

CUDA C: PERFORMANCE MEASUREMENT AND TYPES OF MEMORY

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OUTLINE

- Measuring GPU performance
- Global memory vs. shared memory vs. local memory and registers
- Implementing the dot product

Featured examples:

- `time.cu`
- `pairwise_sum_timed.cu`
- `dot_product.cu`

EVENTS: MEASURING PERFORMANCE ON THE GPU

Event: a time stamp for the GPU.

Use events to measure the amount of time the GPU spends on a task.

TEMPLATE: 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 );
}
```

The variable, `elapsedTime`, is the GPU time spent on the task. You can now print it any way you like.

Note: only GPU elapsed time is measured, not CPU time.

GPU time and CPU time must be measured separately.

ASIDE: MEASURING CPU TIME

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

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

    // SOME CPU CODE YOU WANT TIMED HERE

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

    printf("CPU Time elapsed: %f\n", elapsedTime);
}
```

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() / RANDMAX;
    }
}
```

```

// 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");
}

// 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;
}

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);

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 ) ;
cudaEventDestroy( gpuStart ) ;
cudaEventDestroy( gpuStop ) ;

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

// 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) ;

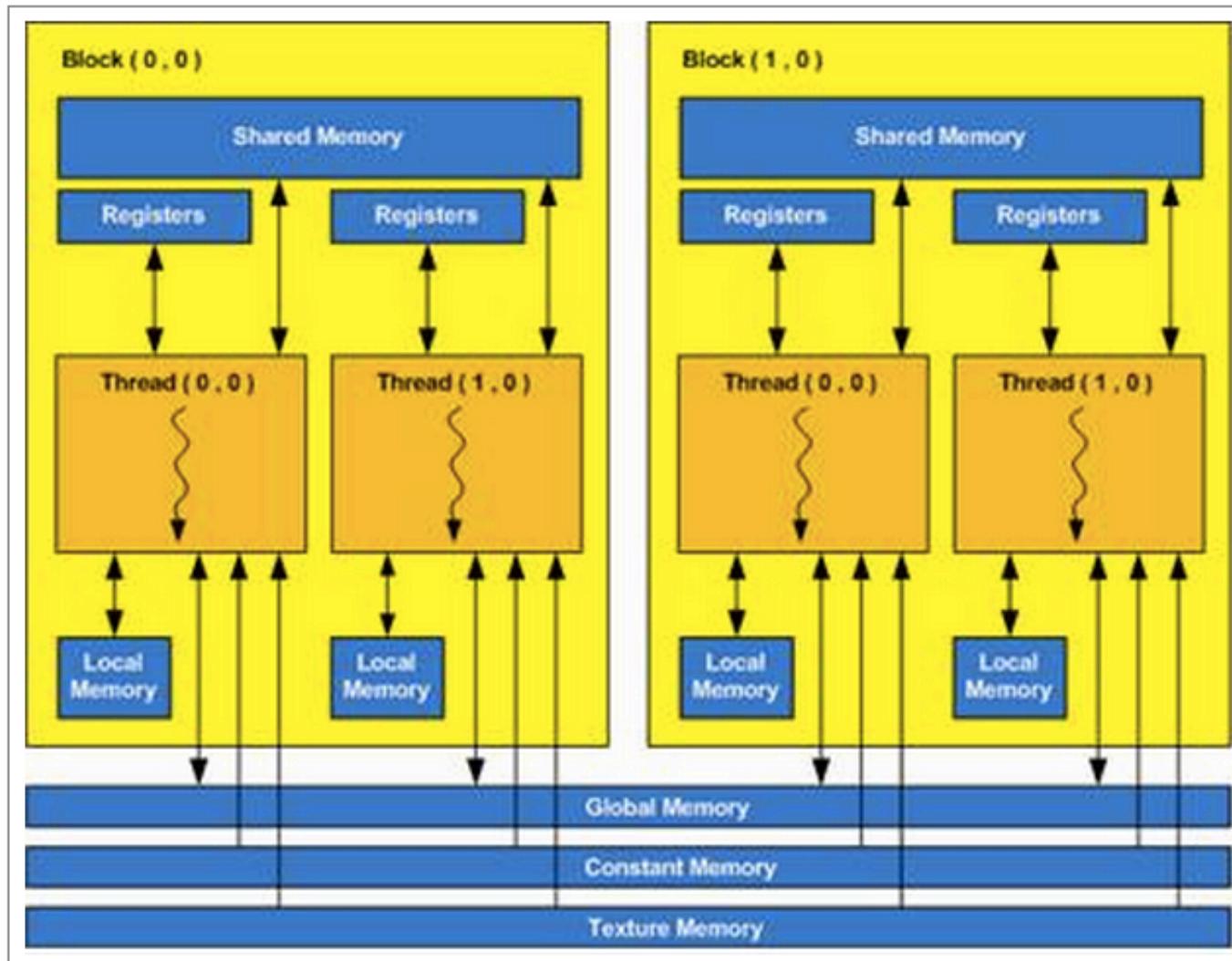
```

}

OUTPUT

```
[landau@impact1 pairwise_sum_timed]$ make
nvcc pairwise_sum_timed.cu -o pairwise_sum_timed
[landau@impact1 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
[landau@impact1 pairwise_sum_timed]$
```

TYPES OF MEMORY



THOUGHT EXPERIMENT: GLOBAL MEMORY VS. SHARED MEMORY VS. LOCAL MEMORY AND REGISTERS

Let's say we have a kernel:

```
--global__ void kernel(int *a){  
    *a = blockIdx.x * blockDim.x + threadIdx.x;  
    int b = blockIdx.x * blockDim.x + threadIdx.x;  
    __shared__ int c = blockIdx.x * blockDim.x + threadIdx.x;  
}
```

What are *a, b, and c after a call to `kernel<<<3, 2>>>(a)`?

***a:** There is one copy of ***a** in GLOBAL MEMORY common to all threads and blocks. Hence, the value of ***a** depends on which thread finishes last.

b: There are $3 \cdot 2 = 6$ copies of **b**, each in either LOCAL MEMORY or REGISTERS, one for each of the six threads. The values of **b** will be:

(Block ID, Thread ID)	(0, 0)	(0, 1)	(1, 0)	(1, 1)	(2, 0)	(2, 1)
Value of b	0	1	2	3	4	5

c: There are three copies of **c** in SHARED MEMORY, one for each block. The values of **c** might be:

(Block ID, Thread ID)	(0, 0)	(0, 1)	(1, 0)	(1, 1)	(2, 0)	(2, 1)
Value of c	0	0	3	3	4	4

depending on which thread finishes last within each block.

NOW, WE'RE READY FOR THE DOT PRODUCT

$$(a_0, a_1, \dots, a_{15}) \bullet (b_0, b_1, \dots, b_{15}) = a_0b_0 + a_1b_1 + \dots + a_{15}b_{15}$$

The basic workflow is:

- Pass vectors **a** and **b** to the GPU.
- Give each block a sub vector of **a** and the analogous subvector of **b**.

For the case of 16-element vectors, let there be 2 blocks and 4 threads per block.

Block 0 works on:

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

Block 1 works on:

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

- Within each block, compute a vector of partial sums of pairwise products:

Block 0:

$$\text{cache} = (a_0 \cdot b_0 + a_8 \cdot b_8, a_1 \cdot b_1 + a_9 \cdot b_9, \dots, a_3 \cdot b_3 + a_{11} \cdot b_{11})$$

Block 1:

$$\text{cache} = (a_4 \cdot b_4 + a_{12} \cdot b_{12}, a_5 \cdot b_5 + a_{13} \cdot b_{13}, \dots, a_7 \cdot b_7 + a_{15} \cdot b_{15})$$

where `cache` is an array in shared memory.

- Within each block, compute the pairwise sum of `cache` and write it to `cache[0]`. In our example:

Block 0:

$$\text{cache}[0] = a_0 \cdot b_0 + \cdots + a_3 \cdot b_3 + a_8 \cdot b_8 + \cdots + a_{11} \cdot b_{11}$$

Block 1:

$$\text{cache}[0] = a_4 \cdot b_4 + \cdots + a_7 \cdot b_7 + a_{12} \cdot b_{12} + \cdots + a_{15} \cdot b_{15}$$

- Fill a new vector in global memory, `partial_c`, with these partial dot products:

$$\text{partial_c} = (\text{block 0 cache}[0], \text{block 1 cache}[0])$$

- Return to the CPU and compute the linear sum of `partial_c` and write it to `partial_c[0]`. Then:

$$\text{partial_c}[0] = a_0 \cdot b_0 + a_1 \cdot b_1 + \cdots + a_{15} \cdot b_{15}$$

First part of the code:

```
#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;
```

What the code would do in a call to `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[1] = cache[2] = cache[3] =	cache[0] = cache[1] = cache[2] = cache[3] =

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

