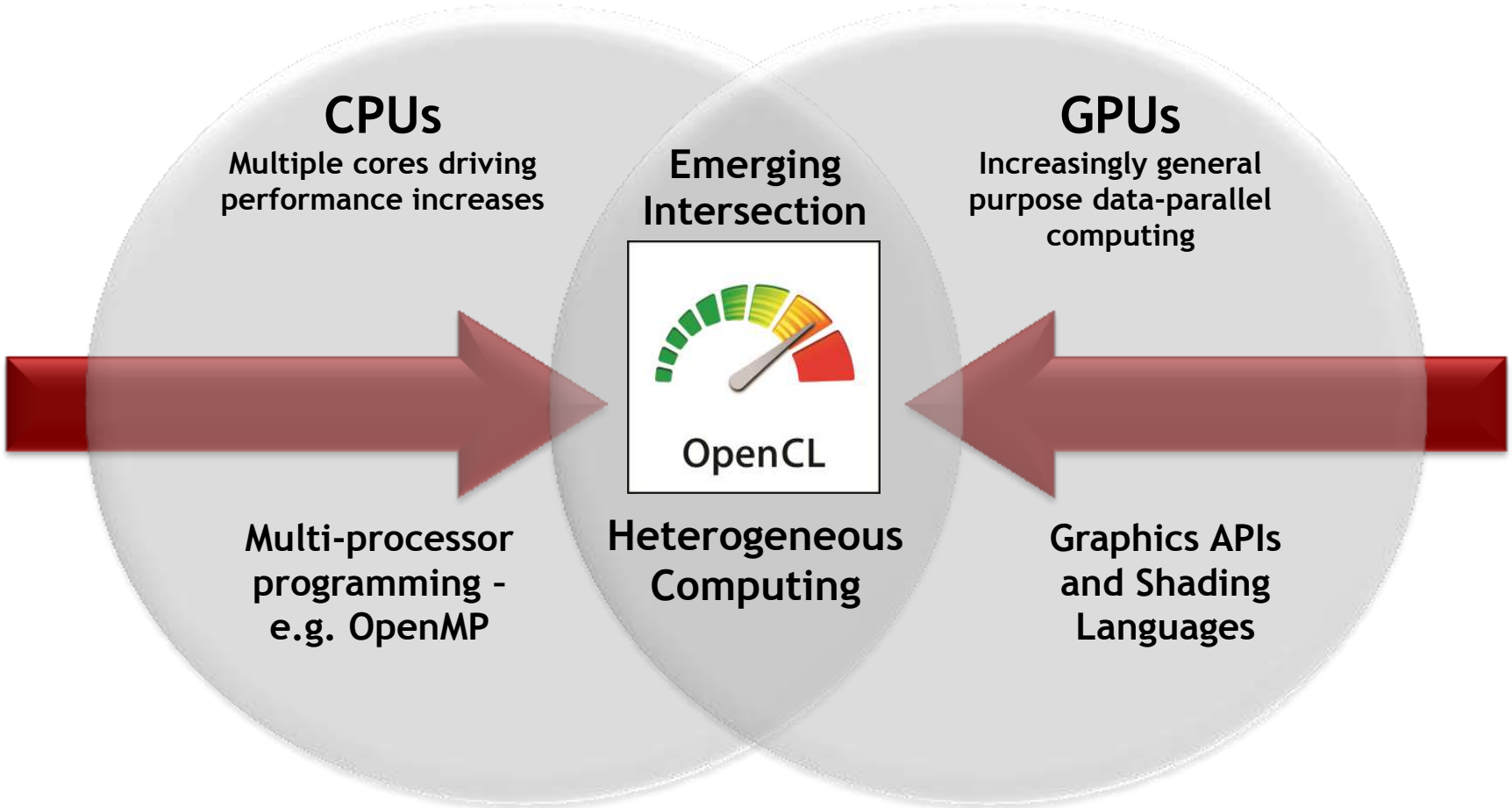
OpenCL Introduction

Neil Trevett
Vice President NVIDIA, President Khronos
OpenCL Working Group Chair

The Inspiration for OpenCL



The BIG Idea behind OpenCL

- OpenCL execution model …
  - Define N-dimensional computation domain
  - Execute a kernel at each point in computation domain

