CUDA C: performance measurement and memory

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Outline

Outline

Measuring CPU time

```
#include <stdio.h>
#include <time.h>

int main(){
  float elapsedTime;
  clock_t start = clock();

  // SOME CPU CODE YOU WANT TO TIME

  elapsedTime = ((double) clock() - start) /
      CLOCKS_PER_SEC;

  printf("CPU time elapsed: %f seconds \n",
      elapsedTime);
  return 0;
}
```

Events

- **Event**: a time stamp on the GPU
- Use events to measure GPU execution time.
- `time.cu`:

```
#include <stdlib.h>
#include <stdio.h>
#include <cuda.h>
#include <cuda_runtime.h>

int main(){
  float   elapsedTime;
  cudaEvent_t start, stop;
  cudaEventCreate(&start);
  cudaEventCreate(&stop);
  cudaEventRecord( start, 0 );

  // SOME GPU WORK YOU WANT TIMED HERE

  cudaEventRecord( stop, 0 );
  cudaEventSynchronize( stop );
  cudaEventElapsedTime( &elapsedTime, start, stop );
  cudaEventDestroy( start );
  cudaEventDestroy( stop );
  printf("GPU Time elapsed: %f milliseconds\n", elapsedTime);
}
```

- GPU time and CPU time must be measured separately.

Example: pairwise_sum_timed.cu

```
#include <stdio.h>
#include <stdlib.h>
#include <math.h>
#include <time.h>
#include <unistd.h>
#include <cuda.h>
#include <cuda_runtime.h>

/* This program computes the sum of the elements of
 * vector v using the pairwise (cascading) sum algorithm. */

#define N 1024 // length of vector v. MUST BE A POWER OF 2!!!

// Fill the vector v with n random floating point numbers.
void vfill(float* v, int n){
  int i;
  for(i = 0; i < n; i++){
    v[i] = (float) rand() / RAND_MAX;
  }
}

// Print the vector v.
void vprint(float* v, int n){
  int i;
  printf("v = \n");
  for(i = 0; i < n; i++){
    printf("%7.3f\n", v[i]);
  }
  printf("\n");
}
```

Example: pairwise_sum_timed.cu

```
// Pairwise-sum the elements of vector v and store the result in v
    [0].
__global__ void psum(float *v){
  int t = threadIdx.x; // Thread index.
  int n = blockDim.x; // Should be half the length of v.

  while (n != 0) {
    if(t < n)
      v[t] += v[t + n];
    __syncthreads();
    n /= 2;
  }
}

// Linear sum the elements of vector v and return the result
float lsum(float *v, int len){
  float s = 0;
  int i;
  for(i = 0; i < len; i++){
    s += v[i];
  }
  return s;
}
```

Example: `pairwise_sum_timed.cu`

```
int main (void){
  float *v_h, *v_d; // host and device copies of our vector,
      respectively

  // dynamically allocate memory on the host for v_h
  v_h = (float*) malloc(N * sizeof(*v_h));

  // dynamically allocate memory on the device for v_d
  cudaMalloc ((float**) &v_d, N *sizeof(*v_d));

  // Fill v_h with N random floating point numbers.
  vfill(v_h, N);

  // Print v_h to the console
  // vprint(v_h, N);

  // Write the contents of v_h to v_d
  cudaMemcpy( v_d, v_h, N * sizeof(float), cudaMemcpyHostToDevice );

  // compute the linear sum of the elements of v_h on the CPU and
      return the result
  // also, time the result.
  clock_t start = clock();
  float s = lsum(v_h, N);
```

Example: pairwise_sum_timed.cu

```
  float elapsedTime = ((float) clock() - start) / CLOCKS_PER_SEC;
  printf("Linear Sum = %7.3f, CPU Time elapsed: %f seconds\n", s,
       elapsedTime);

  // Compute the pairwise sum of the elements of v_d and store the
       result in v_d[0].
  // Also, time the computation.

  float   gpuElapsedTime;
  cudaEvent_t gpuStart, gpuStop;
  cudaEventCreate(&gpuStart);
  cudaEventCreate(&gpuStop);
  cudaEventRecord( gpuStart, 0 );

psum<<< 1, N/2 >>>(v_d);

  cudaEventRecord( gpuStop, 0 );
  cudaEventSynchronize( gpuStop );
  cudaEventElapsedTime( &gpuElapsedTime, gpuStart, gpuStop ); // time
        in milliseconds
  cudaEventDestroy( gpuStart );
  cudaEventDestroy( gpuStop );

  // Write the pairwise sum, v_d[0], to v_h[0].
  cudaMemcpy(v_h, v_d, sizeof(float), cudaMemcpyDeviceToHost );
```

