Making OpenCL™ Simple with Haskell

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January, 2011

AMD

Attribution and WARNING

- The ideas and work presented here are in collaboration with:
  - Garrett Morris (AMD intern 2010 & PhD student Portland State)

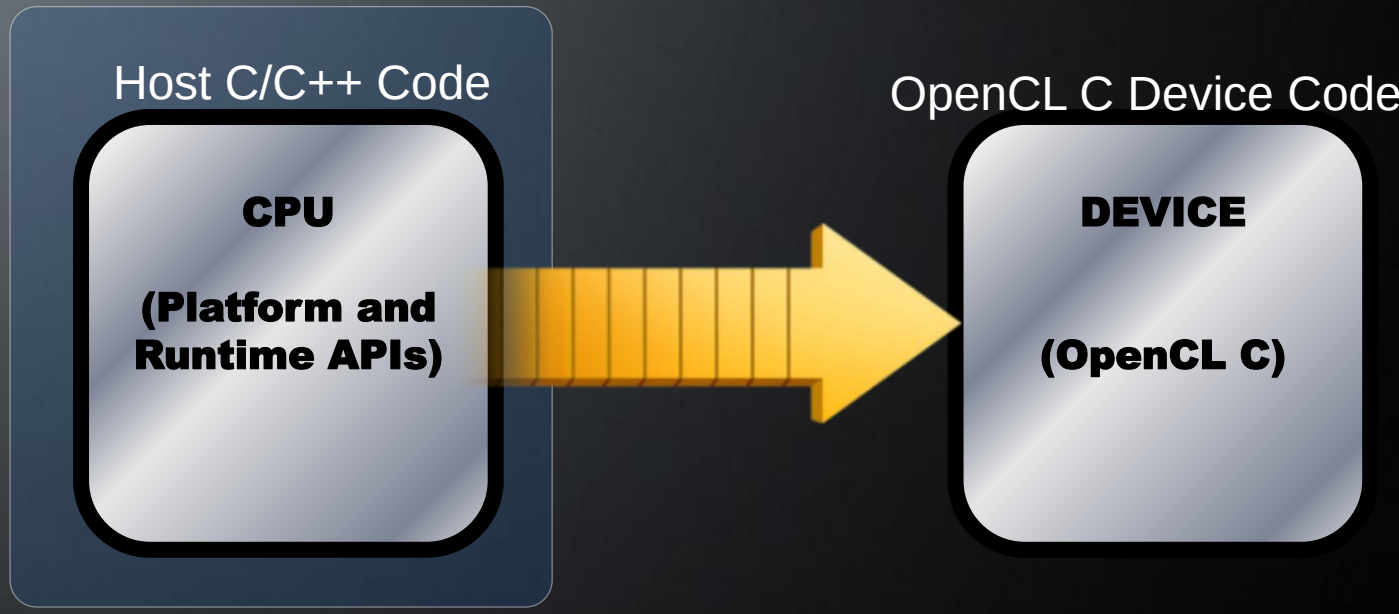
- Garrett is the Haskell expert and knows a lot more than I do about transforming Monads!

AGENDA

- Motivation
- Whistle stop introduction to OpenCL
- Bringing OpenCL to Haskell
- Lifting to something more in the spirit of Haskell
- Quasiquotation
- Issues we face using Haskell at AMD
- Questions

Motivation

OPENCL™ PROGRAM STRUCTURE



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HELLO WORLD OPENCL™ C SOURCE

```
__constant char hw[] = "Hello World\n";
__kernel void hello(__global char * out) {
   size_t tid = get_global_id(0);
  out[tid] = hw[tid];
}
```

HELLO WORLD OPENCL™ C SOURCE

```
__constant char hw[] = "Hello World\n";
    __kernel void hello(__global char * out) {
     size_t tid = get_global_id(0);
    out[tid] = hw[tid];
  }
```

- This is a separate source file (or string)
- Cannot directly access host data
- Compiled at runtime

HELLO WORLD - 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, NULL);


memobjs[0] = clCreateBuffer(context,CL_MEM_WRITE_ONLY,

   sizeof(cl_char)*strlen("Hello World", NULL,
                                          NULL);

// create the program

program = clCreateProgramWithSource(context, 1,
   &program_source, NULL, NULL);
```

```
// 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, (void *) &memobjs[0],
                                  sizeof(cl_mem));

// set work-item dimensions
global_work_size[0] = strlen("Hello World");;

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

// read output array
err = clEnqueueReadBuffer(cmd_queue, memobjs[0],
   CL_TRUE, 0, strlen("Hello World") *sizeof(cl_char),
   dst, 0, NULL, NULL);
```

HELLO WORLD - HOST PROGRAM

Define platform and queues

```
// create the OpenCL context on a GPU device

cl_context = clCreateContextFromType(0

// 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
```

Define Memory objects

```
// allocate the buffer memory objects

memobjs[0] = clCreateBuffer(context, CL_MEM_READ_ONLY |
   CL_MEM_COPY_HOST_PTR, sizeof(cl_char)*strlen("Hello
   World"), srcA, NULL);}

// create the program

program = clCreateProgramWithSource(context, 1,
   &progra
```

Create the program

Build the program

```
//
er                                    , NULL, NULL,
   NULL);
```

Create and setup kernel

```
//
k                                              LL);

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

// 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);
```

Execute the kernel

```
// read output array
err = cl                                    , CL_TRUE,
   0, n*                                    ;
```

Read results on the host

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USING HASKELL OUR GOAL IS TO WRITE THIS

```
import Language.OpenCL.Module

hstr = "Hello world\n“
hlen = length hstr + 1

prog = initCL [$cl|
      __constant char hw[] = $hstr;
      __kernel void hello(__global char * out) {
      size_t tid = get_global_id(0);
     out[tid] = hw[tid];
   }
|]

main :: IO ()
main = withNew prog $
   using (bufferWithFlags hwlen [WriteOnly]) $ \b ->
      do [k] <- theKernels
         invoke k b `overRange` ([0], [hwlen], [1])
         liftIO . putStr . map castCCharToChar . fst =<< readBuffer b 0 (hlen - 1)
```

USING HASKELL OUR GOAL IS TO WRITE THIS

