Introduction to CUDA

1. Our first GPU Program
   - running Newton’s method in complex arithmetic
   - examining the CUDA Compute Capability

2. CUDA Program Structure
   - steps to write code for the GPU
   - code to compute complex roots
   - the kernel function and main program
   - a scalable programming model

MCS 572 Lecture 30
Introduction to Supercomputing
Jan Verschelde, 31 October 2016
Introduction to CUDA

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computing complex square roots

To compute $\sqrt{c}$ for $c \in \mathbb{C}$, we apply Newton’s method on $x^2 - c = 0$:

\[
x_0 := c, \quad x_{k+1} := x_k - \frac{x_k^2 - c}{2x_k}, \quad k = 0, 1, \ldots
\]

Five iterations suffice to obtain an accurate value for $\sqrt{c}$.

Suitable on GPU?
- Finding roots is relevant for scientific computing.
- Data parallelism: compute for many different $c$’s.

Application: complex root finder for polynomials in one variable.
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CUDA Compute Capability

The compute capability of an NVIDIA GPU
- is represented by a version number in the format x.y,
- identifies the features supported by the hardware.

What does it mean for the programmer? Some examples:

1.3 : double-precision floating-point operations
2.0 : synchronizing threads
3.5 : dynamic parallelism
5.3 : half-precision floating-point operations
6.0 : atomic addition operation on 64-bit floats

The compute capability is not the same as the CUDA version.
checking the card with deviceQuery on kepler

$ /usr/local/cuda/samples/1_Utilities/deviceQuery/deviceQuery
/usr/local/cuda/samples/1_Utilities/deviceQuery/deviceQuery Starting...

CUDA Device Query (Runtime API) version (CUDART static linking)

Detected 3 CUDA Capable device(s)

Device 0: "Tesla K20c"
CUDA Driver Version / Runtime Version 6.0 / 5.5
CUDA Capability Major/Minor version number: 3.5
Total amount of global memory: 4800 MBytes (5032706048 bytes)
(13) Multiprocessors, (192) CUDA Cores/MP: 2496 CUDA Cores
GPU Clock rate: 706 MHz (0.71 GHz)
Memory Clock rate: 2600 Mhz
Memory Bus Width: 320-bit
L2 Cache Size: 1310720 bytes
Maximum Texture Dimension Size (x,y,z) 1D=(65536), 2D=(65536, 65536), 3D=(4096, 4096, 4096)
Maximum Layered 1D Texture Size, (num) layers 1D=(16384), 2048 layers
Maximum Layered 2D Texture Size, (num) layers 2D=(16384, 16384), 2048 layers
Total amount of constant memory: 65536 bytes
Total amount of shared memory per block: 49152 bytes
Total number of registers available per block: 65536
Warp size: 32
Maximum number of threads per multiprocessor: 2048
Maximum number of threads per block: 1024
Max dimension size of a thread block (x,y,z): (1024, 1024, 64)
Max dimension size of a grid size (x,y,z): (2147483647, 65535, 65535)
Maximum memory pitch: 2147483647 bytes
Texture alignment: 512 bytes
Concurrent copy and kernel execution: Yes with 2 copy engine(s)
Run time limit on kernels: No
Integrated GPU sharing Host Memory: No
Support host page-locked memory mapping: Yes
Alignment requirement for Surfaces: Yes
Device has ECC support: Enabled
Device supports Unified Addressing (UVA): Yes
Device PCI Bus ID / PCI location ID: 4 / 0
Compute Mode: < Default (multiple host threads can use ::cudaSetDevice() with device simultaneously) >
checking the card with deviceQuery on pascal

$ /usr/local/cuda/samples/1_Utilities/deviceQuery/deviceQuery
/usr/local/cuda/samples/1_Utilities/deviceQuery/deviceQuery Starting...

CUDA Device Query (Runtime API) version (CUDART static linking)

Detected 2 CUDA Capable device(s)