Example: pairwise_sum_timed.cu

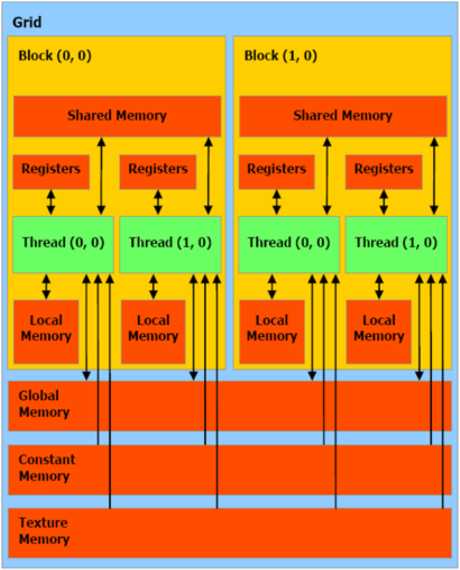
```
  // Print the pairwise sum.
  printf("Pairwise Sum = %7.3f, GPU Time elapsed: %f seconds\n", v_h
       [0], gpuElapsedTime/1000.0);

  // Free dynamically-allocated host memory
  free(v_h);

  // Free dynamically-allocated device memory
  cudaFree(&v_d);
}
```

- Output:

```
> nvcc pairwise_sum_timed.cu -o pairwise_sum_timed
> ./pairwise_sum_timed
Linear Sum = 518.913, CPU Time elapsed: 0.000000 seconds
Pairwise Sum = 518.913, GPU Time elapsed: 0.000037 seconds
```

Outline

Types of memory



What happens in myKernel<<<2, 2>>>(b, t)?

```
__global__ void myKernel(int *b_global, int *
    t_global){

  __shared__ int t;
  __shared__ int b;

  int b_local, t_local;

  *t_global = threadIdx.x;
  *b_global = blockIdx.x;

   t_shared = threadIdx.x;
   b_shared = blockIdx.x;

   t_local = threadIdx.x;
   b_local = blockIdx.x;
}
```

At the end of `myKernel<<<4, 7>>>(b, t)`...

- `b_local` and `t_local` are in local memory (or registers), so each thread gets a copy.

(block, thread)	(0, 0)	(0, 1)	(1, 0)	(1, 1)
`b_local`	0	0	1	1
`t_local`	0	1	0	1

- `b_shared` and `t_shared` are in shared memory, so each block gets a copy.

(block, thread)	(0, 0)	(0, 1)	(1, 0)	(1, 1)
`b_shared`	0	0	1	1
`t_shared`	?	?	?	?

  - ? = last thread in its block to write to `t_shared`.

At the end of `myKernel<<<4, 7>>>(b, t)`...

- `b_global` and `t_global` point to global memory, so there is only one copy.

(block, thread)	(0, 0)	(0, 1)	(1, 0)	(1, 1)
`*b_global`	??	??	??	??
`*t_global`	?	?	?	?

  - ? = last thread in its block to write to `*t_global`.
  - ?? = block of the last thread to write to `*b_global`.

Example: dot product

$$a \bullet b = (a_0, \ldots, a_{15}) \bullet (b_0, \ldots, b_{15}) = a_0 \cdot b_0 + \cdots + a_{15} \cdot b_{15}$$

1. In this example, spawn 2 blocks and 4 threads per block.
2. Give each block a subvector of a and an analogous subvector of b.
   - Block 0:

$$(a_0, a_1, a_2, a_3, \;\; a_8, a_9, a_{10}, a_{11})$$
$$(b_0, b_1, b_2, b_3, \;\; b_8, b_9, b_{10}, b_{11})$$

   - Block 1:

$$(a_4, a_5, a_6, a_7, \;\; a_{12}, a_{13}, a_{14}, a_{15})$$
$$(b_4, b_5, b_6, b_7, \;\; b_{12}, b_{13}, b_{14}, b_{15})$$

Example: dot product

3. Create an array, `cache`, in shared memory:
   - Block 0:

$$\text{cache}[0] = a_0 \cdot b_0 + a_8 \cdot b_8$$
$$\text{cache}[1] = a_1 \cdot b_1 + a_9 \cdot b_9$$
$$\text{cache}[2] = a_2 \cdot b_2 + a_{10} \cdot b_{10}$$
$$\text{cache}[3] = a_3 \cdot b_3 + a_{11} \cdot b_{11}$$