```
import Language.OpenCL.Module

hstr = "Hello world\n“
hlen = length hstr + 1

prog = initCL [$cl| Quasiquoting
      __constant char hw[] = $hstr;
      __kernel void hello(__global char * out) {
      size_t tid = get_global_id(0);
     out[tid] = hw[tid];
   }
|]

main :: IO ()
main = withNew platform $ \p ->
   using (bufferWithFlags hwlen [WriteOnly]) $ \b ->
      do [k] <- theKernels
         invoke k b `overRange` ([0], [hwlen], [1])
         liftIO . putStr . map castCCharToChar . fst =<< readBuffer b 0 (hlen - 1)
```

Monad transformers

Single source

OpenCL C code statically checked at compile time.

No OpenCL or Haskell compiler modifications

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|]

main :: IO ()
main = withNew platform $ \p ->
  using (bufferWithFlags hwlen [WriteOnly]) $ \b ->
    do [k] <- theKernels
       invoke k b `overRange` ([0], [hwlen], [1])
       liftIO . putStr . map castCCharToChar . fst =<< readBuffer b 0 (hlen - 1)
```

Monad transformers

Single source

OpenCL C code statically checked at compile time.

No OpenCL or Haskell compiler modifications

LEARN FROM COMMON USES

- In OpenCL we generally see:
  - Pick single device (often GPU or CL_DEVICE_TYPE_DEFAULT)
  - All “kernels” in cl_program object are used in application

- In CUDA the default for runtime mode is:
  - Pick single device (always GPU)
  - All “kernels” in scope are exported to the host application for specific translation unit, i.e. calling kernels is syntactic and behave similar to static linkage.

Whistle stop introduction to OpenCL™

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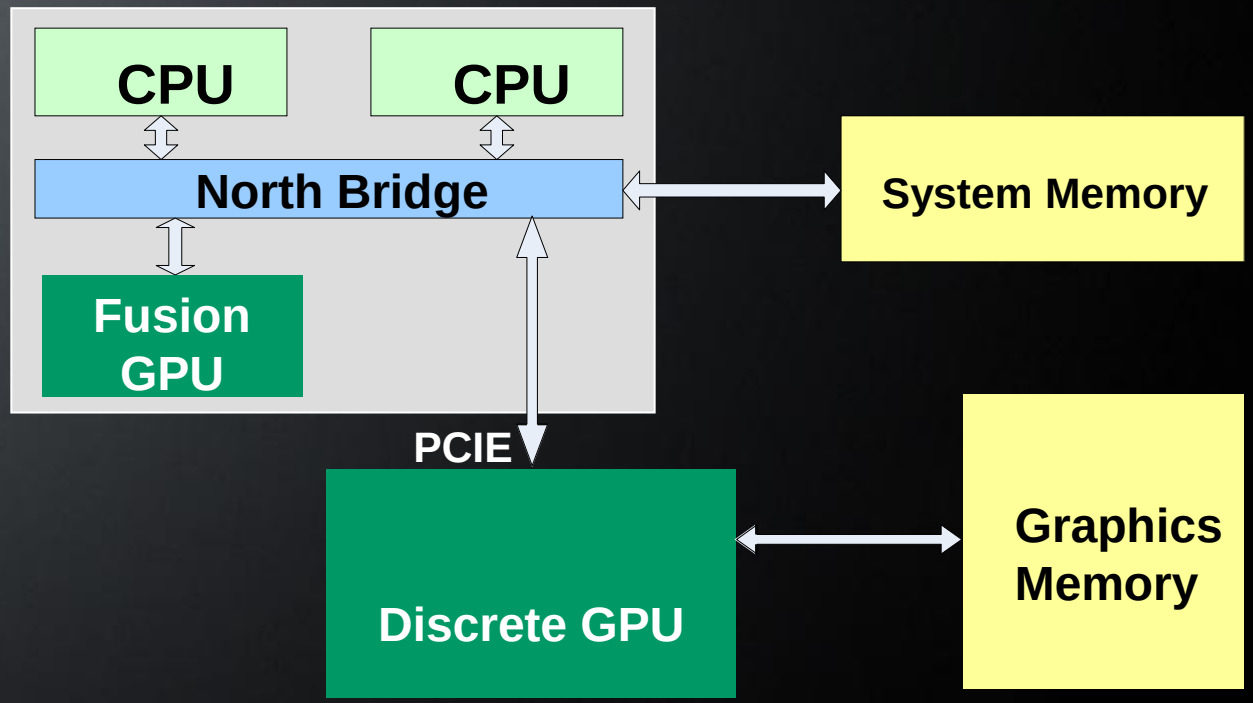
IT'S A HETEROGENEOUS WORLD

- A modern platform Includes:
  - One or more CPUs
  - One or more GPUs
  - And more