Device 0: "Tesla P100-PCIE-16GB"
  CUDA Driver Version / Runtime Version: 8.0 / 8.0
  CUDA Capability Major/Minor version number: 6.0
  Total amount of global memory: 16276 MBytes (17066885120 bytes)
  (56) Multiprocessors, ( 64) CUDA Cores/MP: 3584 CUDA Cores
  GPU Max Clock rate: 405 MHz (0.41 GHz)
  Memory Clock rate: 715 MHz
  Memory Bus Width: 4096-bit
  L2 Cache Size: 4194304 bytes
  Maximum Texture Dimension Size (x,y,z) 1D=(131072), 2D=(131072, 65536), 3D=(16384, 16384, 16384)
  Maximum Layered 1D Texture Size, (num) layers 1D=(32768), 2048 layers
  Maximum Layered 2D Texture Size, (num) layers 2D=(32768, 32768), 2048 layers
  Total amount of constant memory: 65536 bytes
  Total amount of shared memory per block: 49152 bytes
  Total number of registers available per block: 65536
  Warp size: 32
  Maximum number of threads per multiprocessor: 2048
  Maximum number of threads per block: 1024
  Max dimension size of a thread block (x,y,z): (1024, 1024, 64)
  Max dimension size of a grid size (x,y,z): (2147483647, 65535, 65535)
  Maximum memory pitch: 2147483647 bytes
  Texture alignment: 512 bytes
  Concurrent copy and kernel execution: Yes with 2 copy engine(s)
  Run time limit on kernels: No
  Integrated GPU sharing Host Memory: No
  Support host page-locked memory mapping: Yes
  Alignment requirement for Surfaces: Yes
  Device has ECC support: Enabled
  Device supports Unified Addressing (UVA): Yes
  Device PCI Domain ID / Bus ID / location ID: 0 / 2 / 0
  Compute Mode: < Default (multiple host threads can use ::cudaSetDevice() with device simultaneously) >
running bandwidthTest on kepler

$ /usr/local/cuda/samples/1_Utilities/bandwidthTest/bandwidthTest

[CUDA Bandwidth Test] - Starting...
Running on...

Device 0: Tesla K20c
Quick Mode

Host to Device Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes) Bandwidth(MB/s)
  33554432  5819.5

Device to Host Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes) Bandwidth(MB/s)
  33554432  6415.8

Device to Device Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes) Bandwidth(MB/s)
  33554432 143248.0

Result = PASS
running bandwidthTest on pascal

$ /usr/local/cuda/samples/1_Utilities/bandwidthTest/bandwidthTest

[CUDA Bandwidth Test] - Starting...
Running on...

Device 0: Tesla P100-PCIE-16GB
Quick Mode

Host to Device Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes) Bandwidth(MB/s)
  33554432 11530.1

Device to Host Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes) Bandwidth(MB/s)
  33554432 12848.3

Device to Device Bandwidth, 1 Device(s)
PINNED Memory Transfers
  Transfer Size (Bytes) Bandwidth(MB/s)
  33554432 444598.8

Result = PASS

$
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steps to write code for the GPU

Five steps to get GPU code running:

1. C and C++ functions are labeled with CUDA keywords `__device__`, `__global__`, or `__host__`.

2. Determine the data for each thread to work on.

3. Transferring data from/to host (CPU) to/from the device (GPU).

4. Statements to launch data-parallel functions, called *kernels*.

5. Compilation with `nvcc`. 
step 1: CUDA extensions to functions

Three keywords before a function declaration:

**__host__** : The function will run on the host (CPU).

**__device__** : The function will run on the device (GPU).

**__global__** : The function is called from the host but runs on the device. This function is called a *kernel*.

CUDA extensions to C function declarations:

<table>
<thead>
<tr>
<th><strong><strong>device</strong> double D()</strong></th>
<th>executed on</th>
<th>callable from</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>device</td>
<td>device</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong><strong>global</strong> void K()</strong></th>
<th>executed on</th>
<th>callable from</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>device</td>
<td>host</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th><strong><strong>host</strong> int H()</strong></th>
<th>executed on</th>
<th>callable from</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>host</td>
<td>host</td>
</tr>
</tbody>
</table>
step 2: data for each thread

The grid consists of \( N \) blocks, with \( \text{blockIdx}.x \in \{0, N - 1\} \).

Within each block, \( \text{threadIdx}.x \in \{0, \text{blockDim}.x - 1\} \).

```c
int threadId = blockIdx.x * blockDim.x + threadIdx.x
...
float x = input[threadID]
float y = f(x)
output[threadID] = y
...
```
Step 3: Allocating and transferring data

cudaDoubleComplex *xhost = new cudaDoubleComplex[n];

// We copy n complex numbers to the device
size_t s = n*sizeof(cudaDoubleComplex);
cudaDoubleComplex *xdevice;
cudaMalloc((void**)&xdevice,s);

cudaMemcpy(xdevice,xhost,s,cudaMemcpyHostToDevice);

// Allocate memory for the result
cudaDoubleComplex *ydevice;
cudaMalloc((void**)&ydevice,s);