   - Block 1:

$$\text{cache}[0] = a_4 \cdot b_4 + a_{12} \cdot b_{12}$$
$$\text{cache}[1] = a_5 \cdot b_5 + a_{13} \cdot b_{13}$$
$$\text{cache}[2] = a_6 \cdot b_6 + a_{14} \cdot b_{14}$$
$$\text{cache}[3] = a_7 \cdot b_7 + a_{15} \cdot b_{15}$$

Example: dot product

4. Compute the pairwise sum of `cache` in each block and write it to `cache[0]`
   - Block 0:

$$\begin{aligned} \text{cache}[0] &= a_0 \cdot b_0 + a_8 \cdot b_8 \\ &+ a_1 \cdot b_1 + a_9 \cdot b_9 \\ &+ a_2 \cdot b_2 + a_{10} \cdot b_{10} \\ &+ a_3 \cdot b_3 + a_{11} \cdot b_{11} \end{aligned}$$

   - Block 1:

$$\begin{aligned} \text{cache}[0] &= a_4 \cdot b_4 + a_{12} \cdot b_{12} \\ &+ a_5 \cdot b_5 + a_{13} \cdot b_{13} \\ &+ a_6 \cdot b_6 + a_{14} \cdot b_{14} \\ &+ a_7 \cdot b_7 + a_{15} \cdot b_{15} \end{aligned}$$

Example: dot product

5. Compute an array, `partial_c` in global memory:

$$\text{partial\_c}[0] = \text{cache}[0] \text{ from block } 0$$
$$\text{partial\_c}[1] = \text{cache}[0] \text{ from block } 1$$

6. The pairwise sum of `partial_c` is the final answer.

dot_product.cu

```
#include "../common/book.h"
#include <stdio.h>
#include <stdlib.h>
#define imin(a,b) (a<b?a:b)

const int N = 32 * 1024;
const int threadsPerBlock = 256;
const int blocksPerGrid = imin( 32, (N+threadsPerBlock-1) /
     threadsPerBlock );

__global__ void dot( float *a, float *b, float *partial_c ) {

  __shared__ float cache[threadsPerBlock];
  int tid = threadIdx.x + blockIdx.x * blockDim.x;
  int cacheIndex = threadIdx.x;
  float temp = 0;

  while (tid < N) {
    temp += a[tid] * b[tid];
    tid += blockDim.x * gridDim.x;
  }

  // set the cache values
  cache[cacheIndex] = temp;
```

`dot<<<2, 4>>>(a, b, c)` with $N = 16$

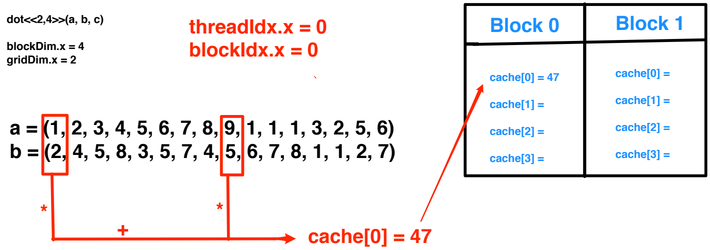
dot<<2,4>>(a, b, c)

blockDim.x = 4
gridDim.x = 2

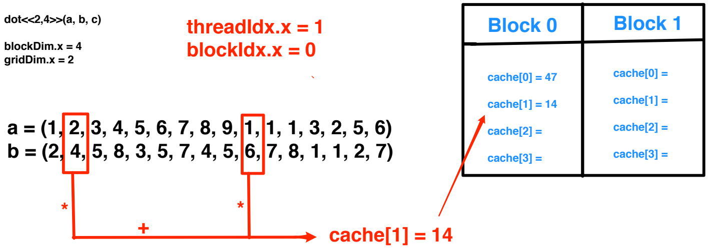
a = (1, 2, 3, 4, 5, 6, 7, 8, 9, 1, 1, 1, 3, 2, 5, 6)
b = (2, 4, 5, 8, 3, 5, 7, 4, 5, 6, 7, 8, 1, 1, 2, 7)

Block 0	Block 1
cache[0] =	cache[0] =
cache[1] =	cache[1] =
cache[2] =	cache[2] =
cache[3] =	cache[3] =

