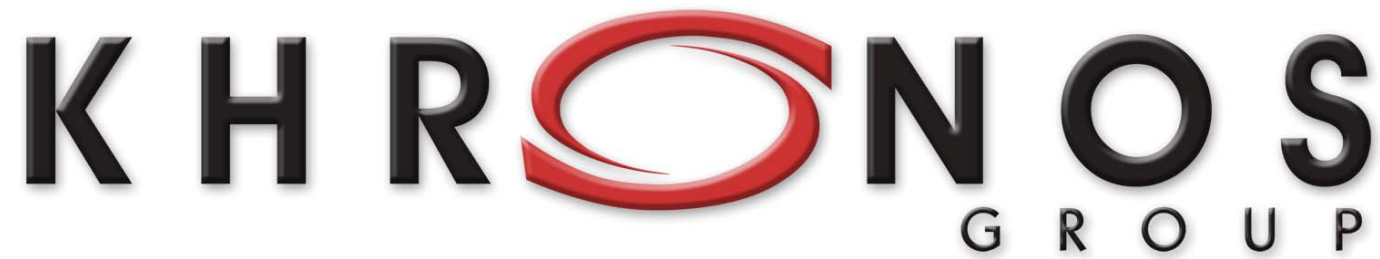
- **Compiling programs can be expensive**
  - Reuse programs or precompile binaries
- **Moving data to/from some devices may be expensive**
  - e.g. Discrete GPU over PCIe
  - Keep data on device
- **Starting a kernel can be expensive**
  - Do a lot of work for each execution
- **Events can be expensive on some devices**
  - Only use events where needed

# Performance: Kernels and Memory

- **Large global work sizes help hide memory latency and overheads**
  - 1000+ work-items preferred
- **Trade-off math precision and performance with half\_ and native\_**
- **Divergent execution can be bad on some devices**
  - All work-items in a work-group should take very similar control flow paths
- **Handle data reuse through local memory when available**
- **Access memory sequentially across work-items**
  - Enables hardware memory coalescing
  - Dramatic bandwidth improvements

# Debugging

- **Start on the CPU**
- **Be very careful about reading/writing out of bounds on the GPU**
  - Use explicit address checks around reads and writes if a kernel is crashing to locate problems
- **Play nicely with other apps**
  - GPUs are not preemptively scheduled
- **Use extra output buffers/images to record intermediate values**
- **Set a context call-back function to report API errors**



# OpenCL C

# OpenCL C Language

- **Derived from ISO C99**
  - No standard C99 headers, function pointers, recursion, variable length arrays, and bit fields
- **Additions to the language for parallelism**
  - Work-items and workgroups
  - Vector types
  - Synchronization
- **Address space qualifiers**
- **Optimized image access**
- **Built-in functions**

# Kernel

- A data-parallel function executed for each work-item

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

get\_global\_id(0)

