Outline

Administrivia

Introduction to Accelerators

GPU Architectures

GPU Programming Models

References
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A5 (final assignment) is out
  Due Dec 11, 2019 at 7PM
  Groups of up to 2 allowed
Homeworks all done
  Please review all of them and their solutions
Two review lectures next week
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Accelerators

- Single-core processors
- Multi-core processors
- What if these aren’t enough?
- Accelerators, specifically GPUs
  - what they are
  - when you should use them
Timeline

- 1980s
  - Geometry Engines
- 1990s
  - Consumer GPUs
  - Out-of-order Superscalars
- 2000s
  - General-purpose GPUs
  - Multicore CPUs
  - Cell BE (Playstation 3)
  - Lots of specialized accelerators in phones
The Graphics Processing Unit (1980s)

- SGI Geometry Engine
- Implemented the *Geometry Pipeline*
  - Hardwired logic
- Embarrassingly Parallel
  - $O(\text{Pixels})$
  - Large number of logic elements
  - High memory bandwidth
- From Kaufman et al. (2009):
GPU 2.0 (circa 2004)

- Like CPUs, GPUs benefited from Moore’s Law
- Evolved from fixed-function hardwired logic to flexible, programmable ALUs
- Around 2004, GPUs were programmable “enough” to do some non-graphics computations
  - Severely limited by graphics programming model (shader programming)
- In 2006, GPUs became “fully” programmable
  - GPGPU: General-Purpose GPU
  - NVIDIA releases “CUDA” language to write non-graphics programs that will run on GPUs
Theoretical GFLOP/s

- NVIDIA GPU Single Precision
- NVIDIA GPU Double Precision
- Intel CPU Double Precision
- Intel CPU Single Precision

FLOPS/s

NVIDIA CUDA C Programming Guide
GPGPU Today

- GPUs are widely deployed as accelerators
- Intel Paper
  - 10x vs 100x Myth
- GPUs so successful that other accelerators are dead
  - Sony/IBM Cell BE
  - Clearspeed RSX
- Tesla V100S GPUs from NVIDIA have performance of 16.4TFlops (peak)
  - CM-5, #1 system in 1993 was 60 Gflops (Linpack)
  - ASCI White (#1 2001) was 4.9 Tflops (Linpack)

Pictures of Summit and Tianhe 1A from the Top500 website.
Accelerator Programming Models

- CPUs have always depended on co-processors
  - I/O co-processors to handle slow I/O
  - Math co-processors to speed up computation
  - H.264 co-processor to play video (Phones)
  - DSPs to handle audio (Phones)
- Many have been transparent
  - Drop in the co-processor and everything sped up
- Or used a function-based model
  - Call a function and it is sped up (e.g. “decode video”)
- The GPU is not a transparent accelerator for general purpose computations
  - Only graphics code is sped up transparently
- Code must be rewritten to target GPUs
Using a GPU

▶ You must retarget code for the GPU
  ▶ Rewrite, recompile, translate, etc.
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The Two Kinds of GPUs

- Type 1: Discrete GPUs
  - More computational power
  - More memory bandwidth
  - Separate memory
The Two Kinds of GPUs #2

- **Type 2: Integrated GPUs**
  - Share memory with processor
  - Share bandwidth with processor
  - Consume Less power
  - Can participate in cache coherence
The NVIDIA Kepler

NVIDIA Kepler GK110 Whitepaper
Using a Discrete GPU

- You must retarget code for the GPU
  - Rewrite, recompile, translate, etc.
- Working set must fit in GPU RAM
- You must copy data to/from GPU RAM
  - “You”: Programmer, Compiler, Runtime, OS, etc.
  - Some recent hardware can do this for you (it’s slow)
NVIDIA Kepler SMX (i.e. CPU core equivalent)
NVIDIA Kepler SMX Details