Traditional Loop

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

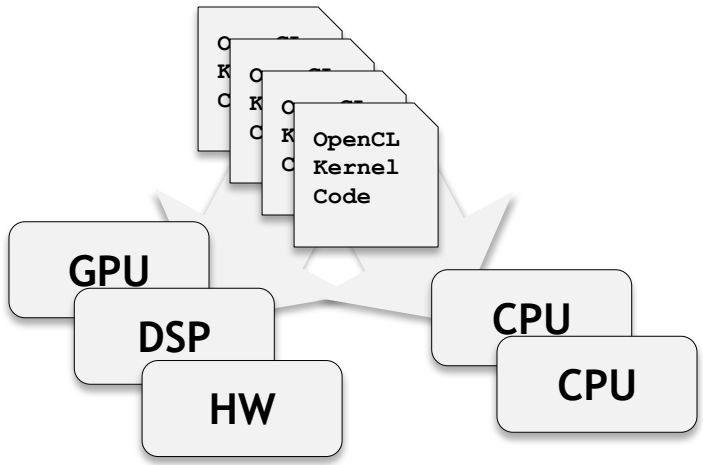
Data Parallel OpenCL

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

    c[id] = a[id] * b[id];
}
```

OpenCL – Portable Heterogeneous Computing

- **Royalty-free native, cross-platform, cross-vendor standard**
  - Targeting supercomputers -> embedded systems -> mobile devices
- **Enables programming of diverse compute resources**
  - CPU, GPU, DSP, FPGA – and hardware blocks
- **One code tree can be executed on CPUs, GPUs, DSPs and hardware**
  - Dynamically interrogate system load and balance across available processors
- **Powerful, low-level flexibility**
  - Foundational access to compute resources for higher-level engines, frameworks and languages

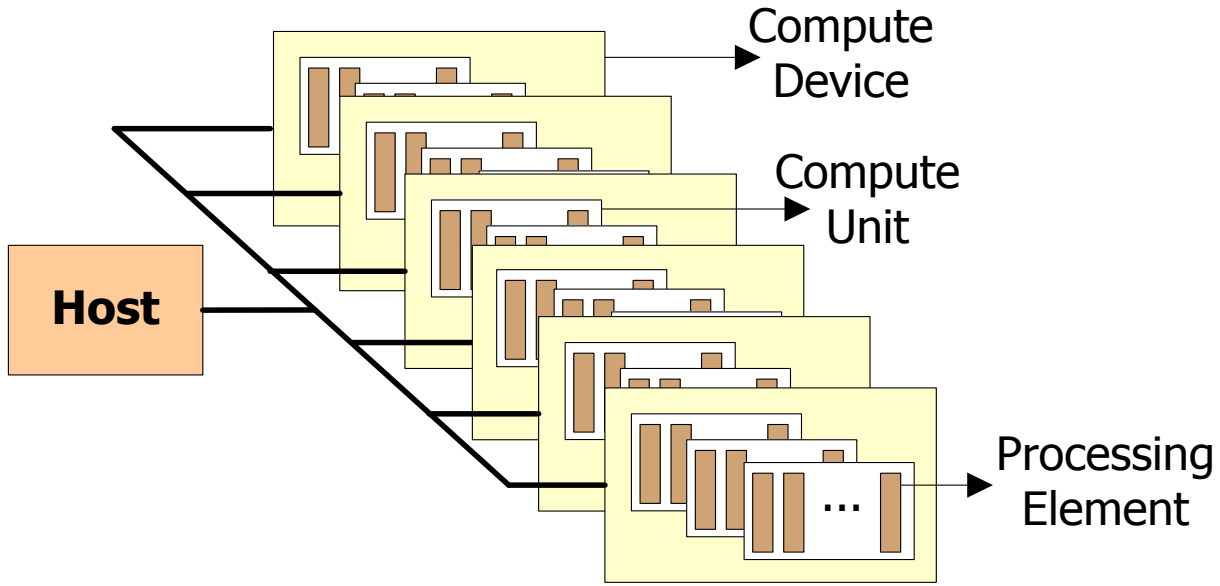


OpenCL Architecture

- **C Platform Layer API**
  - Query, select and initialize compute devices
- **Kernel Language Specification**
  - Subset of ISO C99 with language extensions
  - Well-defined numerical accuracy - IEEE 754 rounding with specified max error
  - Rich set of built-in functions: cross, dot, sin, cos, pow, log …
- **C Runtime API**
  - Runtime or build-time compilation of kernels
  - Execute compute kernels across multiple devices
- **Embedded profile**
  - No need for a separate “ES” spec
  - Reduces precision requirements

OpenCL Platform Model

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



OpenCL Execution Model

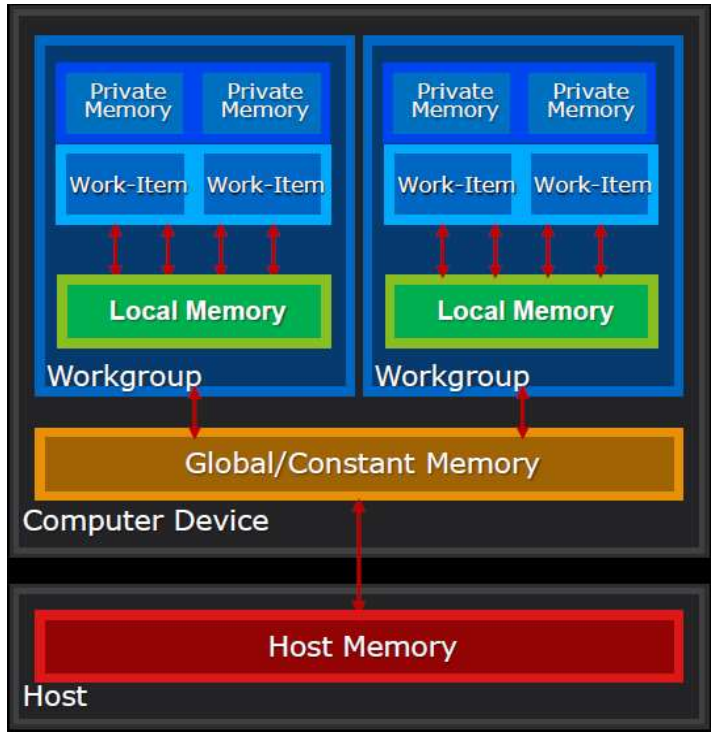
- **Kernel**
  - Basic unit of executable code (~ C function)
  - Data-parallel or task-parallel
- **Program**
  - Collection of kernels and functions (~ dynamic library with run-time linking)
- **Command Queue**
  - Applications queue kernels & data transfers
  - Performed in-order or out-of-order
- **Work-item**
  - An execution of a kernel by a processing element (~ thread)
- **Work-group**
  - A collection of related work-items that execute on a single compute unit (~ core)

Work-group Example

Work-items = # pixels
Work-groups = # tiles
Work-group size = tile width * tile height

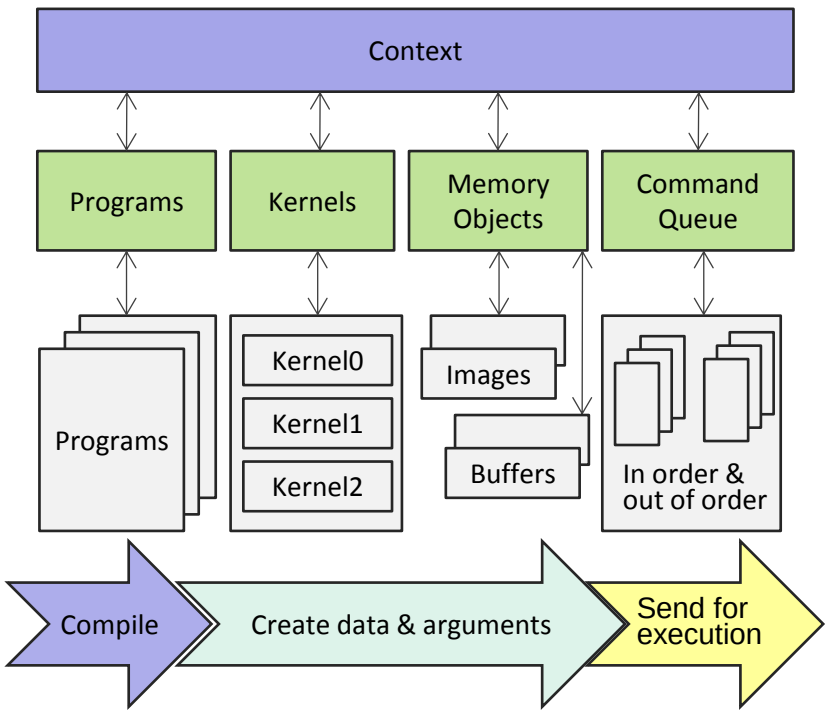