10

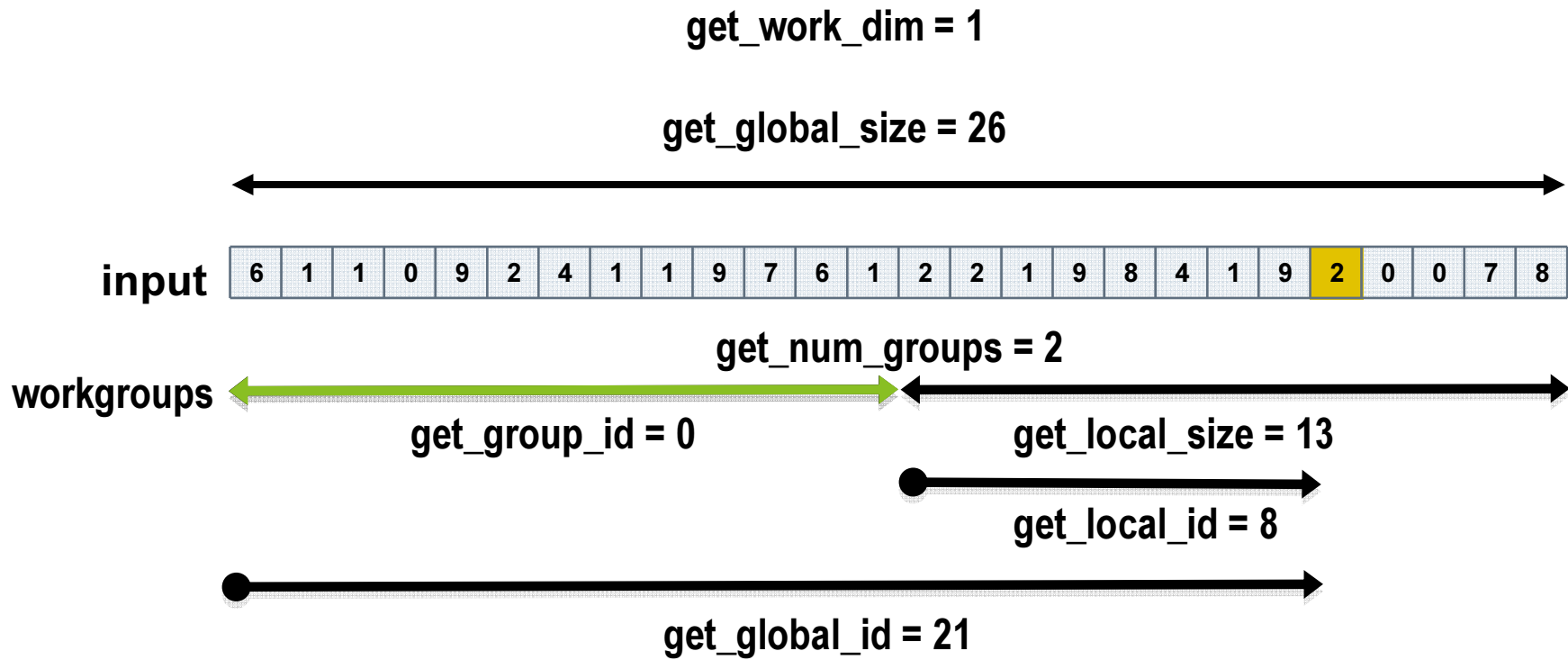
Input

6	1	1	0	9	2	4	1	1	9	7	6	1	2	2	1	9	8	4	1	9	2	0	0	7	8
---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---	---

Output

36	1	1	0	81	4	16	1	1	81	49	36	1	4	4	1	81	64	16	1	81	4	0	0	49	64
----	---	---	---	----	---	----	---	---	----	----	----	---	---	---	---	----	----	----	---	----	---	---	---	----	----

# Work-Items and Workgroup Functions



# Data Types

- **Scalar data types**
  - char , uchar, short, ushort, int, uint, long, ulong
  - bool, intptr\_t, ptrdiff\_t, size\_t, uintptr\_t, void, half (storage)
- **Image types**
  - image2d\_t, image3d\_t, sampler\_t
- **Vector data types**



# Vector Types

- Portable
- Vector length of 2, 4, 8, and 16
- char2, ushort4, int8, float16, double2, ...
- Endian safe
- Aligned at vector length
- Vector operations and built-in functions

# Vector Operations

- **Vector literal**

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

- **Vector components**

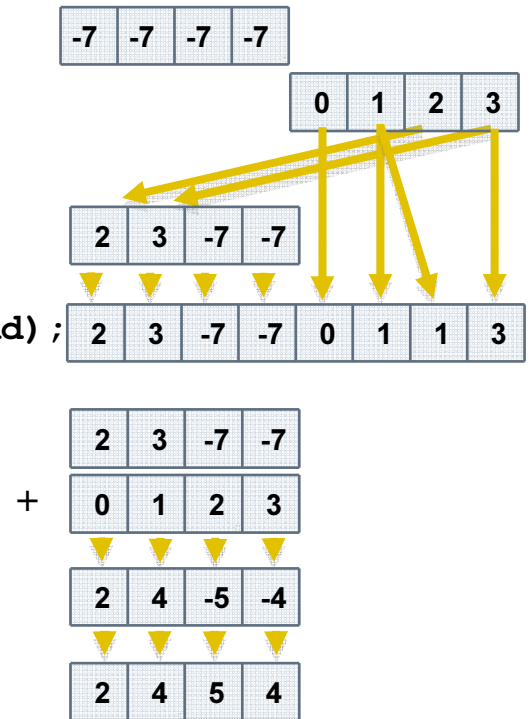
```
vi0.lo = vi1.hi;
```

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

- **Vector ops**

```
vi0 += vi1;
```

```
vi0 = abs(vi0);
```



# Address Spaces

- **Kernel** pointer arguments must use **global**, **local** or **constant**

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

- Default address space for arguments and local variables is **private**

```
kernel void smooth(global float* io) {
    float temp;
    ...
}
```