- 2-wide Inorder
- 4-wide SMT
  - 2048 threads per core (64 warps)
  - 15 cores
  - Each thread runs the same code (hence SIMT)
- 65536 32-bit registers (256KBytes)
  - A thread can use up to 255 of these
  - \textit{Partitioned} among threads (not shared!)
- 192 ALUs
- 64 Double-precision
- 32 Load/store
- 32 Special Functional Unit
- 64 KB L1/Shared Cache
  - Shared cache is software-managed cache
# CPU vs GPU

<table>
<thead>
<tr>
<th>Parameter</th>
<th>CPU</th>
<th>GPU</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clockspeed</td>
<td>&gt; 1 GHz</td>
<td>700 MHz</td>
</tr>
<tr>
<td>RAM</td>
<td>GB to TB</td>
<td>12 GB (max)</td>
</tr>
<tr>
<td>Memory B/W</td>
<td>60 GB/s</td>
<td>&gt; 300 GB/s</td>
</tr>
<tr>
<td>Peak FP</td>
<td>&lt; 1 TFlop</td>
<td>&gt; 1 TFlop</td>
</tr>
<tr>
<td>Concurrent Threads</td>
<td>O(10)</td>
<td>O(1000) [O(10000)]</td>
</tr>
<tr>
<td>LLC cache size</td>
<td>&gt; 100MB (L3) [eDRAM]</td>
<td>&lt; 2MB (L2)</td>
</tr>
<tr>
<td></td>
<td>O(10) [traditional]</td>
<td></td>
</tr>
<tr>
<td>Cache size per thread</td>
<td>O(1 MB)</td>
<td>O(10 bytes)</td>
</tr>
<tr>
<td>Software-managed cache</td>
<td>None</td>
<td>48KB/SMX</td>
</tr>
<tr>
<td>Type</td>
<td>OOO super-scalar</td>
<td>2-way Inorder super-scalar</td>
</tr>
</tbody>
</table>
Using a GPU

- You must retarget code for the GPU
  - Rewrite, recompile, translate, etc.
- Working set must fit in GPU RAM
- You must copy data to/from GPU RAM
  - “You”: Programmer, Compiler, Runtime, OS, etc.
  - Some recent hardware can do this for you
- Data accesses should be streaming
  - Or use scratchpad as user-managed cache
- Lots of parallelism preferred (throughput, not latency)
- SIMD-style parallelism best suited
  - Same instruction, different data
- High arithmetic intensity (FLOPs/byte) preferred
Showcase GPU Applications

▶ Image Processing
▶ Graphics Rendering
▶ Matrix Multiply
▶ FFT

See “Debunking the 100X GPU vs. CPU Myth: An Evaluation of Throughput Computing on CPU and GPU” by V.W.Lee et al. for more examples and a comparison of CPU and GPU.
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## Hierarchy of GPU Programming Models

<table>
<thead>
<tr>
<th>Model</th>
<th>GPU</th>
<th>CPU Equivalent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vectorizing Compiler</td>
<td>PGI CUDA Fortran</td>
<td>gcc, icc, etc.</td>
</tr>
<tr>
<td>“Drop-in” Libraries</td>
<td>cuBLAS</td>
<td>ATLAS</td>
</tr>
<tr>
<td>Directive-driven</td>
<td>OpenACC, OpenMP-to-CUDA</td>
<td>OpenMP</td>
</tr>
<tr>
<td>High-level languages</td>
<td>pyCUDA</td>
<td>python</td>
</tr>
<tr>
<td>Mid-level languages</td>
<td>OpenCL, CUDA</td>
<td>pthreads + C/C++</td>
</tr>
<tr>
<td>Low-level languages</td>
<td>PTX, Shader</td>
<td>-</td>
</tr>
<tr>
<td>Bare-metal</td>
<td>SASS</td>
<td>Assembly/Machine code</td>
</tr>
</tbody>
</table>
“Drop-in” Libraries

“Drop-in” replacements for popular CPU libraries, examples from NVIDIA:

- CUBLAS/NVBLAS for BLAS (e.g. ATLAS)
- CUFFT for FFTW
- MAGMA for LAPACK and BLAS

These libraries may still expect you to manage data transfers manually.