OpenCL Memory Model

- **Hierarchy of memory types**
  - Private memory -
    - Per work-item
  - Local memory (green)
    - Per work-group
    - Available to work-items in a given work-group
  - Global/Constant memory
    - Not synchronized
  - Host memory
    - On the CPU
- **Memory management is explicit:**
  - Application must move data from host → global → local and back



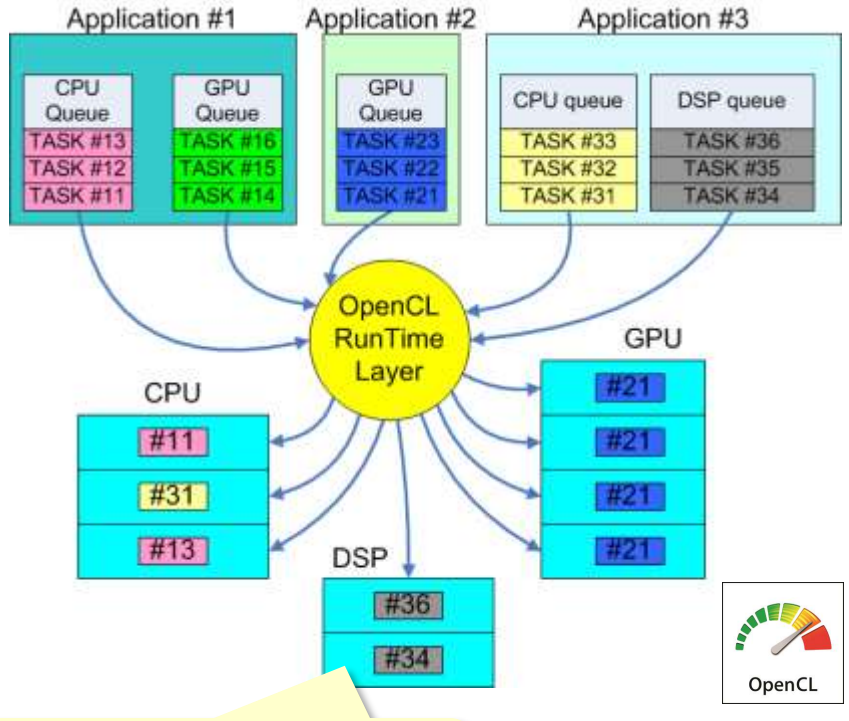
Executing OpenCL Programs

1. Query host for OpenCL devices
2. Create a context to associate OpenCL devices
3. Create programs for execution on one or more associated devices
4. Select kernels to execute from the programs
5. Create memory objects accessible from the host and/or the device
6. Copy memory data to the device as needed
7. Provide kernels to command queue for execution
8. Copy results from the device to the host



OpenCL Built-in Kernels

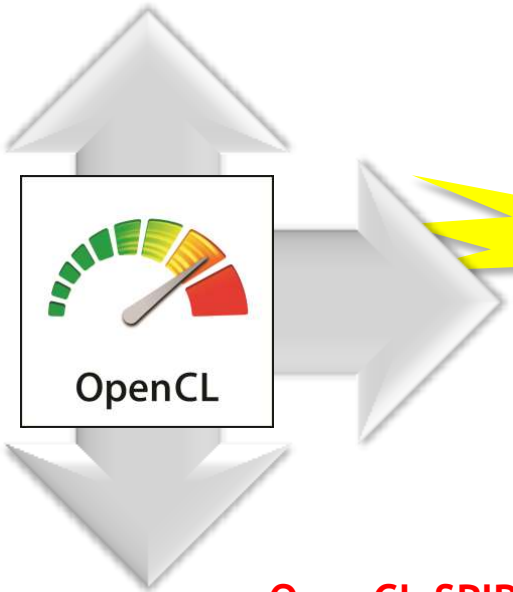
- **Used to control non-OpenCL C-capable resources on an SOC – 'Custom Devices'**
  - E.g. Video encode/decode, Camera ISP …
- **Represent functions of Custom Devices as an OpenCL kernel**
  - Can enqueue Built-in Kernels to Custom Devices alongside standard OpenCL kernels
- **OpenCL run-time a powerful coordinating framework for ALL SOC resources**
  - Programmable *and* custom devices controlled by one run-time



Built-in kernels enable control of specialized processors and hardware from OpenCL run-time

OpenCL Related Specification Roadmap

OpenCL HLM (High Level Model)
High-level programming model, unifying host and device execution environments through language syntax for increased usability and broader optimization opportunities



OpenCL 2.0 Finalized here at SIGGRAPH Asia 2013!

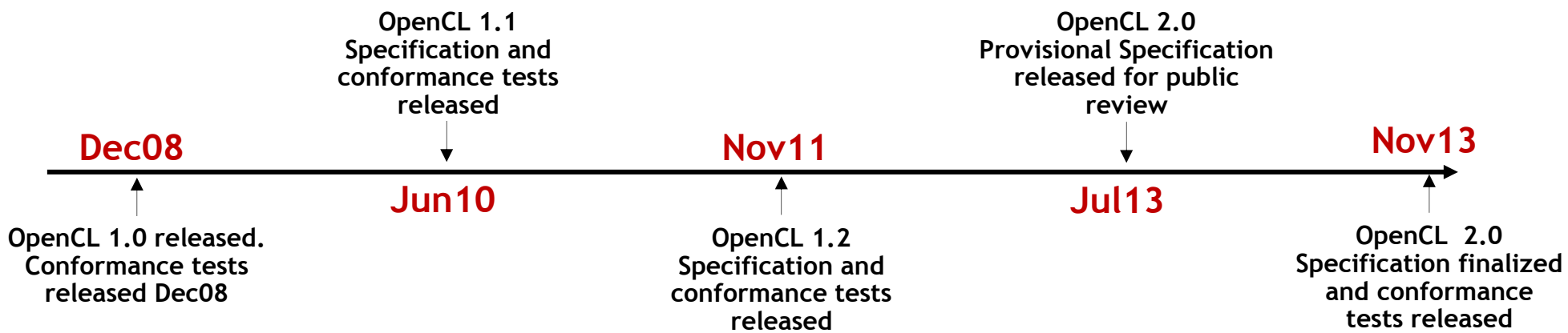
OpenCL 2.0
Significant enhancements to memory and execution models to expose emerging hardware capabilities and provide increased flexibility, functionality and performance to developers

OpenCL SPIR 1.2 Provisional released at SIGGRAPH 2013

SPIR (Standard Parallel Intermediate Representation)
LLVM-based, low-level Intermediate Representation for IP Protection and as target back-end for alternative high-level languages