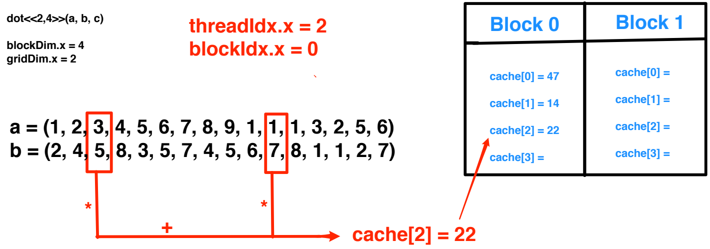
`dot<<<2, 4>>>(a, b, c)` with $N = 16$



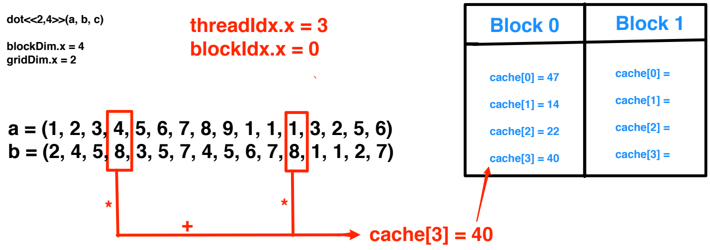
dot<<<2, 4>>>(a, b, c) with $N = 16$



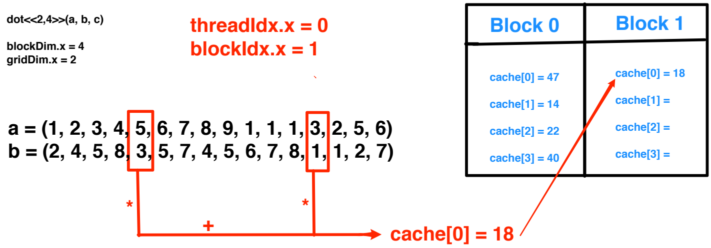
dot<<<2, 4>>>(a, b, c) with $N = 16$



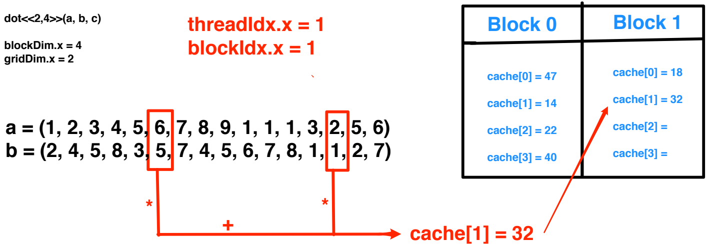
dot<<<2, 4>>>(a, b, c) with $N = 16$



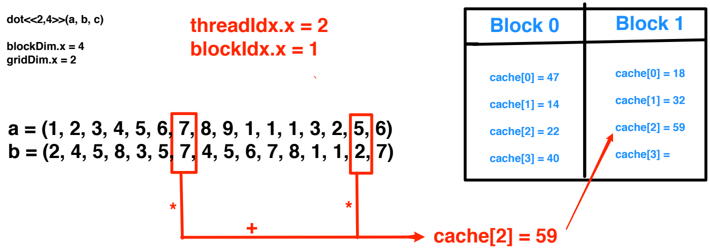
`dot<<<2, 4>>>(a, b, c)` with $N = 16$



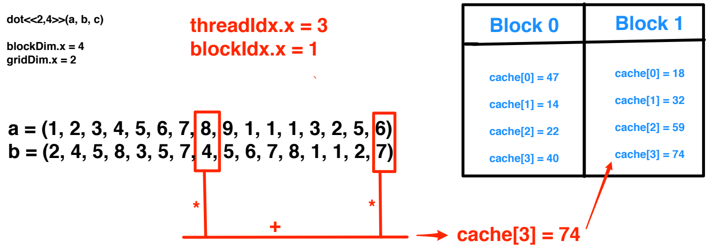
dot<<<2, 4>>>(a, b, c) with $N = 16$



dot<<<2, 4>>>(a, b, c) with $N = 16$



`dot<<<2, 4>>>(a, b, c)` with $N = 16$



- Make sure cache is full before continuing.

```
// synchronize threads in this block
__syncthreads();
```

- Execute a pairwise sum of cache for each block.

```
  // threadsPerBlock must be a power of 2
  int i = blockDim.x/2;
  while (i != 0) {
    if (cacheIndex < i)
      cache[cacheIndex] += cache[cacheIndex + i];
    __syncthreads();
    i /= 2;
  }
```

- Record the result in `partial_c`.

