

OPENCL[™] **C++**

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OPENCL™ TODAY
WHAT WORKS, WHAT DOESN'T

THE PROBLEM TODAY

- OpenCL™ out of the box provides:
 - C API
 - C Kernel language
- Excellent performance, but programming can be longwinded and difficult
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- OpenCL™ out of the box provides:
 - C API
 - C Kernel language
- Excellent performance, but programming can be longwinded and difficult
- For example, to enqueue a kernel, the programmer must:
 - Select a platform
 - Select a device
 - Create a context
 - Allocate memory objects
 - Copy data to the device
 - Create and compile the program
 - Create a kernel
 - Create a command queue
 - Enqueue the kernel for execution
 - Copy data back from the device

EXAMPLE – VECTOR ADDITION (HOST PROGRAM)

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

```
// get the list of GPU devices associated with context
clGetContextInfo(context, CL_CONTEXT_DEVICES, 0, NULL, &cb);
devices = malloc(cb);
clGetContextInfo(context, CL_CONTEXT_DEVICES, cb, devices, NULL);
```

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

```
// allocate the buffer memory objects
memobj[0] = clCreateBuffer(context, CL_MEM_READ_ONLY | CL_MEM_WRITE_ONLY, sizeof(float) * n, NULL, &err);
memobj[1] = clCreateBuffer(context, CL_MEM_READ_ONLY | CL_MEM_WRITE_ONLY, sizeof(float) * n, NULL, &err);
memobj[2] = clCreateBuffer(context, CL_MEM_WRITE_ONLY, sizeof(float) * n, NULL, &err);
```

```
// create the program
program = clCreateProgramWithSource(context, 1, &program,
```

```
// build the program
err = clBuildProgram(program, 0, NULL, NULL, NULL, NULL);
```

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

// set the args values
err = clSetKernelArg(kernel, 0, sizeof(cl_mem), (void *) memobj[0]);
err |= clSetKernelArg(kernel, 1, sizeof(cl_mem), (void *) memobj[1]);
err |= clSetKernelArg(kernel, 2, sizeof(cl_mem), (void *) memobj[2]);
```

```
// set work-item dimensions
global_work_size[0] = n;
```

```
// execute kernel
err = clEnqueueNDRangeKernel(cmd_queue, kernel, 1, NULL, global_work_size, NULL, 0, NULL, NULL);
```

```
// read output array
err = clEnqueueReadBuffer(cmd_queue, memobj[2], CL_TRUE, 0, n*sizeof(float), dst, 0, NULL, NULL);
```

Define platform and queues

Ugly, isn't it.

Extreme portability.

Luckily... Same boiler-plate code
across virtually every OpenCL host
code

objects

kernel

Execute the kernel

Read results on the host

OPENCL™ C++
*IMPROVING THE PROGRAMMING
MODEL*

OPENCL™ C++ FEATURES

- Khronos has defined a common C++ header file containing a high level interface to OpenCL
- It's much easier than using the C API, but it still needed work
- Improved C++ host API:
 - Interface for all OpenCL C API
 - Statically checked information routines (type safe versions of `clGetInfoXX()`)
 - Automatic reference counting (no need for `clRetain()/clRelease()`)

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- Khronos has defined a common C++ header file containing a high level interface to OpenCL
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- Improved C++ host API:
 - Interface for all OpenCL C API
 - Statically checked information routines (type safe versions of `clGetInfoXX()`)
 - Automatic reference counting (no need for `clRetain()/clRelease()`)
 - Defaults (platform, context, command queues, and so on.)
 - Kernel functors
 - and more...

INTERFACE FOR ALL OPENCL™ C API

- Single header file and inside a single namespace