OpenCL Milestones

- **24 month cadence for major OpenCL 2.0 update**
  - Slightly longer than 18 month cadence between versions of OpenCL 1.X
- **Significant feedback from the developer community on Provisional Specification**
  - Many suggestions were incorporated into the final 2.0 specification
  - Other feedback will be considered for future specification versions

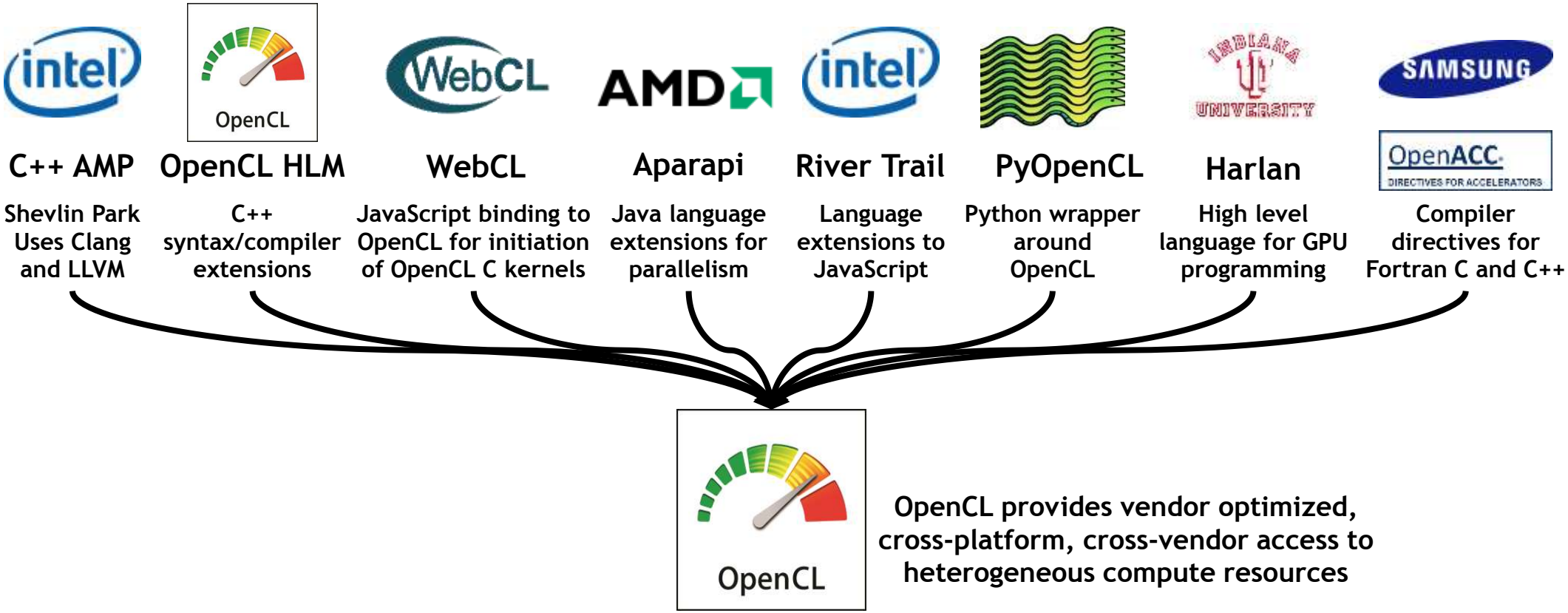


Broad OpenCL Implementer Adoption

- **Multiple conformant implementations shipping on desktop and mobile**
  - For CPUs and GPUs on multiple OS
- **Android ICD extension released in latest extension specification**
  - OpenCL implementations can be discovered and loaded as a shared object
- **Multiple implementations shipping in Android NDK**
  - ARM, Imagination, Vivante, Qualcomm, Samsung …

OpenCL as Parallel Compute Foundation

- 100+ tool chains and languages leveraging OpenCL
  - Heterogeneous solutions emerging for the most popular programming languages

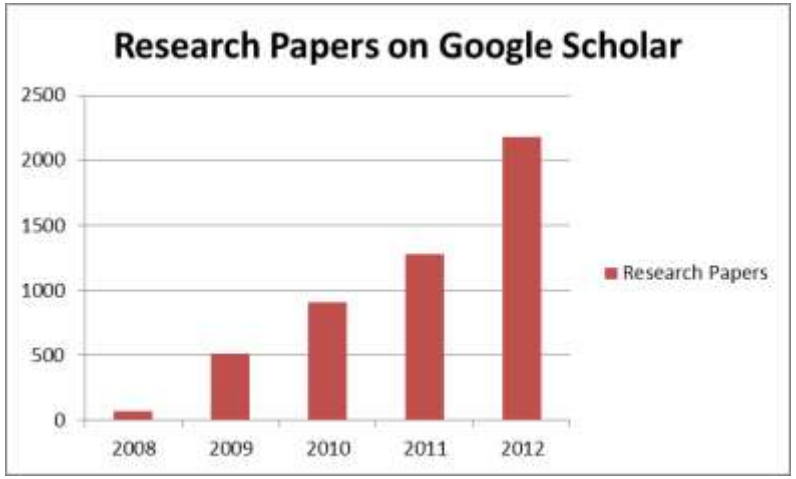


Widespread Developers Leveraging OpenCL

- **Broad uptake of OpenCL in commercial applications**
  - For desktop and increasingly mobile apps
- **"OpenCL" on Sourceforge, Github, Google Code, BitBucket finds over 2,000 projects**
  - x264
  - Handbrake
  - FFMPEG
  - JPEG
  - VLC
  - OpenCV
  - GIMP
  - ImageMagick
  - IrfanView
  - Hadoop, Memcched
  - Aparapi – A parallel API (for Java)
  - Bolt – a Unified Heterogeneous Library
  - Sumatra – next generation of compute enabled Java
  - WinZip
  - Crypto++
  - Bullet physics library
  - Etc. Etc.


OpenCL Academic Traction

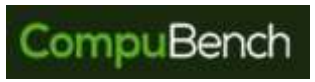
- **OpenCL at over 100 Universities Worldwide**
  Teaching multi-faceted programming courses
  - Research with top-tier Universities globally
- **Complete University Kits available**
  - Presentation w/instructor & speaker notes
  - Example code, & sample application
- **Growing textbook ecosystem**
  - US, Japan, Europe, China and India
- **Number of papers referencing OpenCL on Google Scholar is growing rapidly**
