18-643 Lecture 11: OpenCL and Altera OpenCL

James C. Hoe
Department of ECE
Carnegie Mellon University
Housekeeping

• Your goal today: understand Altera’s interpretation of OpenCL on FPGA

• Notices
  – Handout #4: lab 2, due noon, 10/7
  – 3 weeks to project proposal

• Readings
  – skim Ch 10, Reconfigurable Computing
Khronos’ OpenCL
Two Parts to OpenCL

1. Platform model
   - **host** (processor & memory)
   - 1 or more accelerator devices
     + device-side mem hierarchy: **global/local/private**
   - APIs for **host-thread** to interact with devices
     • launch compute **kernels** to devices
     • prepare (load/unload) device memory

2. Kernel programming language
   - perfect triply-nested loops
   - no loop-carried dependence
OpenCL Platform Model

What are these “compute devices”???
Basic Host Program Example

```c
main ( ) {
    ... get device handle and queue ...
    ... allocate memory buf objects ...
    ... get kernel object ...
    while ( ) {
        ... initialize memory buf data ...
        ... bind buf objects to kernel arguments ...
        ... add kernel and buf objects to device queue ...
        ... wait for kernel to finish ...
        ... retrieve memory buf object for result ...
    }
}
```

What are these “kernels”???
What are these kernels?

Specifically talking about OpenCL C
Conceptually . . .

```c
for (int i=0; i < R_0; i++)
    for (int j=0; j < R_1; j++)
        for (int k=0; k < R_2; k++) {
            << local variable declarations >>
            << arbitrary C-code with access to global memory >>
        }
```

- Loop body must be data-parallel
  - local variables limited to scope
  - disallow loop-carried dependencies through global memory

==> statements from different iterations can interleave in any order (using disambiguated local variables)
Concretely . . .

• Only specify loop body as a **kernel function**

```c
__kernel foo(<< pointers to global mem buf>>) { 
    int i=get_global_id(2), j=get...(1), k=get...(0);
    << local variable declarations >>
    << arbitrary C-code with access to 
global memory >>
}
```

• Triply-nested loops hardwired as **NDRange**
  – specified as 3 integer constants, i.e., the loop 
bounds \((R_0, R_1, R_2)\)
  – 1 execution of kernel function is a **work-item**
    work-item has **private memory** for local var’s
  – 1 kernel execution is \(R_0 \times R_1 \times R_2\) work-items
Example: N-by-N MMM

```c
__kernel mmm(__global float *A, ... *B, ... *C) {
    int i=get_global_id(1);
    int j=get_global_id(0);

    for(int k=0; k<N; k++)
        C[i*N+j]=C[i*N+j]+A[i*N+k]*B[k*N+j];
}
```

- NDRange=(N, N, 1)
  - kernel function executed by NxNx1 work-items
  - each work-item sees a different combination of dimension-0 and dimension-1 global id’s
  - no assumption about work-items’ relative progress
float A[N][N], B[N][N], C[N][N];

for(int i=0; i<N; i++)
    for(int j=0; j<N; j++) {
        for(int k=0; k<N; k++)
            C[i][j]=C[i][j]+A[i][k]*B[k][j]
    }

• Note:
  – Loop body of the inner-most loop is not data-parallel---dependency through C[i][j]
  – Loop body of the second inner-most loop is
Work-Group

• Partition NDRRange of $R_0 \times R_1 \times R_2$ work-items into 3D work-groups of $G_0 \times G_1 \times G_2$ work-items
  – $G_{0/1/2}$ must divide $R_{0/1/2}$ evenly
  – `get_local_id(dimem)`: id within group
  – `get_group_id(dimem)`: id of group

• Work-group signifies “locality” btwn work-items
  – execute together by a processing element
  – can share per-group local memory
  – can synchronize by `barrier()`

Why do we need this?
OpenCL Kernels on GPGPUs

- Work-items is a **CUDA thread**
- Work-group executes as a **thread block**---broken down into 32-work-item SIMD **Warps**
- Work-groups from same and different kernels are interleaved on a **Streaming Processor**
  
  128-SIMD lanes, 1 INT+1 FMA per lane, 1.73GHz

- 1 kernel can execute on upto 20 StrmProc’s (as 1 compute device), peak 8,873 GFLOPS
- Global=GDDR; local=**shared memory** 96KB SRAM; private=**register file** 256KB SRAM

  *Nvidia terms in **italic-bold**; numbers for GTX 1080*
Aside: Barrel Processor [HEP, Smith]

- Each cycle, select a “ready” thread from scheduling pool
  - only one instruction per thread in flight at once
  - on a long latency stall, remove the thread from scheduling

- Simpler and faster pipeline implementation since
  - no data dependence, hence no stall or forwarding
  - no penalty in making pipeline deeper
To get 8,873 GFLOPS . . .