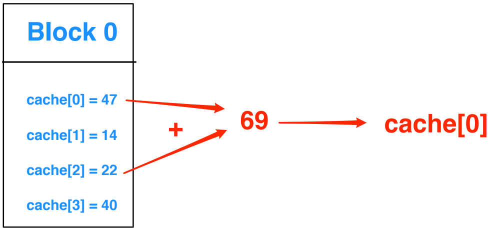
```
  if (cacheIndex == 0)
    partial_c[blockIdx.x] = cache[0];
}
```

dot<<<2, 4>>>(a, b, c) with $N = 16$

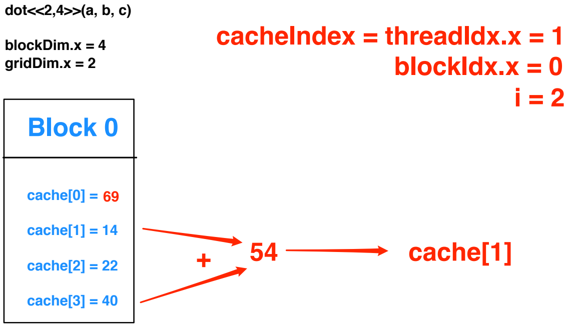
dot<<2,4>>(a, b, c)

blockDim.x = 4
gridDim.x = 2

cacheIndex = threadIdx.x = 0
blockIdx.x = 0
i = 2



dot<<<2, 4>>>(a, b, c) with $N = 16$



dot<<<2, 4>>>(a, b, c) with $N = 16$

dot<<2,4>>(a, b, c)

blockDim.x = 4
gridDim.x = 2

Block 0

cache[0] = 69

cache[1] = 54

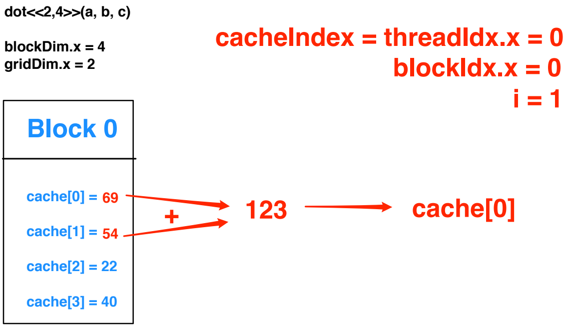
cache[2] = 22

cache[3] = 40

cacheIndex = threadIdx.x = 1
blockIdx.x = 0
i = 2

__synchthreads();

dot<<<2, 4>>>(a, b, c) with $N = 16$



dot<<<2, 4>>>(a, b, c) with $N = 16$

dot<<2,4>>(a, b, c)

blockDim.x = 4
gridDim.x = 2

Block 0

cache[0] = 123
cache[1] = 54
cache[2] = 22
cache[3] = 40

cacheIndex = threadIdx.x = 0
blockIdx.x = 0
i = 1

__synchthreads();

`dot<<<2, 4>>>(a, b, c)` with $N = 16$

`dot<<2,4>>(a, b, c)`

blockDim.x = 4
gridDim.x = 2

Block 0

cache[0] = 123
cache[1] = 54
cache[2] = 22
cache[3] = 40

cacheIndex = threadIdx.x = 0
blockIdx.x = 0
i = 0

i = 0, so end the pairwise sum.

The result for block 0 is cache[0] = 123.

Sum up partial_c inside int main()

```
dot<<<blocksPerGrid,threadsPerBlock>>>( dev_a,
      dev_b, dev_partial_c );

// copy partial_c to the CPU
cudaMemcpy( partial_c, dev_partial_c,
     blocksPerGrid*sizeof(float),
     cudaMemcpyDeviceToHost);

// finish up on the CPU side
c = 0;
for (int i=0; i<blocksPerGrid; i++) {
  c += partial_c[i];
}
```

Outline

Resources

- Guides:

1. J. Sanders and E. Kandrot. CUDA by Example. Addison-Wesley, 2010.
2. D. Kirk, W.H. Wen-mei, and W. Hwu. *Programming massively parallel processors: a hands-on approach.* Morgan Kaufmann, 2010.
3. Michael Romero and Rodrigo Urra. CUDA Programming. Rochester Institute of Technology. http://cuda.ce.rit.edu/cudaoverview/cudaoverview.html.

- Code:
  - time.cu
  - pairwise_sum_timed.cu
  - dot_product.cu

That's all for today.

- Series materials are available at http://will-landau.com/gpu.