  - Over 2000 papers in 2012
- **Commercial OpenCL training courses**
  - http://www.accelereyes.com/services/training



http://developer.amd.com/Resources/library/Pages/default.aspx

Major Benchmarks Leveraging OpenCL

- **PCMark 8 uses OpenCL**
  - Video Chat and Video Group Chat
  - Batch Video Edit
- **BasemarkCL, CompuBench use OpenCL as leading indicators of platform performance**
- **Reviewed performance benchmarks use heterogeneous computing via OpenCL**
  - AnandTech, Tom's Hardware Guide
- **End-user benchmarks transitioning to use heterogeneous computing**
  - E.g. Ludashi (China) is using OpenCL



Give us YOUR Feedback!

- **Full OpenCL 2.0 Documentation available**
  - Final Specification
  - Header files
  - Reference Card
  - Online Reference pages
- **OpenCL Registry contains all specifications**
  - www.khronos.org/registry/cl/
- **Open Resources Area**
  - Community submitted resources
  - http://www.khronos.org/opencl/resources
- **Public Forum and Bugzilla is open for comments**
  - All feedback welcome!

OpenCL Presentations in This Session

- **OpenCL 2.0 Overview**
  - Allen Hux, Intel
- **Accelerated Science – use of OpenCL in Land Down Under**
  - Tomasz Bednarz, CSIRO
  - Sydney Khronos Chapter Leader

OpenCL 2.0 Overview

Allen Hux
Intel Corporation

Goals

- Enable New Programming Patterns
- Performance Improvements
- Well-defined Execution & Memory Model
- Improve CL / GL sharing

Shared Virtual Memory

- **In OpenCL 1.2 buffer objects can only be passed as kernel arguments**
- **Buffer object described as pointer to type in kernel**
- **Restrictions**
  - Pass a pointer + offset as argument value
  - Store pointers in buffer object(s)
- **Why?**
  - Host and OpenCL device may not share the same virtual address space
  - No guarantee that the same virtual address will be used for a kernel argument across multiple enqueues

KHRONOS GROUP

Shared Virtual Memory

- **clSVMAlloc – allocates a shared virtual memory buffer**
  - Specify size in bytes
  - Specify usage information
  - Optional alignment value
- **SVM pointer can be shared by the host and OpenCL device**
- **Examples**