```
#include <CL/cl.hpp>           // Khronos C++ Wrapper API
using namespace cl;
```

- Each base object in the OpenCL C API has a corresponding OpenCL C++ class

- cl_device_id → cl::Device
- cl_platform_id → cl::Platform
- cl_context → cl::Context
- etc...

- Unlike C API, multiple ways of constructing OpenCL objects are possible through object constructors

- Can still get to corresponding C object through operator()

AUTOMATIC REFERENCE COUNTING

- OpenCL™ object lifetimes are explicitly managed through reference counting (retain, release)
 - Common source of program errors!
 - OpenCL C++ can do this implicitly through object destructors

```
cl_context = clCreateContextFromType(0, CL_DEVICE_TYPE_GPU, NULL, NULL, NULL);
cmd_queue = clCreateCommandQueue(context, devices[0], 0, NULL);
program = clCreateProgramWithSource(context, 1, &program_source, NULL, NULL);
err = clBuildProgram(program, 0, NULL, NULL, NULL, NULL);
kernel = clCreateKernel(program, "vec_add", NULL);
err = clSetKernelArg(kernel, 0, sizeof(cl_mem), (void *) &memobjs[0]);
err = clSetKernelArg(kernel, 1, sizeof(cl_mem), (void *) &memobjs[1]);
err = clSetKernelArg(kernel, 2, sizeof(cl_mem), (void *) &memobjs[2]);
```

```
err = clReleaseKernel(kernel);
err = clReleaseProgram(program);
err = clReleaseMemObject(memobjs[0]);
err = clReleaseMemObject(memobjs[1]);
err = clReleaseMemObject(memobjs[2]);
err = clReleaseCommandQueue(cmd_queue);
err = clReleaseProgram(program);
```

OpenCL C API reference counts objects

Explicit release is required

DEFAULTS

- OpenCL™ C++ introduces defaults for common use cases
 - Allows for a simple approach to writing basic applications
 - Excellent for beginners
- Provided defaults include:
 - Platform: simply pick the first one
 - Device: use the `CL_DEVICE_TYPE_DEFAULT` macro
 - Context: created from the default device
 - CommandQueue: created on the default device and context
- Each OpenCL C++ class includes a static member function:
 - `static Type getDefault();`
- Supports routines to set defaults, which have a transitive effect

KERNEL FUNCTORS

- Current OpenCL™ interface for kernels is extremely verbose:

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

// set the args values
err = clSetKernelArg(kernel, 0, sizeof(cl_mem), (void *) &memobjs[0]);
err |= clSetKernelArg(kernel, 1, sizeof(cl_mem), (void *) &memobjs[1]);
err |= clSetKernelArg(kernel, 2, sizeof(cl_mem), (void *) &memobjs[2]);

// set work-item dimensions
global_work_size[0] = n;

// execute kernel
err = clEnqueueNDRangeKernel(cmd_queue, kernel, 1, NULL, global_work_size, NULL, 0, NULL, NULL);
```

- No guarantee of static type safety (both for arguments types or number of arguments)
- OpenCL C++ introduces kernel functors:
 - Type safe, directly callable kernels

```
std::function<Event (const EnqueueArgs&, Buffer, Buffer, Buffer)> vadd =
    make_kernel<Buffer, Buffer, Buffer>(Program(program_source), "vadd");

vadd(EnqueueArgs(NDRange(n)), memobj[0], memobj[1], memobj[2]));
```

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- Current OpenCL™ interface for kernels is extremely verbose:

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

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// set work-item dimensions
global_work_size[0] = n;

// execute kernel
err = clEnqueueNDRangeKernel(cmd_queue, kernel, 1, NULL, global_work_size, NULL, NULL);
```

Kernel dispatch is just a function call

- No guarantee of static type safety (both for arguments type and number of arguments)
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```
std::function<Event (const EnqueueArgs&, Buffer, Buffer, Buffer)> vadd =
    make_kernel<Buffer, Buffer, Buffer>(Program(program_source), "vadd");

vadd(EnqueueArgs(NDRange(n)), memobj[0], memobj[1], memobj[2]);
```