- **image2d\_t** and **image3d\_t** are always in **global** address space

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

# Address Spaces

- Program (global) variables must be in constant address space

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

- Casting between different address spaces is undefined

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

# Conversions

- Scalar and pointer conversions follow C99 rules
- No implicit conversions for vector types

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

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

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

- Casts have other problems

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

- Wrong for:

- 0.5f - 1 ulp (rounds up not down)
- negative numbers (wrong answer)

- There is hardware to do it on many devices

# Conversions

- **Explicit conversions:** `convert_destType<_sat><_roundingMode>`
  - Scalar and vector types
  - No ambiguity

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

<b>f4</b>	-5.0f	254.5f	254.6	1.2E9f
<b>c4</b>	0	254	255	255

Saturate to 0

Round down to nearest even

Round up to nearest value

Saturated to 255

# Reinterpret Data: *as\_typen*

- Reinterpret the bits to another type
- Types must be the same size
- OpenCL provides a **select** built-in

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

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

# Built-in Math Functions

- IEEE 754 compatible rounding behavior for single precision floating-point
- IEEE 754 compliant behavior for double precision floating-point
- Defines maximum error of math functions as ULP values
- Handle ambiguous C99 library edge cases
- Commonly used single precision math functions come in three flavors
  - eg.  $\log(x)$ 
    - Full precision  $\leq 3$ ulps
    - Half precision/faster. `half_log`—minimum 11 bits of accuracy,  $\leq 8192$  ulps
    - Native precision/fastest. `native_log`: accuracy is implementation defined
  - Choose between accuracy and performance



# Built-in Work-group Functions

- Synchronization
  - Barrier
- Work-group functions
  - Encountered by all work-items in the work-group
  - With the same argument values

```
kernel read(global int* g, local int* shared)
{
    if (get_global_id(0) < 5)
        barrier(CLK_GLOBAL_MEM_FENCE); ← work-item 0
    else
        k = array[0]; ← work-item 6
}
```

Illegal since not all work-items  
encounter barrier

# Built-in Work-group Functions

- **async\_work\_group\_copy**
  - Copy from global to local or local to global memory
  - Use DMA engine or do a memcpy across work-items in work-group
  - Returns an event object
- **wait\_group\_events**
  - wait for events that identify **async\_work\_group\_copy** operations to complete

# Built-in Functions

- **Integer functions**

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

- **Image functions**

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

- **Common, Geometric and Relational Functions**

- **Vector Data Load and Store Functions**

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

# Built-in Functions

## Math Functions

gentype acos (gentype)  
gentype acosh (gentype)  
gentype acospi (gentype x)  
gentype asin (gentype)  
gentype asinh (gentype)  
gentype asinpi (gentype x)  
gentype atan (gentype y\_over\_x)  
gentype atan2 (gentype y, gentype x)  
gentype atanh (gentype)  
gentype atanpi (gentype x)  
gentype atan2pi (gentype y, gentype x)  
gentype cbrt (gentype)  
gentype ceil (gentype)  
gentype copysign (gentype x, gentype y)  
gentype cos (gentype)  
gentype cosh (gentype)  
gentype cospi (gentype x)  
gentype erfc (gentype)  
gentype erf (gentype)  
gentype exp (gentype x)  
gentype exp2 (gentype)  
gentype exp10 (gentype)  
gentype expm1 (gentype x)  
gentype fabs (gentype)  
gentype fdim (gentype x, gentype y)  
gentype floor (gentype)  
gentype fma (gentype a, gentype b, gentype c)  
gentype fmax (gentype x, float y)  
gentype fmin (gentype x, gentype y)  
gentype fmin (gentype x, float y)  
gentype fmod (gentype x, gentype y)  
gentype fract (gentype x, gentype \*ptr)  
gentype frexp (gentype x, intrn \*exp)  
gentype hypot (gentype x, gentype y)  
intrn ilogb (gentype x)  
gentype ldexp (gentype x, intrn n)  
gentype ldexp (gentype x, int n)  
gentype lgamma (gentype x)  
gentype lgamma\_r (gentype x, intrn \*signp)  
gentype log (gentype)  
gentype log2 (gentype)  
gentype log10 (gentype)  
gentype log1p (gentype x)  
gentype logb (gentype x)  
gentype mad (gentype a, gentype b, gentype c)  
gentype modf (gentype x, gentype \*iptr)  
gentype nan (uintn nancode)  
gentype nextafter (gentype x, gentype y)