```
clSVMAlloc(ctx, CL_MEM_READ_WRITE, 1024 * 1024, 0)

clSVMAlloc(ctx, CL_MEM_READ_ONLY, 1024 * 1024, sizeof(cl_float4))
```

- **Free SVM buffers**
  - clEnqueueSVMFree, clSVMFree

Shared Virtual Memory

- clSetKernelArgSVMPointer
  - SVM pointers as kernel arguments
  - A SVM pointer
  - A SVM pointer + offset

```
kernel void
vec_add(float *src, float *dst)
{
    size_t id = get_global_id(0);
    dst[id] += src[id];
}
```

```
// allocating SVM pointers
cl_float *src = (cl_float *)clSVMAlloc(ctx, CL_MEM_READ_ONLY, size, 0);
cl_float *dst = (cl_float *)clSVMAlloc(ctx, CL_MEM_READ_WRITE, size, 0);
```

```
// Passing SVM pointers as arguments
clSetKernelArgSVMPointer(vec_add_kernel, 0, src);
clSetKernelArgSVMPointer(vec_add_kernel, 1, dst);
```

```
// Passing SVM pointer + offset as arguments
clSetKernelArgSVMPointer(vec_add_kernel, 0, src + offset);
clSetKernelArgSVMPointer(vec_add_kernel, 1, dst + offset);
```

Shared Virtual Memory

- clSetKernelExecInfo
  - Passing SVM pointers in other SVM pointers or buffer objects

```
// allocating SVM pointers
my_info_t *pA = (my_info_t *)clSVMAlloc(ctx,
        CL_MEM_READ_ONLY, sizeof(my_info_t), 0);
pA->pB = (cl_float *)clSVMAlloc(ctx,
        CL_MEM_READ_WRITE, size, 0);
```

```
// Passing SVM pointers
clSetKernelArgSVMPointer(my_kernel, 0, pA);

clSetKernelExecInfo(my_kernel,
                CL_KERNEL_EXEC_INFO_SVM_PTRS,
                1 * sizeof(void *), &pA->pB);
```