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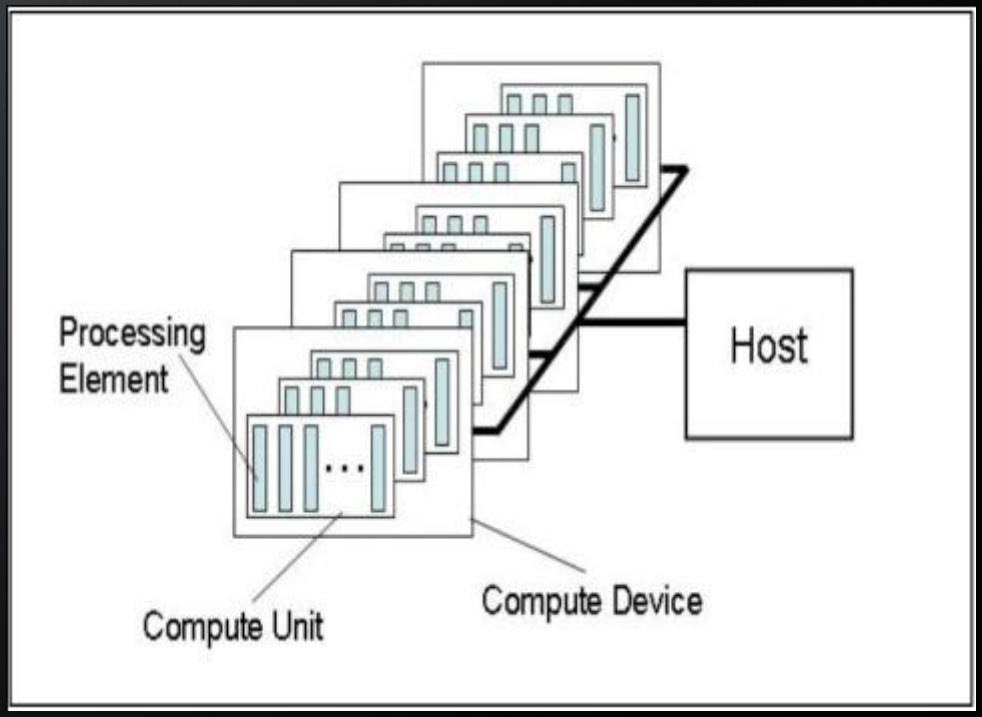
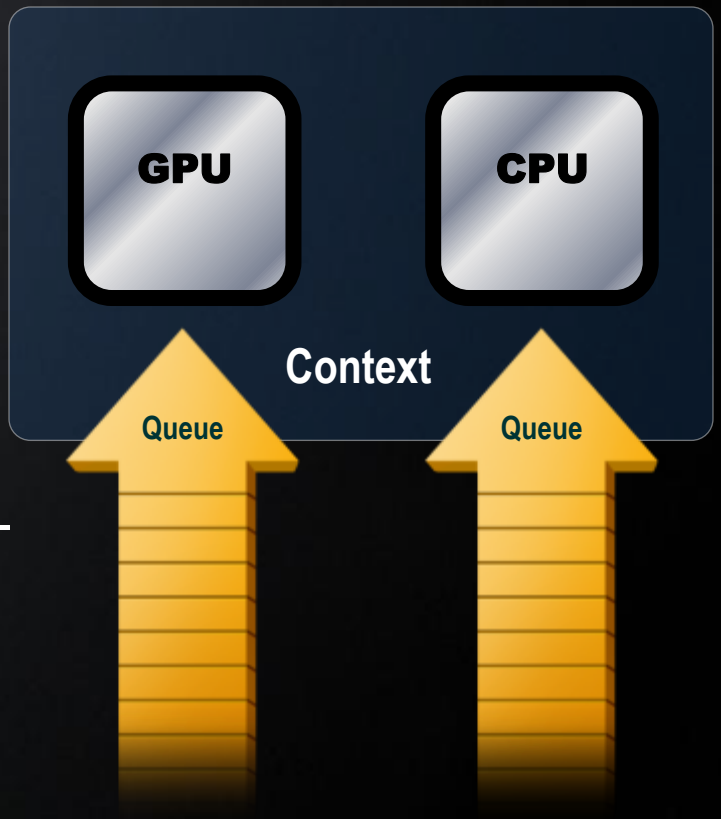
OPENCL™ PLATFORM MODEL

- One Host + one or more Compute Devices
  - Each Compute Device is composed of one or more Compute Units
    - Each Compute Unit is further divided into one or more Processing Elements



OPENCL™ EXECUTION MODEL

- An OpenCL application runs on a host which submits work to the compute devices
  - **Work item**: the basic unit of work on an OpenCL device
  - **Kernel**: the code for a work item. Basically a C function
  - **Program**: Collection of kernels and other functions (Analogous to a dynamic library)
  - **Context**: The environment within which work-items executes … includes devices and their memories and command queues
- Applications queue kernel execution instances
  - Queued in-order … one queue to a device
  - Executed in-order or out-of-order



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THE BIG IDEA BEHIND OPENCL™

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

Traditional loops

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

THE BIG IDEA BEHIND OPENCL™

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

Traditional loops

```
void
trad_mul(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

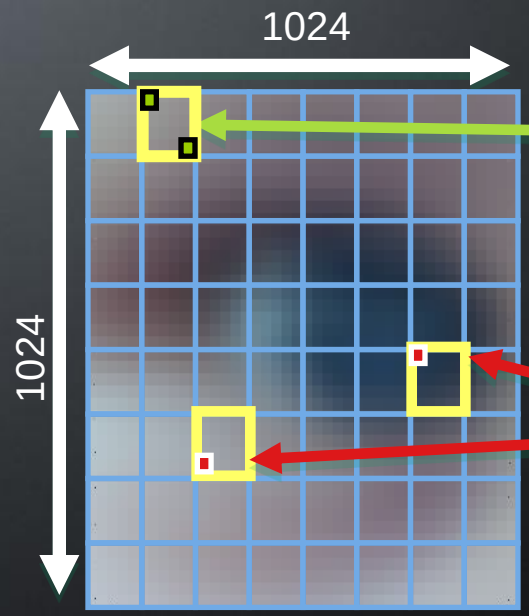
```
kernel void
dp_mul(global const float *a,
       global const float *b,
       global float *c)
{
  int id = get_global_id(0);