gentype pow (gentype x, gentype y)  
gentype pown (gentype x, intrn y)  
gentype powr (gentype x, gentype y)  
gentype remainder (gentype x, gentype y)  
gentype remquo (gentype x, gentype y, intrn \*quo)  
gentype rint (gentype)  
gentype rootn (gentype x, intrn y)  
gentype round (gentype x)  
gentype rsqrt (gentype)  
gentype sin (gentype)  
gentype sincos (gentype x, gentype \*cosval)  
gentype sinh (gentype)  
gentype sinpi (gentype x)  
gentype sqrt (gentype)  
gentype tan (gentype)  
gentype tanh (gentype)  
gentype tanpi (gentype x)  
gentype tgamma (gentype)  
gentype trunc (gentype)

## Integer Ops

ugentype abs (gentype x)  
ugentype abs\_diff (gentype x, gentype y)  
gentype add\_sat (gentype x, gentype y)  
gentype hadd (gentype x, gentype y)  
gentype rhadd (gentype x, gentype y)  
gentype ciz (gentype x)  
gentype mad\_hi (gentype a, gentype b, gentype c)  
gentype mad\_sat (gentype a, gentype b, gentype c)  
gentype max (gentype x, gentype y)  
gentype min (gentype x, gentype y)  
gentype mul\_hi (gentype x, gentype y)  
gentype rotate (gentype v, gentype i)  
gentype sub\_sat (gentype x, gentype y)  
shortn upsample (intrn hi, uintn lo)  
ushortn upsample (uintn hi, uintn lo)  
intrn upsample (intrn hi, uintn lo)  
uintn upsample (uintn hi, uintn lo)  
longn upsample (intrn hi, uintn lo)  
ulongn upsample (uintn hi, uintn lo)  
gentype mad24 (gentype x, gentype y, gentype z)  
gentype mul24 (gentype x, gentype y)  
Common Functions  
gentype clamp (gentype x, gentype minval, gentype maxval)  
gentype clamp (gentype x, float minval, float maxval)  
gentype degrees (gentype radians)  
gentype max (gentype x, gentype y)  
gentype max (gentype x, float y)  
gentype min (gentype x, gentype y)  
gentype min (gentype x, float y)

gentype mix (gentype x, gentype y, gentype a)  
gentype mix (gentype x, gentype y, float a)  
gentype radians (gentype degrees)  
gentype sign (gentype x)  
Geometric Functions  
float4 cross (float4 p0, float4 p1)  
float dot (gentype p0, gentype p1)  
float distance (gentype p0, gentype p1)  
float length (gentype p)  
float fast\_distance (gentype p0, gentype p1)  
float fast\_length (gentype p)  
gentype fast\_normalize (gentype p)

## Relational Ops

int isequal (float x, float y)  
intrn isequal (floatn x, floatn y)  
int isnotequal (float x, float y)  
intrn isnotequal (floatn x, floatn y)  
int isgreater (float x, float y)  
intrn isgreater (floatn x, floatn y)  
int isgreaterequal (float x, float y)  
intrn isgreaterequal (floatn x, floatn y)  
int isless (float x, float y)  
intrn isless (floatn x, floatn y)  
int islessequal (float x, float y)  
intrn islessequal (floatn x, floatn y)  
int islessgreater (float x, float y)  
intrn islessgreater (floatn x, floatn y)  
int isfinite (float)  
intrn isfinite (floatn)  
int isnan (float)  
intrn isnan (floatn)  
int isnormal (float)  
intrn isnormal (floatn)  
int isordered (float x, float y)  
intrn isordered (floatn x, floatn y)  
int isunordered (float x, float y)  
intrn isunordered (floatn x, floatn y)  
int signbit (float)  
intrn signbit (floatn)  
int any (igentype x)  
int all (igentype x)  
gentype biselect (gentype a, gentype b, gentype c)  
gentype select (gentype a, gentype b, igentype c)  
gentype select (gentype a, gentype b, ugentype c)  
Vector Loads/Store Functions  
gentypen vloadn (size\_t offset, const global gentype \*p)  
gentypen vloadn (size\_t offset, const \_\_local gentype \*p)  
gentypen vloadn (size\_t offset, const \_\_constant gentype \*p)  
gentypen vloadn (size\_t offset, const \_\_private gentype \*p)