PUTTING IT ALL TOGETHER: OPENCL™ C++ VECTOR ADD

```
std::function<Event (const EnqueueArgs&, Buffer, Buffer, Buffer)> vadd =  
    make_kernel<Buffer, Buffer, Buffer>(Program(program_source), "vadd");  
  
memobj[0] = Buffer (CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR, sizeof(float) * n, srcA);  
memobj[1] = Buffer (CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR, sizeof(float) * n, srcB);  
memobj[2] = Buffer (CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR, sizeof(float) * n);  
  
vadd(EnqueueArgs(NDRange(n)), memobj[0], memobj[1], memobj[2]);  
  
enqueueReadBuffer(memobj[2], CL_TRUE, sizeof(float) * n, dest);
```

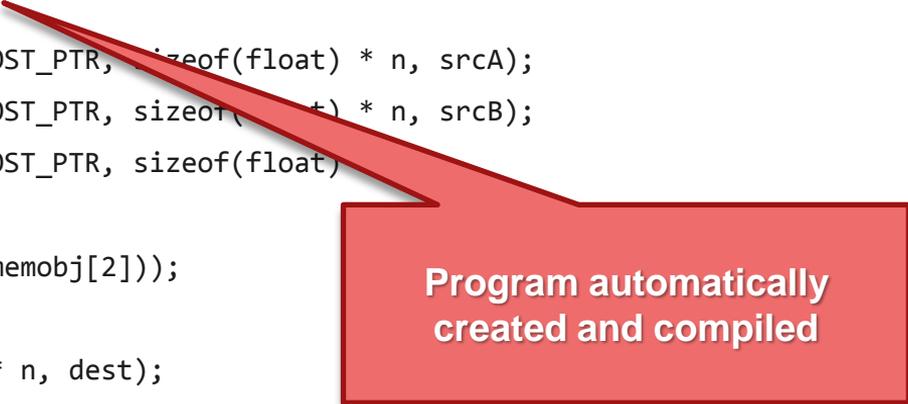
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memobj[2] = Buffer (CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR, sizeof(float) * n, dest);
```

```
vadd(EnqueueArgs(NDRange(n)), memobj[0], memobj[1], memobj[2]);
```

```
enqueueReadBuffer(memobj[2], CL_TRUE, sizeof(float) * n, dest);
```



Program automatically
created and compiled

PUTTING IT ALL TOGETHER: OPENCL™ C++ VECTOR ADD

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memobj[2] = Buffer (CL_MEM_READ_ONLY | CL_MEM_COPY_HOST_PTR, sizeof(float) * n, dest);
```

```
vadd(EnqueueArgs(NDRange(n)), memobj[0], memobj[1], memobj[2]);
```

```
enqueueAndBuffer(memobj[2], CL_TRUE, sizeof(float) * n, dest);
```

**Program automatically
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**Defaults, no need to
reference context,
command queue**

PUTTING IT ALL TOGETHER: OPENCL™ C++ VECTOR ADD

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```
vadd(EnqueueArgs(NDRange(n)), memobj[0], memobj[1], memobj[2]);
```

```
enqueueAndBuffer(memobj[2], CL_TRUE, sizeof(float) * n, dest);
```

**Program automatically
created and compiled**

**Defaults, no need to
reference context,
command queue**

**No clReleaseXXX cleanup
code required**

PUTTING IT ALL TOGETHER: OPENCL™ C++ VECTOR ADD

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vadd(EnqueueArgs(NDRange(n)), memobj[0], memobj[1], memobj[2]);  
  
enqueueReadBuffer(memobj[2], CL_TRUE, sizeof(float) * n, dest);
```

OPENCL™ C++
KERNEL LANGUAGE ENHANCEMENTS

OPENCL™ C++ ADDRESS SPACES

- OpenCL programming model includes address spaces to explicitly manage memory hierarchy
 - global, local, constant and private address spaces
 - Example:

```
kernel void foo(global int * g, local int * l)
```

- This mostly extends naturally to OpenCL C++, however:

```
struct Colour {  
    int r_, g_, b_;  
    Colour(int r, int g, int b);  
};  
kernel foo(global Colour& gColour) {  
    Colour pColour = gColour;  
}
```

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```

C++ class member functions carry an implicit this pointer. What is its address space? Note that there is an implicit copy constructor here.