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

} // execute over "n" work-items
```

AN N-DIMENSION DOMAIN OF WORK-ITEMS

- Global Dimensions: 1024 x 1024 (whole problem space)
- Local Dimensions: 128 x 128 (work group … executes together)



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

Cannot synchronize outside of a workgroup

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

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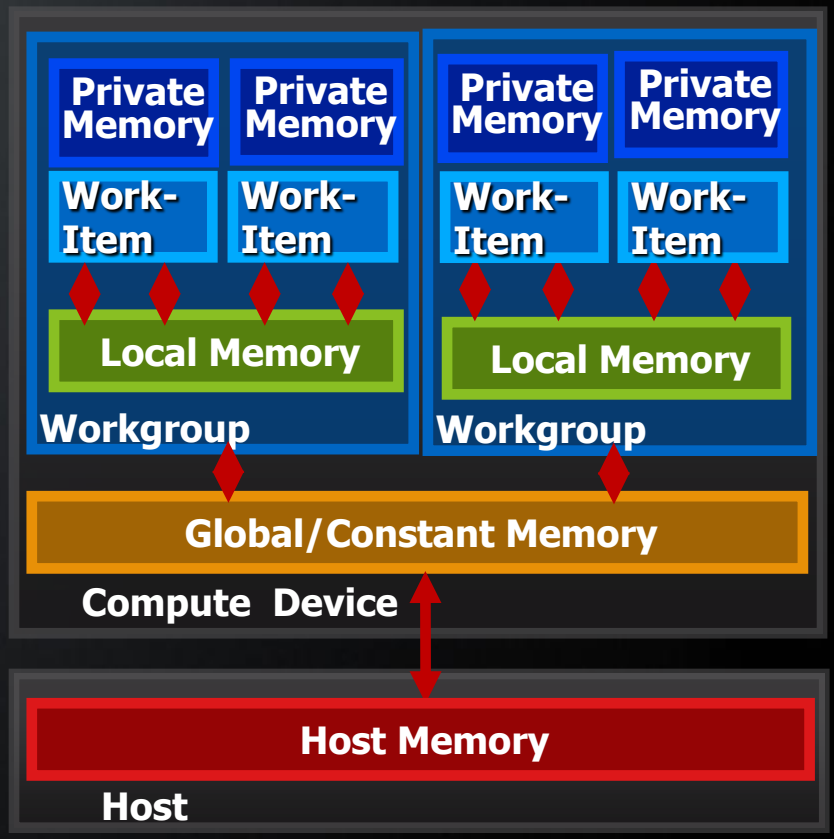
OPENCL™ MEMORY MODEL

- **Private Memory**
  - –Per work-item
- **Local Memory**
  - –Shared within a workgroup
- **Global/Constant Memory**
  - –Visible to all workgroups
- **Host Memory**
  - –On the CPU



Memory management is Explicit

You must move data from host -> global -> local … *and* back

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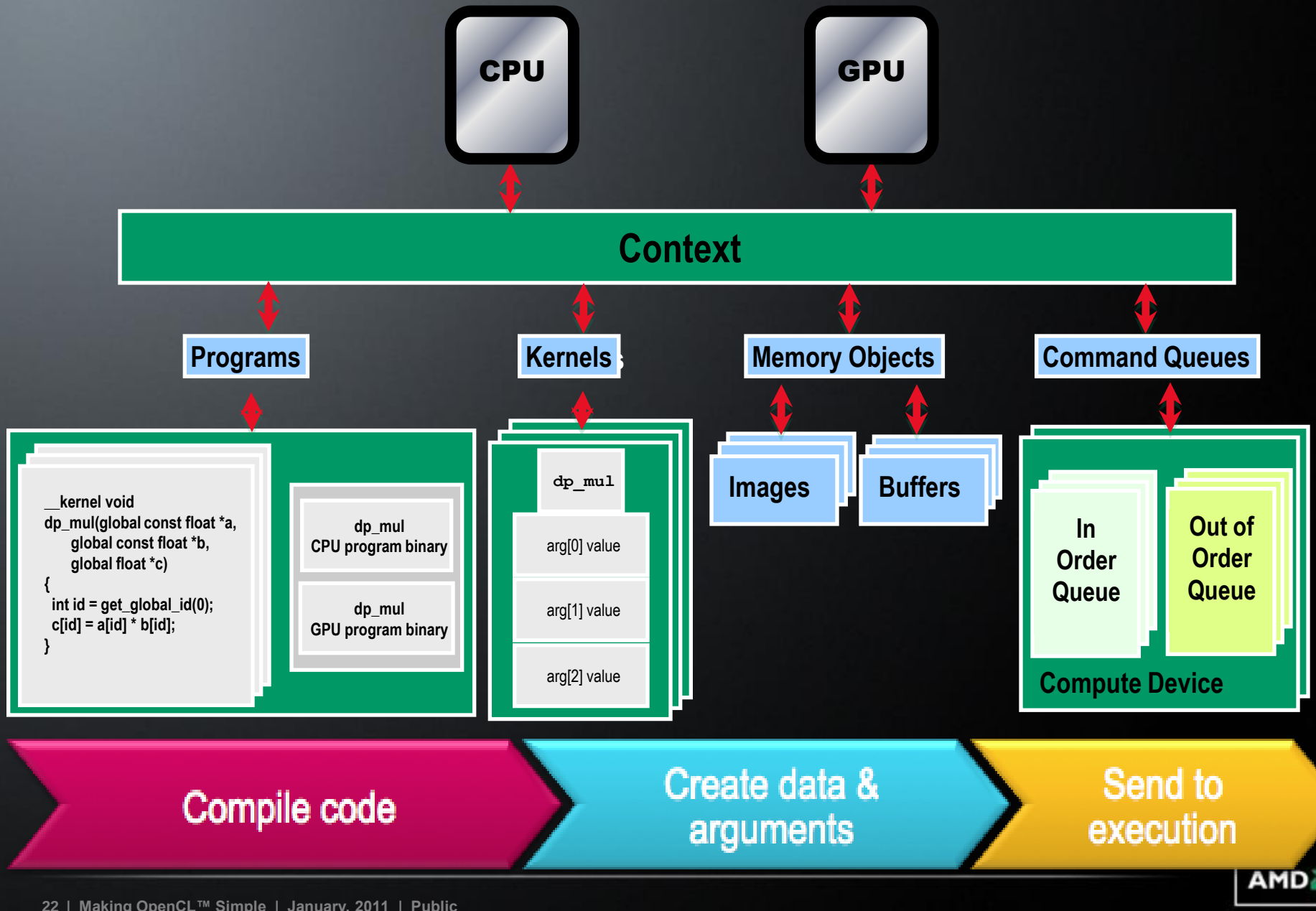
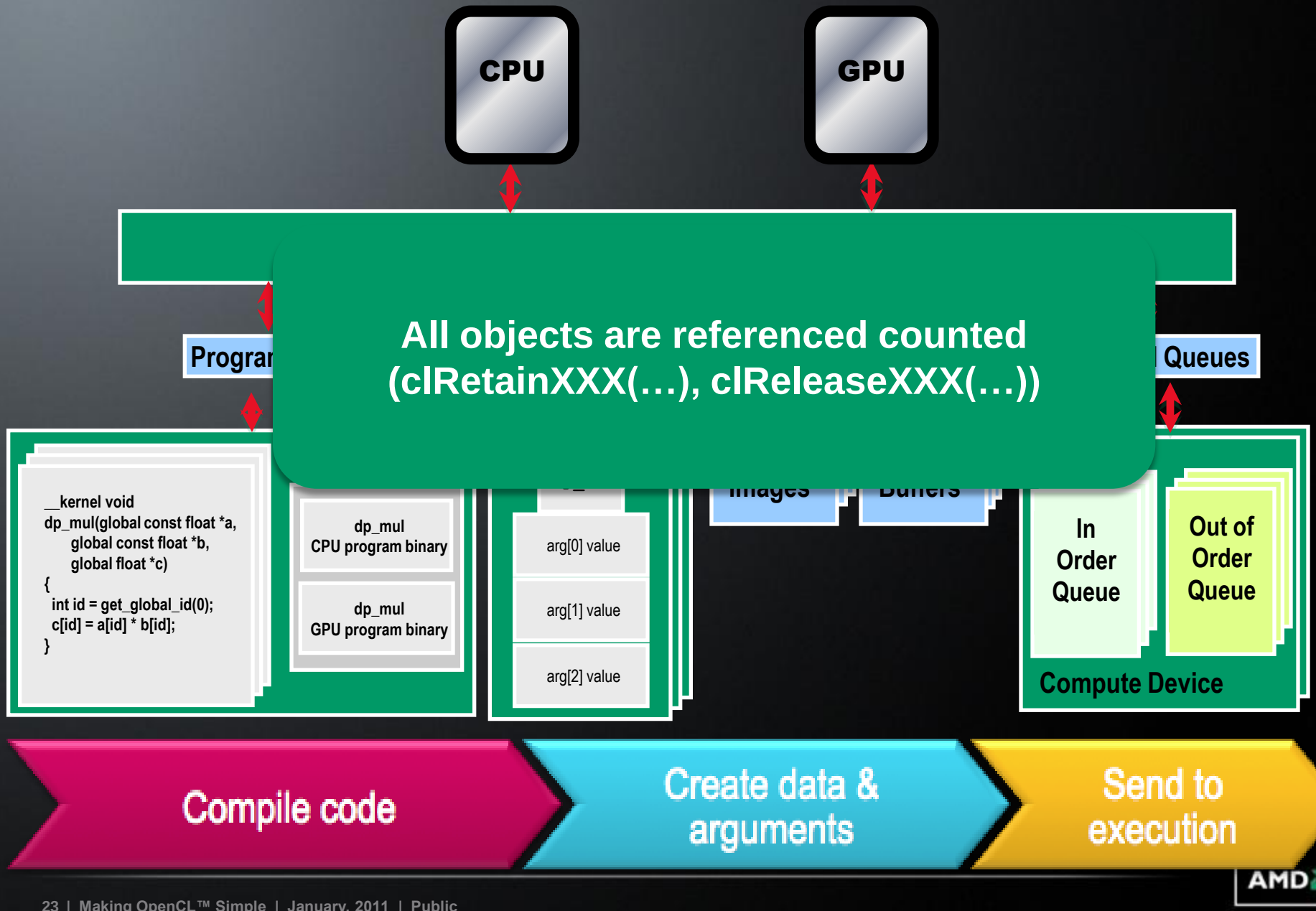
OPENCL™ SUMMARY



OPENCL™ SUMMARY



SYNCHRONIZATION: QUEUES & EVENTS

- Each individual queue can execute in-order or out-of-order
  - For in-order queue, all commands execute in order

- You must explicitly synchronize between queues
  - Multiple devices each have their own queue
  - Multiple queues per device
  - Use events to synchronize

- Events