```
typedef struct {
   …
   float *pB;
   …
} my_info_t;

kernel void
my_kernel(global my_info_t *pA, …)
{
    …
    do_stuff(pA->pB, …);
    …
}
```

Shared Virtual Memory

- **Three types of sharing**
  - Coarse-grained buffer sharing
  - Fine-grained buffer sharing
  - System sharing

Shared Virtual Memory – Coarse & Fine Grained

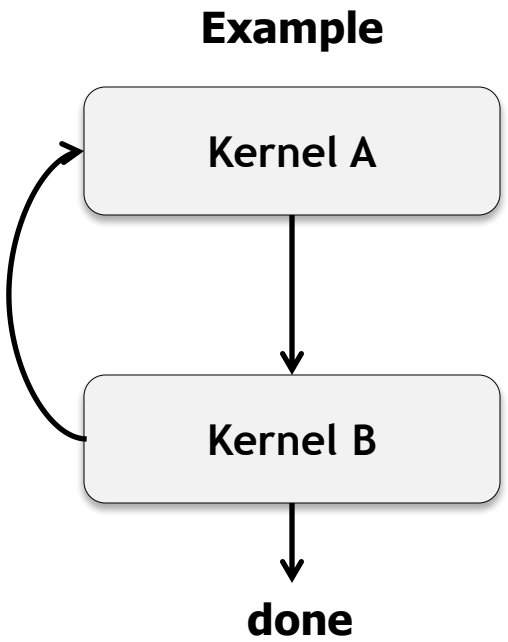
- **SVM buffers allocated using clSVMAlloc**
- **Coarse grained sharing**
  - Memory consistency only guaranteed at synchronization points
  - Host still needs to use synchronization APIs to update data
    - clEnqueueSVMMap / clEnqueueSVMUnmap or event callbacks
    - Memory consistency is at a buffer level
  - Allows sharing of pointers between host and OpenCL device
- **Fine grained sharing**
  - No synchronization needed between host and OpenCL device
    - Host and device can update data in buffer concurrently
    - Memory consistency using C11 atomics and synchronization operations
  - Optional Feature

Shared Virtual Memory – System Sharing

- **Can directly use any pointer allocated on the host**
  - No OpenCL APIs needed to allocate SVM buffers
- **Both host and OpenCL device can update data using C11 atomics and synchronization functions**
- **Optional Feature**

Nested Parallelism

- In OpenCL 1.2 only the host can enqueue kernels
- Iterative algorithm example
  - kernel A queues kernel B
  - kernel B decides to queue kernel A again
- Requires host - device interaction and for the host to wait for kernels to finish execution
  - Can use callbacks to avoid waiting for kernels to finish but still overhead
- A very simple but extremely common nested parallelism example



Nested Parallelism

- **Allow a device to queue kernels to itself**
  - Allow a work-item(s) to queue kernels
- **Use similar approach to how host queues commands**
  - Queues and Events
  - Functions that queue kernels and other commands
  - Event and Profiling functions

Nested Parallelism

- Use clang Blocks to describe kernel to queue

```
kernel void my_func(global int *a, global int *b)
{
   …
   void (^my_block_A)(void) =
         ^{
            size_t id = get_global_id(0);
            b[id] += a[id];
          };

  enqueue_kernel(get_default_queue(),
                 CLK_ENQUEUE_FLAGS_WAIT_KERNEL,
                 ndrange_1D(…),
                 my_block_A);
}
```

Nested Parallelism

```
int enqueue_kernel(queue_t queue,
                   kernel_enqueue_flags_t flags,
                   const ndrange_t ndrange,
                   void (^block)())

int enqueue_kernel(queue_t queue,
                   kernel_enqueue_flags_t flags,
                   const ndrange_t ndrange,
                   uint num_events_in_wait_list,
                   const clk_event_t *event_wait_list,
                   clk_event_t *event_ret,
                   void (^block)())
```

Nested Parallelism

- Queuing kernels with pointers to local address space as arguments

```
int enqueue_kernel(queue_t queue,
                   kernel_enqueue_flags_t flags,
                   const ndrange_t ndrange,
                   void (^block)(local void *, …), uint size0, …)

int enqueue_kernel(queue_t queue,
                   kernel_enqueue_flags_t flags,
                   const ndrange_t ndrange,
                   uint num_events_in_wait_list,
                   const clk_event_t *event_wait_list,
                   clk_event_t *event_ret,
                   void (^block)(local void *, …), uint size0, …)
```

Nested Parallelism

- Example showing queuing kernels with local address space arguments

```
void my_func_local_arg (global int *a, local int *lptr, …) { … }

kernel void my_func(global int *a, …)
{
   …
   uint local_mem_size = compute_local_mem_size(…);

   enqueue_kernel(get_default_queue(),
                  CLK_ENQUEUE_FLAGS_WAIT_KERNEL,
                  ndrange_1D(…),
                  ^(local int *p){my_func_local_arg(a, p, …);},
                  local_mem_size);
}
```

Nested Parallelism

- **Specify when a child kernel can begin execution (pick one)**
  - Don't wait on parent
  - Wait for kernel to finish execution
  - Wait for work-group to finish execution

- **A kernel's execution status is complete**
  - when it has finished execution
  - *and* all its child kernels have finished execution

Nested Parallelism

- **Other Commands**
  - Queue a marker
- **Query Functions**
  - Get workgroup size for a block
- **Event Functions**
  - Retain & Release events
  - Create user event
  - Set user event status
  - Capture event profiling info
- **Helper Functions**
  - Get default queue
  - Return a 1D, 2D or 3D ND-range descriptor

Generic Address Space

- In OpenCL 1.2, function arguments that are a pointer to a type must declare the address space of the memory region pointed to
- Many examples where developers want to use the same code but with pointers to different address spaces