OPENCL™ C++ ADDRESS SPACES CONTINUED

- The copy constructor's address space must be inferred
- First of all we have allowed the developer to specify the address space:

```
struct Shape {  
    int setColour(Colour) global + local;  
    int setColour(Colour) private;  
};
```

- This would not have helped with the implicit copy constructor

OPENCL™ C++ ADDRESS SPACES CONTINUED

- We have extended the type system to infer the address space from context
 - I'm keeping this brief because Ben Gaster will discuss this in more detail later in this session

- Use of auto and decltype allows even explicit *this* pointer use to work

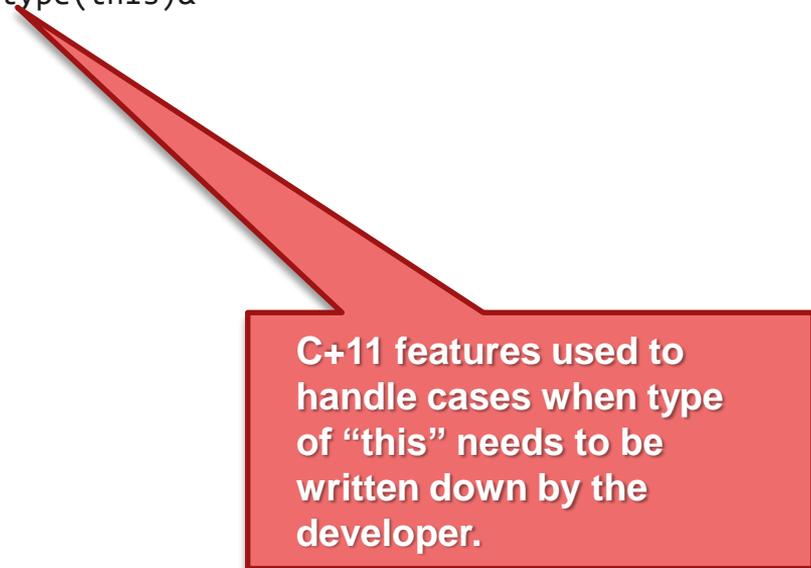
```
operator (const decltype(this)& rhs) -> decltype(this)&
{
    if (this == &rhs) { return *this; }
    ...
    return *this;
}
```

OPENCL™ C++ ADDRESS SPACES CONTINUED

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operator (const decltype(this)& rhs) -> decltype(this)&
{
    if (this == &rhs) { return *this; }
    ...
    return *this;
}
```



C++11 features used to handle cases when type of “this” needs to be written down by the developer.

OPENCL™ C++ ADDRESS SPACES CONT'D

- Further, we added the ability to parameterise on address spaces:

```
template<address-space aspace>
struct Shape {
    int foo(aspace Colour&) global + local;
    int foo(aspace Colour&) private;
    int bar(void);
};
```

OPENCL™ C++ ADDRESS SPACES CONT'D

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**Abstract over address
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Abstract over address space qualifiers.

Methods can be annotated with address spaces, controls “this” pointer location. Extended to overloading.

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Abstract over address space qualifiers.

Methods can be annotated with address spaces, controls “this” pointer location. Extended to overloading.

Default address space for “this” is deduced automatically. Support default constructors.

SOME FUTURE EXTENSIONS

NOT YET PUBLIC, BUT YOU NEVER

KNOW

WE'VE LOOKED AT POSSIBLE NEW FEATURES FOR THE FUTURE.

- Smart pointers
 - To smoothly reuse code between discrete and shared memory infrastructures
 - To allow integration of specialized descriptors and similar features in the future

- Application of \mathcal{E} cute descriptors to OpenCL C++
 - Support optimised code generation through separate descriptions of execution and memory mappings

SMART POINTERS

- A pointer type designed to work on current hardware
- Uses standard C++ design methodologies like custom allocators
 - Strongly typed; maintain locality; could store base and offset