  - Commands return events and obey waitlists
  - **clEnqueue***(. . . , **num_events_in_waitlist, *event_waitlist, *event**);

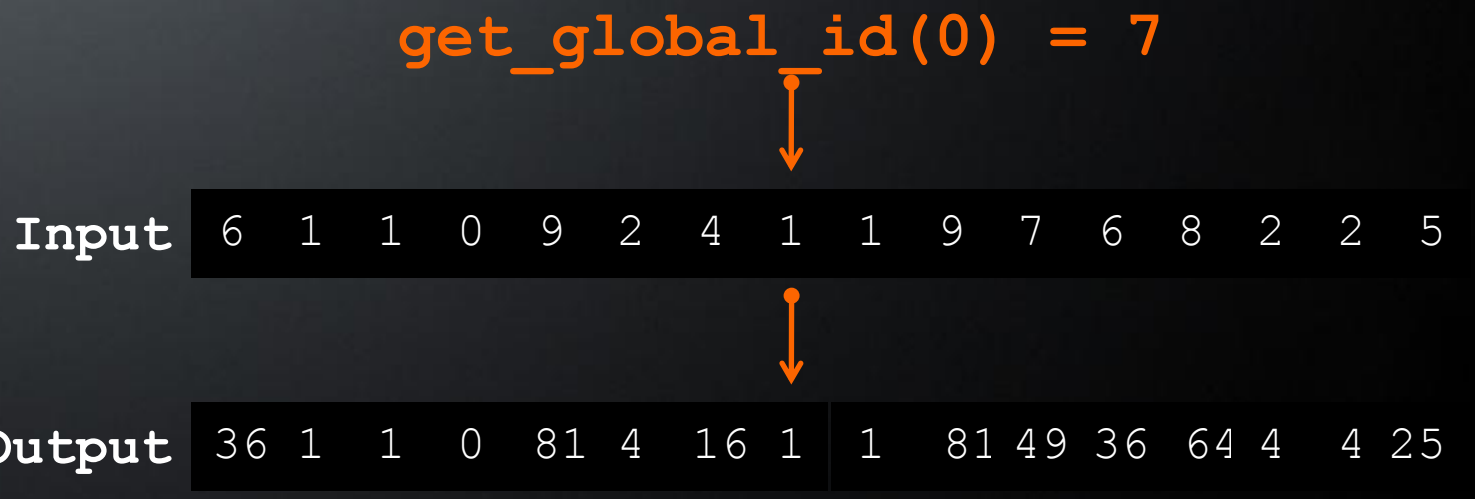
PROGRAMMING KERNELS: OPENCL™ C

- Derived from ISO C99
  - But without some C99 features such as standard C99 headers, function pointers, recursion, variable length arrays, and bit fields
- Language Features Added
  - Work-items and workgroups
  - Vector types
  - Synchronization
  - Address space qualifiers
- Also includes a large set of built-in functions
  - Image manipulation
  - Work-item manipulation,
  - Math functions, etc.

PROGRAMMING KERNELS: WHAT IS A KERNEL

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

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



PROGRAMMING KERNELS: DATA TYPES

- Scalar data types
  - char , uchar, short, ushort, int, uint, long, ulong, float
  - bool, intptr_t, ptrdiff_t, size_t, uintptr_t, void, half (storage)
- Image types
  - image2d_t, image3d_t, sampler_t
- Vector data types
  - Vector lengths 2, 4, 8, & 16 (char2, ushort4, int8, float16, **double2**, …)
  - Endian safe
  - Aligned at vector length
  - Vector operations

Double is an optional type in OpenCL 1.0

Bringing OpenCL™ to Haskell

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THE BASICS - HELLO WORLD