void vstoren (gentypen data, size\_t offset, global gentype \*p)  
void vstoren (gentypen data, size\_t offset, \_\_local gentype \*p)  
void vstoren (gentypen data, size\_t offset, \_\_private gentype \*p)  
void vstore\_half (float data, size\_t offset, global half \*p)  
void vstore\_half\_rte (float data, size\_t offset, global half \*p)  
void vstore\_half\_rtz (float data, size\_t offset, global half \*p)  
void vstore\_half\_rtp (float data, size\_t offset, global half \*p)  
void vstore\_half\_rtn (float data, size\_t offset, global half \*p)  
void vstore\_half (float data, size\_t offset, \_\_local half \*p)  
void vstore\_half\_rte (float data, size\_t offset, \_\_local half \*p)  
void vstore\_half\_rtz (float data, size\_t offset, \_\_local half \*p)  
void vstore\_half\_rtp (float data, size\_t offset, \_\_local half \*p)  
void vstore\_half\_rtn (float data, size\_t offset, \_\_local half \*p)  
void vstore\_half (float data, size\_t offset, \_\_private half \*p)  
void vstore\_half\_rte (float data, size\_t offset, \_\_private half \*p)  
void vstore\_half\_rtz (float data, size\_t offset, \_\_private half \*p)  
void vstore\_half\_rtp (float data, size\_t offset, \_\_private half \*p)  
void vstore\_half\_rtn (float data, size\_t offset, \_\_private half \*p)  
void vstore\_halfn (floatn data, size\_t offset, global half \*p)  
void vstore\_halfn\_rte (floatn data, size\_t offset, global half \*p)  
void vstore\_halfn\_rtz (floatn data, size\_t offset, global half \*p)  
void vstore\_halfn\_rtp (floatn data, size\_t offset, global half \*p)  
void vstore\_halfn\_rtn (floatn data, size\_t offset, global half \*p)  
void vstore\_halfn (floatn data, size\_t offset, \_\_local half \*p)  
void vstore\_halfn\_rte (floatn data, size\_t offset, \_\_local half \*p)  
void vstore\_halfn\_rtz (floatn data, size\_t offset, \_\_local half \*p)  
void vstore\_halfn\_rtp (floatn data, size\_t offset, \_\_local half \*p)  
void vstore\_halfn\_rtn (floatn data, size\_t offset, \_\_local half \*p)  
void vstore\_halfn (floatn data, size\_t offset, \_\_private half \*p)  
void vstore\_halfn\_rte (floatn data, size\_t offset, \_\_private half \*p)  
void vstore\_halfn\_rtz (floatn data, size\_t offset, \_\_private half \*p)  
void vstore\_halfn\_rtp (floatn data, size\_t offset, \_\_private half \*p)  
void vstore\_halfn\_rtn (floatn data, size\_t offset, \_\_private half \*p)

# Extensions

- **Atomic functions to global and local memory**
  - add, sub, xchg, inc, dec, cmp\_xchg, min, max, and, or, xor
  - 32-bit/64-bit integers
- **Select rounding mode for a group of instructions at compile time**
  - For instructions that operate on floating-point or produce floating-point values
  - `#pragma opencl_select_rounding_mode rounding_mode`
  - All 4 rounding modes supported
- **Extension: Check `clGetDeviceInfo` with `CL_DEVICE_EXTENSIONS`**

# Summary

- **Portable and high-performance framework**
  - Ideal for computationally intensive algorithms
  - Access to all compute resources
  - Portable across different devices
  - Well-defined computation/memory model
- **Efficient parallel programming language**
  - C99 with extensions for task and data parallelism
  - Rich set of built-in functions
- **Defines hardware and numerical precision requirements**
- **Open standard for heterogeneous parallel computing**