- \# work-items \geq 128 \times \text{StrmProc pipeline depth} \times 20
- Computation entirely of Fused-Multiply-Add
  Interleaved warps so no worries about RAW stalls
- No if-then-else (branch divergence)

**BTW:**

- ld’s and st’s take up inst. issue BW of-the-top
- 320 GB/sec DRAM BW \Rightarrow \text{AI} > 108 \text{ SP FP / float}
  - only certain access pattern can sustain peak BW
  - SIMD ld’s and st’s in a warp has to go to the same memory line (memory coalescing)
Altera’s Take on OpenCL
OpenCL FPGA Platform Model

Compute devices synthesized from kernel functions
Example: N-by-N MM“Add”

```c
__kernel mma(__global float *A, ... *B, ... *C) {
    int i=get_global_id(1);
    int j=get_global_id(0);

}
```

- **NDRange=(N, N, 1)**
- **Note in this example:**
  - data-parallel kernel function
  - no loop in kernel function
Fully-pipelined Kernel Datapath

\[ \text{NDRange} = (N, N, 1) \]
\[ \text{(gid0, gid1) stream } = (0, 1), \ldots (0, N-1), (1, 0), \ldots (1, N-1), \ldots (N-1, 0), \ldots (N-1, N-1) \]

```
A
  addr
  calc

B
  addr
  calc

C
  addr
  calc
```

```
load
  &A[i*N+j]
  &B[i*N+j]
  &C[i*N+j]

add
  A[i*N+j]
  B[i*N+j]

store
```

Fully unrolled loop in kernel fxn also okay
What about MMM?

```c
__kernel mmm(__global float *A, ... *B, ... *C) {
    int i=get_global_id(1);
    int j=get_global_id(0);

    for(int k=0; k<N; k++)
        C[i*N+j]=C[i*N+j]+A[i*N+k]*B[k*N+j];
}
```

- NDRange=(N, N, 1)
- Can’t pipeline work-items like before
- PE pipelines the k iterations
  - dependency on C[i*N+j]
  - kernel function scope limits the tricks we can play
Single Work-Item Kernel

```cpp
__kernel mmm(__global float *A, ... *B, ... *C) {
  for(int i=0; i<N; i++)
    for(int j=0; j<N; j++)
      for(int k=0; k<N; k++)
```

- NDRange=(1, 1, 1) never do this on GPU!!
- Arbitrary control flow (loops, if’s) and dependencies
- Becomes just “regular” C-to-HW synthesis
  - pipeline and parallelize loops
  - schedule for initiation-interval, resource, etc.

Only want OpenCL’s platform model and API; “work-group” & “work-item” not too meaningful
Altera Kernel-Kernel Channels

- GPU multi-kernel OpenCL program
  - kernel computes from global-mem to global-mem
  - next kernel continues from last kernel’s output buf
  - producer and consumer kernels fully serialized
- For streaming processing on FPGA, connect kernels with streaming channels to bypass DRAM
  - concurrent producer and consumer kernels
  - reduce DRAM and PCIe bandwidth requirements

Also supports OpenCL 2.0 Pipes
Parting Thoughts

- OpenCL = platform model/API + SIMD language
  - kernel language forces regular and explicit parallelism
  - SIMD parallelism manifest differently on GPUs vs FPGAs
- Altera’s OpenCL = platform model/API + regular HLS
  - single-work-item kernel unlocks parallelism style
  - kernel-kernel channels alleviate DRAM and PCIe bottleneck for streaming use cases
  - develop/debug/analysis tools integral to appeal

GPUs great at SIMD; FPGAs good for more than SIMD