```
main = do (p:_) <- getPlatforms
          putStrLn . ("Platform is by: " ++) =<< getPlatformInfo p PlatformVendor
          c <- createContextFromType
            (pushContextProperty ContextPlatform p noProperties) (bitSet [GPU])
          p <- createProgramWithSource c . (:[]) =<< readFile “hello_world.cl"
          ds <- getContextInfo c ContextDevices
          buildProgram p ds ""
          k <- createKernel p "hello"
          b :: Buffer CChar <- createBuffer c (bitSet [WriteOnly]) hwlen
          setKernelArg k 0 b
          q <- createCommandQueue c (head ds) (bitSet [])
          enqueueNDRangeKernel q k [0] [hwlen] [1] []
          putStr . map castCCharToChar =<<
                    enqueueBlockingReadBuffer q b 0 (hwlen - 1) []
```

MAPPING OPENCL™ STATIC VALUES

```
class Const t u | t -> u
  where value :: t -> u
```

```
data Platform_
type Platform = Ptr Platform_

type CLPlatformInfo = Word32
```

```
data PlatformInfo t
  where PlatformProfile    :: PlatformInfo String
        PlatformVersion    :: PlatformInfo String
        PlatformName       :: PlatformInfo String
        PlatformVendor     :: PlatformInfo String
        PlatformExtensions :: PlatformInfo String

instance Const (PlatformInfo t) CLPlatformInfo
  where value PlatformProfile    = 0x0900
        value PlatformVersion    = 0x0901
        value PlatformName       = 0x0902
        value PlatformVendor     = 0x0903
        value PlatformExtensions = 0x0904
```

MAPPING OPENCL™ API

```
getPlatforms :: IO [Platform]
getPlatforms = appendingLocation "getPlatforms" $
               getCountedArray clGetPlatformIDs

getPlatformInfo :: Platform -> PlatformInfo u -> IO u
getPlatformInfo platform plInf =
    case plInf of
      PlatformProfile    -> get
      PlatformVersion    -> get
      PlatformName       -> get
      PlatformVendor     -> get
      PlatformExtensions -> get
    where get = appendingLocation "getPlatformInfo" $
                getString (clGetPlatformInfo platform (value plInf))
```

AND SO ON FOR THE REST OF OPENCL™ API

- Standard use of Haskell FFI to implement the calls in an out of Haskell into the OpenCL C world:

```
foreign import stdcall "cl.h clGetPlatformIDs" clGetPlatformIDs
        :: CLCountedArrayGetter(Platform)