```
cl::Pointer<int> x = cl::malloc<int>(N);
for (int i = 0; i < N; i++) {
    *(x+i) = rand();
}
```

```
std::function<
    Event (const cl::EnqueueArgs&,
           cl::Pointer<int>)> plus =
    make_kernel<
        cl::Pointer<int>, int>(
        "kernel void plus(global Pointer<int> io)"
        "{int i = get_global_id(0);
         *(io+i) = *(io+i) * 2;}");
```

```
plus(EnqueueArgs(NDRange(N)), x);
for (int i = 0; i < N; i++) {
    cout << *(x+i) << endl;
}
```

SMART POINTERS

Construct pointer with specialized allocator

- A pointer type designed to work on current hardware
- Uses standard C++ design methodologies like custom allocator
 - Strongly typed; maintain locality; could store base and offset

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>
```

Assign and read pointer

Pass pointer to kernel functor.

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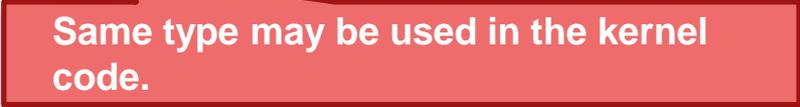
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```
plus(EnqueueArgs(NDRange(N)), x);
for (int i = 0; i < N; i++) {
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}
```



Same type may be used in the kernel code.

SMART POINTERS

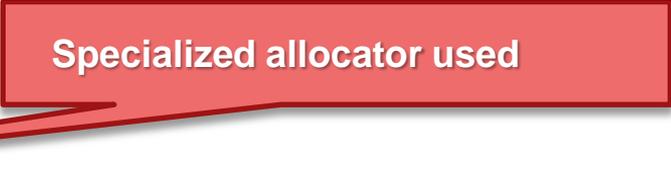
- Smart pointers can be used for allocating complex pointer-based data structures
 - Storing the buffer offset allows this to work