Libraries may support multiple accelerators (GPU + CPU + Xeon Phi)
GPU Libraries

- NVIDIA Thrust
  - Like C++ STL, but executes on the GPU
- Modern GPU
  - At first glance: high-performance library routines for sorting, searching, reductions, etc.
  - A deeper look: Specific “hard” problems tackled in a different style
- NVIDIA CUB
  - Low-level primitives for use in CUDA kernels
Directive-Driven Programming

- OpenACC, new standard for “offloading” parallel work to an accelerator
  - Currently supported only by PGI Accelerator compiler
  - gcc 5.0 support is ongoing
- OpenMPC, a research compiler, can compile OpenMP code + extra directives to CUDA
  - OpenMP 4.0 also supports offload to accelerators
  - Not for GPUs yet

```c
int main(void) {
    double pi = 0.0f; long i;
    
    #pragma acc parallel loop reduction(+:pi)
    for (i=0; i<N; i++) {
        double t= (double)((i+0.5)/N);
        pi +=4.0/(1.0+t*t);
    }
    
    printf("pi=%16.15f\n",pi/N);
    return 0;
}
```
import pycuda.autoinit
import pycuda.driver as drv
import numpy
from pycuda.compiler import SourceModule

mod = SourceModule(""
__global__ void multiply_them(float *dest, float *a, float *b)
{
    const int i = threadIdx.x;
    dest[i] = a[i] * b[i];
}
""
)

multiply_them = mod.get_function("multiply_them")

a = numpy.random.randn(400).astype(numpy.float32)
b = numpy.random.randn(400).astype(numpy.float32)

dest = numpy.zeros_like(a)

multiply_them(
    drv.Out(dest), drv.In(a), drv.In(b),
    block=(400,1,1), grid=(1,1))

print dest-a*b
OpenCL

- C99-based dialect for programming heterogenous systems
  - Originally based on CUDA
  - nomenclature is different
- Supported by more than GPUs
  - Xeon Phi, FPGAs, CPUs, etc.
- Source code is portable (somewhat)
  - Performance may not be!
- Poorly supported by NVIDIA
CUDA

- “Compute Unified Device Architecture”
- First language to allow general-purpose programming for GPUs
  - preceded by shader languages
- Promoted by NVIDIA for their GPUs
- Not supported by any other accelerator
  - though commercial CUDA-to-x86/64 compilers exist
- We will focus on CUDA programs
CUDA Architecture

- From 10000 feet – CUDA is like pthreads
  - CUDA language – C++ dialect
- Host code (CPU) and GPU code in same file
- Special language extensions for GPU code
- CUDA Runtime API
  - Manages runtime GPU environment
  - Allocation of memory, data transfers, synchronization with GPU, etc.
  - Usually invoked by host code
- CUDA Device API
  - Lower-level API that CUDA Runtime API is built upon
CUDA Limitations

- No standard library for GPU functions
- No parallel data structures
- No synchronization primitives (mutex, semaphores, queues, etc.)
  - you can roll your own
  - only atomic*() functions provided
- Toolchain not as mature as CPU toolchain
  - Felt intensely in performance debugging
- It’s only been a decade :)}
Conclusions

- GPUs are very interesting parallel machines
- They’re not going away
  - Xeon Phi was interesting, but Intel has abandoned it
- They’re here and now
  - Your laptop probably already contains one
  - Your phone definitely has one
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- **NVIDIA CUDA**
  - [http://docs.nvidia.com](http://docs.nvidia.com)
  - Start with the CUDA C++ Programming Guide

- **OpenCL**
  - [https://www.khronos.org/opencl/](https://www.khronos.org/opencl/)
  - The OpenCL C 2.0 Specification
  - The OpenCL C++ 1.0 Specification