// Copy results from device to host
cudaDoubleComplex *yhost = new cudaDoubleComplex[n];

cudaMemcpy(yhost,ydevice,s,cudaMemcpyDeviceToHost);
step 4: launching the kernel

The kernel is declared as

```c
__global__ void squareRoot
( int n, cudaDoubleComplex *x, cudaDoubleComplex *y )
// Applies Newton’s method to compute the square root
// of the n numbers in x and places the results in y.
{
    int i = blockIdx.x*blockDim.x + threadIdx.x;
    ...
}
```

For frequency $f$, dimension $n$, and block size $w$, we do:

```c
// invoke the kernel with n/w blocks per grid
// and w threads per block
for(int i=0; i<f; i++)
    squareRoot<<<n/w,w>>>(n,xdevice,ydevice);
```
step 5: compiling with \texttt{nvcc}

Then if the \texttt{makefile} contains

\begin{verbatim}
runCudaComplexSqrt:
   nvcc -o /tmp/run_cmpsqrt -arch=sm_13 \ 
   runCudaComplexSqrt.cu
\end{verbatim}

typing \texttt{make runCudaComplexSqrt} does

\begin{verbatim}
nvcc -o /tmp/run_cmpsqrt -arch=sm_13 runCudaComplexSqrt.cu
\end{verbatim}

The \texttt{-arch=sm_13} \textbf{is needed for double arithmetic}, for the K20C.
The option \texttt{-arch=sm_13} \textbf{is no longer recognized} on the new P100.
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defining complex numbers

```c
#ifndef __CUDADOUBLECOMPLEX_CU__
define __CUDADOUBLECOMPLEX_CU__

#include <cmath>
#include <cstdlib>
#include <iomanip>
#include <vector_types.h>
#include <math_functions.h>

typedef double2 cudaDoubleComplex;

We use the double2 of vector_types.h to define complex numbers because double2 is a native CUDA type allowing for coalesced memory access.
```
random complex numbers

__host__ cudaDoubleComplex randomDoubleComplex()
// Returns a complex number on the unit circle
// with angle uniformly generated in [0,2*pi].
{
    cudaDoubleComplex result;
    int r = rand();
    double u = double(r)/RAND_MAX;
    double angle = 2.0*M_PI*u;
    result.x = cos(angle);
    result.y = sin(angle);
    return result;
}
__device__ double radius ( const cudaDoubleComplex c )
// Returns the radius of the complex number.
{
    double result;
    result = c.x*c.x + c.y*c.y;
    return sqrt(result);
}
overloading for output

```cpp
__host__ std::ostream& operator<<
( std::ostream& os, const cudaDoubleComplex& c)
// Writes real and imaginary parts of c,
// in scientific notation with precision 16.
{
    os << std::scientific << std::setprecision(16)
        << c.x << " " << c.y;
    return os;
}
```
defining complex addition

```
__device__ cudaDoubleComplex operator+( const cudaDoubleComplex a, const cudaDoubleComplex b )
// Returns the sum of a and b.
{
    cudaDoubleComplex result;
    result.x = a.x + b.x;
    result.y = a.y + b.y;
    return result;
}
```

The rest of the arithmetical operations are defined in a similar manner.

All definitions related to complex numbers are stored in the file `cudaDoubleComplex.cu`. 
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the kernel function

#include "cudaDoubleComplex.cu"

__global__ void squareRoot
( int n, cudaDoubleComplex *x, cudaDoubleComplex *y )
// Applies Newton’s method to compute the square root
// of the n numbers in x and places the results in y.
{
    int i = blockIdx.x*blockDim.x + threadIdx.x;
    cudaDoubleComplex inc;
    cudaDoubleComplex c = x[i];
    cudaDoubleComplex r = c;
    for(int j=0; j<5; j++)
    {
        inc = r + r;
        inc = (r*r - c)/inc;
        r = r - inc;
    }
    y[i] = r;
}
the main function — command line arguments

```c
int main ( int argc, char*argv[] )
{
    if(argc < 5)
    {
        cout << "call with 4 arguments : " << endl;
        cout << "dimension, block size, frequency, and check (0 or 1)" << endl;
    }
    else
    {
        int n = atoi(argv[1]); // dimension
        int w = atoi(argv[2]); // block size
        int f = atoi(argv[3]); // frequency
        int t = atoi(argv[4]); // test or not
        // we generate n random complex numbers on the host
        cudaDoubleComplex *xhost = new cudaDoubleComplex[n];
        for(int i=0; i<n; i++) xhost[i] = randomDoubleComplex();
```