foreign import stdcall "cl.h clGetPlatformInfo" clGetPlatformInfo
        :: Platform -> CLPlatformInfo -> CLGetter
```

- Simple extensions to handle OpenGL interop, with the HOpenGL (GLUT) packages. Allows performance, directly from Haskell, close to original C version.

Lifting to something more in the spirit of Haskell

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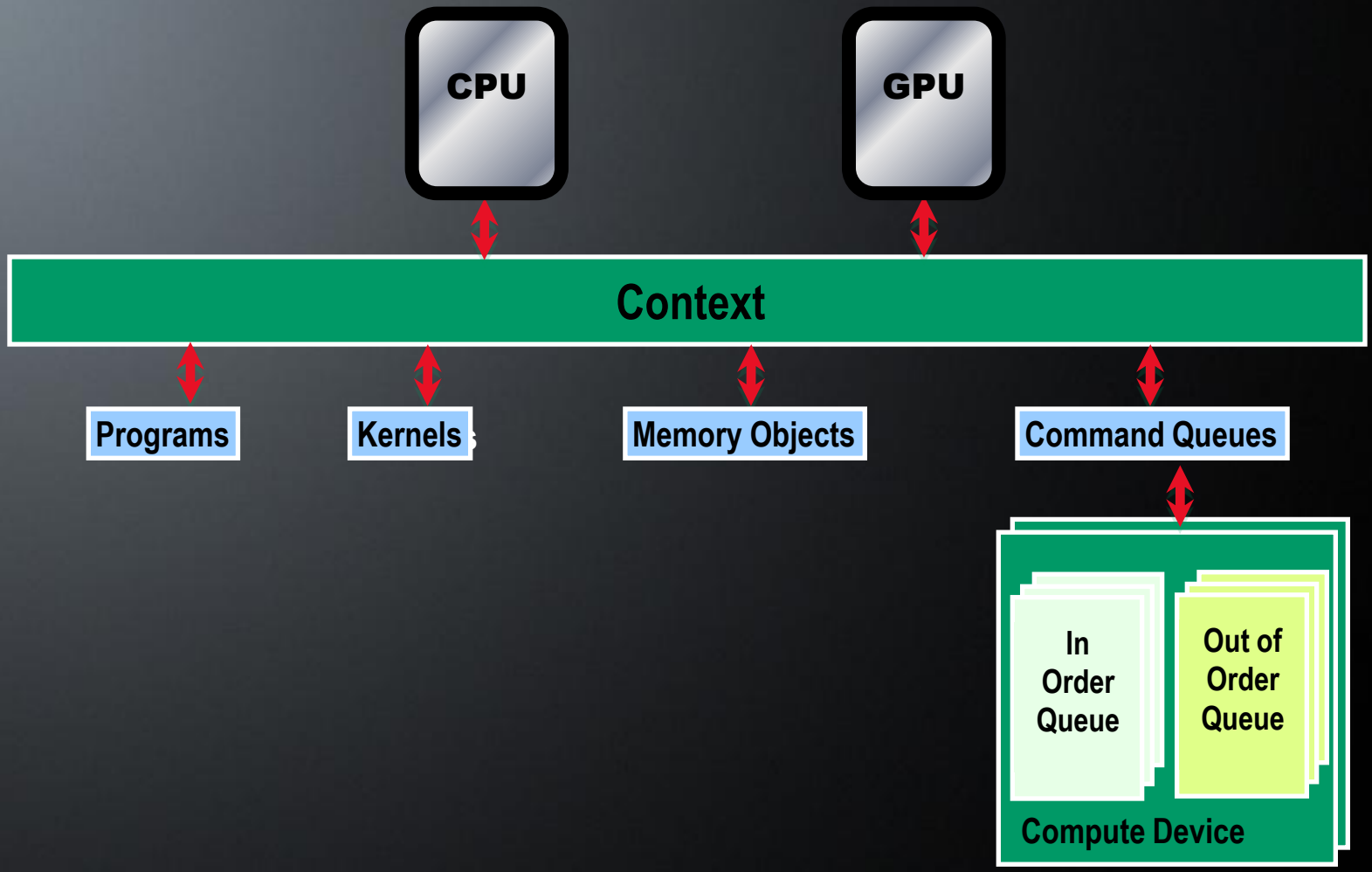
SO FAR NOTHING THAT INTERESTING

- HOpenCL Native API
  - Standard native function interface within the IO monad
  - Little advantage over programming in C++ or PyOpenCL

- HOpenCL Contextual API
  - Monad transformers to lift HOpenCL Native API beyond the IO monad
  - Quasiquotation to lift OpenCL source into Haskell as a first class citizen.

MOVE TO AN IMPLICIT MODEL



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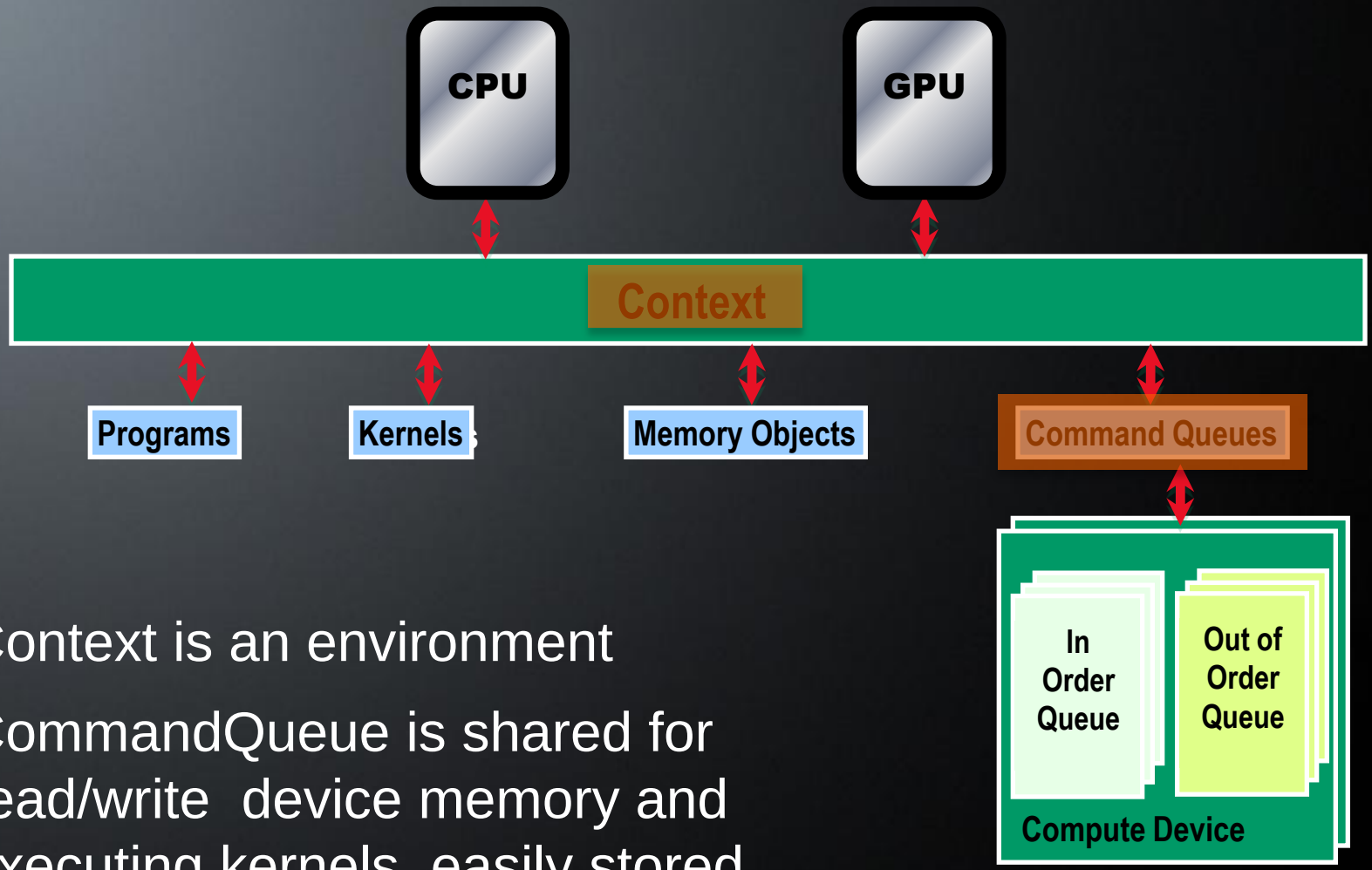
MOVE TO AN IMPLICIT MODEL



- Context is an environment
- CommandQueue is shared for read/write device memory and executing kernels, easily stored implicitly with an environment

CONTEXTUAL/QUEUED MONADS

- Function like reader monads for OpenCL *Context* and *CommandQueue* objects, avoiding having to pass *Contexts* and/or *CommandQueues* as the first parameter to many OpenCL operations.

- Introducing new classes gets around the dependency on the *MonadReader* class that would prevent asserting both *MonadReader Context m* and *MonadReader CommandQueue m* for the same type *m*.

EMBEDDING MONADS

- *Wraps* class provides a uniform way to embed one computation into another, for example:

```
with :: MonadIO m => Context -> ContextM t -> m t
```

embeds a computation in *ContextM* (a contextual monad) into any IO monad.

EMBEDDING MONADS

- In fact, the only way we expect to use a context/command queue/etc. is to populate a contextual/queued computation, so we provide a function that combines construction in the outer monad with computation in the inner monad:

```
withNew :: MonadIO m => m Context -> ContextM t -> m t
```

- This mechanism is extensible: the quasiquotation support uses a single data structure to contain context, queue, and device information; however, by adding it to the 'Contextual‘, 'Queued', and 'Wraps' classes we can use the same code we would have with the more conventional initialization.

LIFESPAN

- Many OpenCL objects are reference counted, with *clRetainXXX* and *clReleaseXXX* functions. We overload *retain* and *release* operators for all reference counted CL objects.

- We can use those to build C#-like control structures to automatically release objects: *using* for newly constructed objects and *retaining* for parameters:

```
using :: (Lifespan t, MonadIO m) => m t -> (t -> m u) -> m u
retaining :: (Lifespan t, MonadIO m) => t -> (t -> m u) -> m u
```

- In fact, the *withNew* function also uses the *Lifespan* class to automatically release the objects used to run the sub-computation

Quasiquotation

THE ROAD TO SINGLE SOURCE

- Embedded OpenCL C concrete syntax into Haskell with quasiquation

- Set of default qausiquoters:
  - [$cl| … |] OpenCL defult device, command queue and so on
  - [$clCPU| … |] OpenCL CPU device, command queue, and so on
  - [$clALL| … |] all OpenCL devices, with N command queues, and so on
  - and on and on … (it would be nice to automatically compute these)

- Statically check OpenCL C source
- Antiquoting can be used to reference Haskell values
- Save OpenCL binaries for reloading at runtime (guarantees correctness)

HELLO WORLD REVISITED

```
import Language.OpenCL.Module

hstr = "Hello world\n“
hlen = length hstr + 1

prog = initCL [$cl|
      __constant char hw[] = $hstr;
      __kernel void hello(__global char * out) {
      size_t tid = get_global_id(0);
     out[tid] = hw[tid];
   }
|]

main :: IO ()
main = withNew prog $
   using (bufferWithFlags hwlen [WriteOnly]) $ \b ->
      do [k] <- theKernels
         invoke k b `overRange` ([0], [hwlen], [1])
         liftIO . putStr . map castCCharToChar . fst =<< readBuffer b 0 (hlen - 1)
```

SIMPLIFIED VERSION

```
data CLMod = CLModule String DeviceType
    deriving(Show, Typeable, Data)

parseCLProg :: Monad m => Src -> String -> m CLModule

initCL :: CatchIO m => CLModule -> m Module
initCL (CLModule src dtype) =
  do (p:_) <- CL.platforms
     withNew (CL.contextFromType p [dtype]) $
       using (CL.programFromSource src) $ \prog ->
       do c <- CL.theContext
          ds <- CL.queryContext ContextDevices
          CL.buildProgram prog ds ""
          ks <- kernels prog
          q <- queue (head ds)
          return (Mod c ks q)
```

REALLY WE WOULD LIKE TO WRITE

```
import Language.OpenCL.Module

hstr = "Hello world\n“
hlen = length hstr + 1

prog = [$cl|
      __constant char hw[] = $hstr;
      __kernel void hello(__global char * out) {
      size_t tid = get_global_id(0);
     out[tid] = hw[tid];
   }
|]

main :: IO ()
main = withNew prog $
   using (bufferWithFlags hwlen [WriteOnly]) $ \b ->
      do [k] <- theKernels
           invoke k b `overRange` ([0], [hwlen], [1])
           liftIO . putStr . map castCCharToChar . fst =<< readBuffer b 0 (hlen - 1)
```

BUT THERE IS A PROBLEM (I THINK)

- Quasiquotation requires instances for Typeable and Data

- Remember that HOpenCL has definitions of the form:

```
data Platform_
type Platform = Ptr Platform_
```

- No way to derive Typeable and Data for Platform_

- This makes sense in the case that we want to build and retain values of type Platform at compile time, what does it mean to preserve a pointer?

WHAT WE REALLY WANT

- Build a delayed instance of CatchIO m that when evaluated at runtime performs OpenCL initialization
- Quasiquoting does not seem to allow this due to the requirement of Typeable and Data instances.
- Remember we do not want to build data values containing Platform_, rather we want to construct a function that will perform the act at runtime.
- Question: is there a known solution to this problem?

WE COULD THEN GENERATE KERNEL WRAPPERS

```
hello :: KernelInvocation r => Buffer Char -> r
hello = invoke …
```

or

```
hello :: Wraps t m n => [Char] -> n [Char]
hello = …
```

Issues we face using Haskell at AMD

USING HASKELL AT AMD

- Monads are a simple idea but they are not easy to explain and use in practice. At least for many people.
  - Originally looking at Garrett's Monad transformers I said it seemed complicated. His response was " you need to look at them sideways"! (He was right ☺)

- Haskell is not the Miranda that I learned as an undergraduate, it is big and a lot of very complicated type theory stuff. Really scary for many people!
  - Benjamin C. Pierce has a great talk discussing just this phenomena;
    - **Types Considered Harmful**, May 2008. Invited talk at *Mathematical Foundations of Programming Semantics (MFPS)."*
    - "I have long advocated type systems…but I've changed my mind"

USING HASKELL AT AMD

- Many Universities in the US do not teach Haskell!

- Perception of Haskell is often low:
  - "You probably know every Haskell programmer"
  - "Why not use Python or …"

- Finally, it is not easy to find interns with the required Haskell experience to work on these kinds of projects.

To be fair no one has said don't use Haskell!

QUESTIONS

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