```
void
my_func (local int *ptr, …)
{
    …
    foo(ptr, …);
    …
}
```

```
void
my_func (global int *ptr, …)
{
    …
    foo(ptr, …);
    …
}
```

- Above example is not supported in OpenCL 1.2
- Results in developers having to duplicate code

KHRONOS GROUP

Generic Address Space

- OpenCL 2.0 no longer requires an address space qualifier for arguments to a function that are a pointer to a type
  - Except for kernel functions
- Generic address space assumed if no address space is specified
- Makes it really easy to write functions without having to worry about which address space arguments point to

```
void
my_func (int *ptr, …)
{
   …
}

kernel void
foo(global int *g_ptr, local int *l_ptr, …)
{
   …
   my_func(g_ptr, …);
   my_func(l_ptr, …);
}
```

Generic Address Space – Casting Rules

- Implicit casts allowed from named to generic address space
- Explicit casts allowed from generic to named address space
- Cannot cast between constant and generic address spaces

```
kernel void foo()
{
    int *ptr;
    local int *lptr;
    global int *gptr;
    local int val = 55;

    ptr = gptr; // legal
    lptr = ptr; // illegal
    lptr = gptr; // illegal
    ptr = &val; // legal
    lptr = (local int *)ptr; // legal
}
```

Generic Address Space – Built-in Functions

- **global gentype* to_global(const gentype*)**
  local gentype* to_local(const gentype *)
  private gentype* to_private(const gentype *)
  - Returns NULL if cannot cast
- **cl_mem_fence_flags get_fence(const void *ptr)**
  - Returns the memory fence flag value
  - Needed by work_group_barrier and mem_fence functions

C11 Atomics

- **Implements a subset of the C11 atomic and synchronization operations**
  - Enable assignments in one work-item to be visible to others
- **Atomic operations**
  - loads & stores
  - exchange, compare & exchange
  - fetch and modify (add, sub, or, xor, and, min, max)
  - test and set, clear
- **Fence operation**
- **Atomic and Fence operations take**
  - Memory order
  - Memory scope
- **Operations are supported for global and local memory**

C11 Atomics

- **memory_order_relaxed**
  - Atomic operations with this memory order are not synchronization operations
  - Only guarantee atomicity
- **memory_order_acquire, memory_order_release, memory_order_acq_rel**
  - Atomic store in work-item A for variable M is tagged with memory_order_release
  - Atomic load in work-item B for same variable M is tagged with memory_order_acquire
  - Once the atomic load is completed work-item B is guaranteed to see everything work-item A wrote to memory before atomic store
  - Synchronization is only guaranteed between work-items releasing and acquiring the same atomic variable
- **memory_order_seq_cst**
  - Same as memory_order_acq_rel, and
  - A single total order exists in which all work-items observe all modifications

C11 Atomics

- **Memory scope - specifies scope of memory ordering constraints**
  - Work-items in a work-group
  - Work-items of a kernel executing on a device
  - Work-items of a kernel & host threads executing across devices and host
    - For shared virtual memory

C11 Atomics

- **Supported Atomic Types**
  - atomic_int, atomic_uint
  - atomic_long, atomic_ulong
  - atomic_float
  - atomic_double
  - atomic_intptr_t, atomic_uintptr_t, atomic_ptrdiff_t
  - atomic_size_t
  - atomic_flag
- **Atomic types have the same size & representation as the non-atomic types except for atomic_flag**
- **Atomic functions must be lock-free**

Images

- **2D image from buffer**
  - GPUs have dedicated and fast hardware for texture addressing & filtering
  - Accessing a buffer as a 2D image allows us to use this hardware
  - Both buffer and 2D image use the same data storage
- **Reading & writing to an image in a kernel**
  - Declare images with the read_write qualifier
  - Use barrier between writes and reads by work-items to the image
    - work_group_barrier(CLK_IMAGE_MEM_FENCE)
  - Only sampler-less reads are supported

Images

- **Writes to 3D images is now a core feature**
- **New image formats**
  - sRGB
  - Depth
- **Extended list of required image formats**
- **Improvements to CL / GL sharing**
  - Multi-sampled GL textures
  - Mip-mapped GL textures

Pipes

- Memory objects that store data organized as a FIFO
- Kernels can read from or write to a pipe object
- Host can only create pipe objects

Pipes

- **Why introduce a pipe object?**
  - Allow vendors to implement dedicated hardware to support pipes
  - Read from and write to a pipe without requiring atomic operations to global memory
  - Enable producer – consumer relationships between kernels

Pipes – Read & Write Functions

- **Work-item read pipe functions**
  - Read a packet from a pipe
  - Read with reservation
    - Reserve n packets for reading
    - Read individual packets (identified by reservation ID and packet index)
    - Confirm that the reserved packets have been read
- **Work-item write pipe functions**
  - Write a packet to a pipe
  - Write with reservation
- **Work-group pipe functions**
  - Reserve and commit packets for reading / writing

Other 2.0 Features

- **Program scope variables**
- **Flexible work-groups**
- **New work-item functions**
  - get_global_linear_id, get_local_linear_id
- **Work-group functions**
  - broadcast, reduction, vote (any & all), prefix sum
- **Sub-groups**
- **Sharing with EGL images and events**