The main program generates $n$ random complex numbers with radius 1.
transferring data and launching the kernel

```c
// copy the n random complex numbers to the device
size_t s = n*sizeof(cudaDoubleComplex);
cudaDoubleComplex *xdevice;
cudaMalloc((void**)&xdevice,s);
cudaMemcpyp(xdevice,xhost,s,cudaMemcpyHostToDevice);
// allocate memory for the result
cudaDoubleComplex *ydevice;
cudaMalloc((void**)&ydevice,s);
// invoke the kernel with n/w blocks per grid
// and w threads per block
for(int i=0; i<f; i++)
    squareRoot<<<n/w,w>>>(n,xdevice,ydevice);
// copy results from device to host
cudaDoubleComplex *yhost = new cudaDoubleComplex[n];
cudaMemcpyp(yhost,ydevice,s,cudaMemcpyDeviceToHost);
```
testing one random number

```c
if(t == 1) // test the result
{
    int k = rand() % n;
    cout << "testing number " << k << endl;
    cout << " x = " << xhost[k] << endl;
    cout << " sqrt(x) = " << yhost[k] << endl;
    cudaDoubleComplex z = Square(yhost[k]);
    cout << "sqrt(x)^2 = " << z << endl;
}
return 0;
```
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a scalable programming model

multithreaded CUDA program

block 0 block 1 block 2 block 3 block 4 block 5 block 6 block 7

GPU with 2 cores

core 0 core 1

block 0 block 1

block 2 block 3

block 4 block 5

block 6 block 7

GPU with 4 cores

core 0 core 1 core 2 core 3

block 0 block 1 block 2 block 3

block 4 block 5 block 6 block 7
running the code on kepler

A test on the correctness:

```
$ /tmp/run_cmpsqrt 1 1 1 1
testing number 0
  x = 5.3682227446949737e-01 -8.4369535119816541e-01
  sqrt(x) = 8.7659063264145631e-01 -4.8123680528950746e-01
  sqrt(x)^2 = 5.3682227446949726e-01 -8.4369535119816530e-01
```

On 64,000 numbers, 32 threads in a block, doing it 10,000 times:

```
$ time /tmp/run_cmpsqrt 64000 32 10000 1
testing number 50325
  x = 7.9510606509728776e-01 -6.0647039931517477e-01
  sqrt(x) = 9.4739275517002119e-01 -3.2007337822967424e-01
  sqrt(x)^2 = 7.9510606509728765e-01 -6.0647039931517477e-01

real   0m1.618s
user   0m0.526s
sys    0m0.841s
$
changing #threads in a block

$ time /tmp/run_cmpsqrt 128000 32 100000 0

real    0m17.345s
user    0m9.829s
sys     0m7.303s

$ time /tmp/run_cmpsqrt 128000 64 100000 0

real    0m10.502s
user    0m5.711s
sys     0m4.497s

$ time /tmp/run_cmpsqrt 128000 128 100000 0

real    0m9.295s
user    0m5.231s
sys     0m3.865s
running the code on pascal

$ time /tmp/run_cmpsqrt 128000 32 100000 0
real  0m2.516s
user  0m1.250s
sys   0m1.236s

$ time /tmp/run_cmpsqrt 128000 64 100000 0
real  0m2.521s
user  0m1.245s
sys   0m1.234s

$ time /tmp/run_cmpsqrt 128000 128 100000 0
real  0m2.496s
user  0m1.288s
sys   0m1.195s
In five steps we wrote our first complete CUDA program.

We started chapter 3 of the textbook by Kirk & Hwu, covering more of the CUDA Programming Guide.

Available in /usr/local/cuda/doc are

- CUDA C Best Practices Guide
- CUDA Programming Guide

Also available online at nvidia.com.

Many examples of CUDA applications are available in /usr/local/cuda/samples.
exercises

1. Instead of 5 Newton iterations in `runCudaComplexSqrt.cu` use $k$ iterations where $k$ is entered by the user at the command line. What is the influence of $k$ on the timings?

2. Modify the kernel for the complex square root so it takes on input an array of complex coefficients of a polynomial of degree $d$. Then the root finder applies Newton’s method, starting at random points. Test the correctness and experiment to find the rate of success, i.e.: for polynomials of degree $d$ how many random trials are needed to obtain $d/2$ roots of the polynomial?