```
struct Node {
    int value;
    Pointer<Node> next;
};
Pointer<Node> createNode(int x) {
    Pointer<Node> result = malloc<Node>(1);
    result->value = x;
    result->next = Pointer<Node>();
    return result;
}
```

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```



Specialized allocator used

ACCESS/EXECUTE DESCRIPTORS

- Pointers are often a limitation to parallelism
 - Aliasing can be hard to prove
 - Analysing bounds of pointer accesses can be impossible
 - Computing data movement in advance is infeasible in the general case
- In loop nest, not in generated kernel
 - The loop nest may carry dependencies if we can analyse it
 - The generated kernel may have lost this inter-iteration information
- Various techniques partially address this
 - restrict
 - Parallelism guarantees such as the basic implicit vector parallelism provided by OpenCL kernels
 - Automated data movement may still be infeasible or unsafe

ACCESS/EXECUTE DESCRIPTORS

- The decoupled access/execute model attempts to alleviate this
 - Separate the execution domain from its memory accesses
 - Declaratively specify as much as possible of the memory access pattern to enable stronger optimisations
- We might, for example, specify two extended pointers and their metadata:

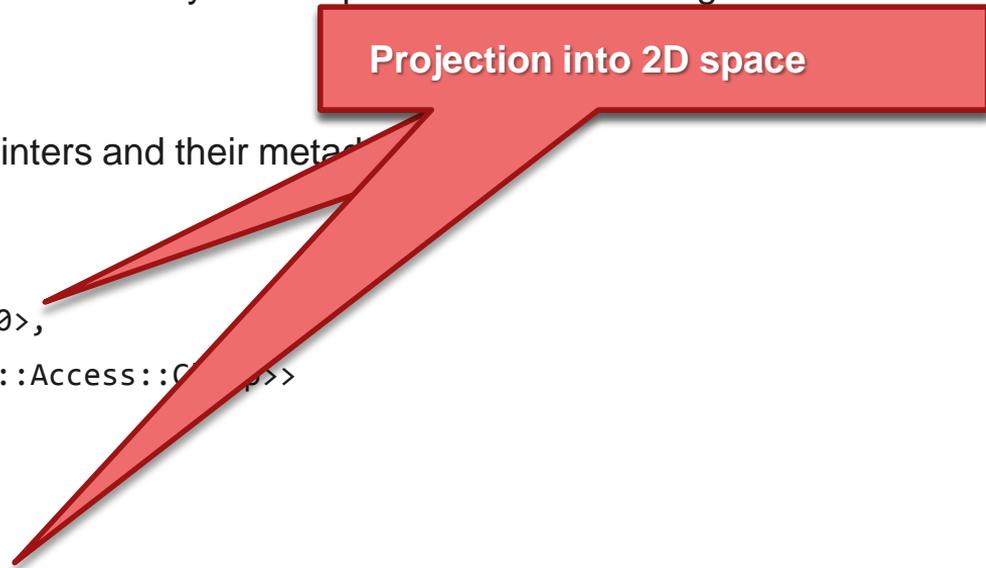
```
typedef cl::Pointer<int,  
    cl::Access::Mapping<  
        cl::Access::Project<100, 100>,  
        cl::Access::Region<3, 3, cl::Access::Clamp>>  
    AEcutePointerIN;  
typedef cl::Pointer<float,  
    cl::Access::Mapping<  
        cl::Access::Project<100, 100>>  
    AEcutePointerOUT;
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    AExecutePointerOUT;
```



Projection into 2D space

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typedef cl::Pointer<float,  
    cl::Access::Mapping<  
        cl::Access::Project<100, 100>>  
    AEcutePointerOUT;
```



Memory access is a 3x3 region around the projected centre.

ÆCUTE DESCRIPTORS

- We then use the pointers in a kernel:

```
kernel void plus( global const AEcutePointerIN in, global AEcutePointerOUT out) {  
    int2 wid = (int2)(get_global_id(0), get_global_id(1));  
    float sum = 0.f;  
    for( int i = 0; i < 3; ++i ) {  
        for( int j = 0; j < 3; ++j ) {  
            sum += (float)in(j, i);  
        }  
    }  
    out = sum / 9.f;  
};
```

i and ***j*** directly iterate over the ***region***, not the input addresses. The region may have been copied locally with no update to the addressing necessary

SOME ANALYSIS

*DID WE MAKE THINGS GO SLOWLY
AND WHAT DID WE GAIN?*

PERFORMANCE

- C++ commonly is thought to have a performance overhead
- It isn't the only myth out there, but it's the relevant one for today

PERFORMANCE

- C++ commonly is thought to have a performance overhead
- It isn't the only myth out there, but it's the relevant one for today
- Performance measurements on the host code showed no difference from OpenCL™ C API
 - Not a bad thing!
 - Productivity, not performance enhancement
- Performance measurements on the device code show no difference from OpenCL C code
 - Not unexpected
 - Static C++ is essentially zero overhead

CODE SIZE REDUCTION

- Sometimes substantial reduction in code size:

Application	C lines	C++ lines	Reduction
Vector addition	268	140	47.7%
Pi computation	306	166	45.8%
Ocean simulation	1386	533	61.5%
Particle simulation	733	601	18.0%
Radix sort	627	593	5.4%

CONCLUSION

- OpenCL™ C++
 - Productivity abstraction over OpenCL's C interfaces
 - Abstracts both host and device components

- Available today:
 - Downloadable header from www.khronos.org (supports OpenCL 1.2)
 - Header and OpenCL C++ kernel language support in AMD APP SDK 2.7
 - <http://developer.amd.com>

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