```
blockDim.x = 4  
gridDim.x = 2
```

threadIdx.x = 0
blockIdx.x = 0

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

*

+

*

cache[0] = 47

Block 0	Block 1
cache[0] = 47 cache[1] = cache[2] = cache[3] =	cache[0] = cache[1] = cache[2] = cache[3] =

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

```
blockDim.x = 4  
gridDim.x = 2
```

threadIdx.x = 1
blockIdx.x = 0

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)

*

+

*

cache[1] = 14

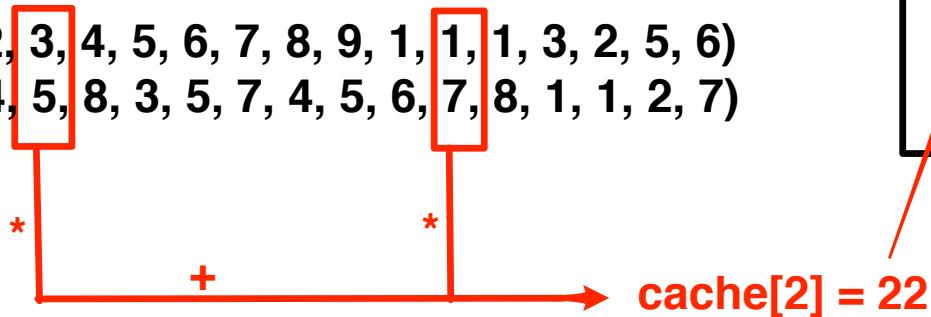
Block 0	Block 1
cache[0] = 47 cache[1] = 14 cache[2] = cache[3] =	cache[0] = cache[1] = cache[2] = cache[3] =

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

```
blockDim.x = 4  
gridDim.x = 2
```

threadIdx.x = 2
blockIdx.x = 0

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)



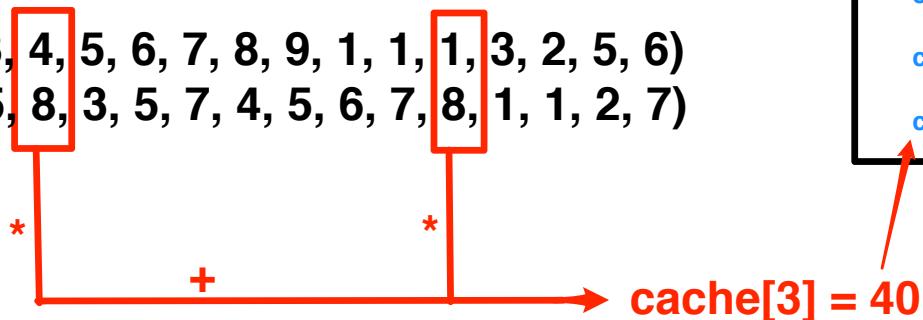
Block 0	Block 1
cache[0] = 47 cache[1] = 14 cache[2] = 22 cache[3] =	cache[0] = cache[1] = cache[2] = cache[3] =

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

```
blockDim.x = 4  
gridDim.x = 2
```

threadIdx.x = 3
blockIdx.x = 0

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)

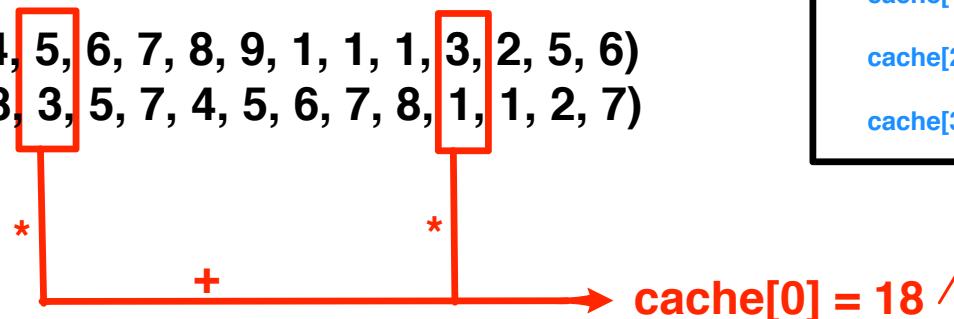


Block 0	Block 1
cache[0] = 47	cache[0] =
cache[1] = 14	cache[1] =
cache[2] = 22	cache[2] =
cache[3] = 40	cache[3] =

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



threadIdx.x = 0
blockIdx.x = 1

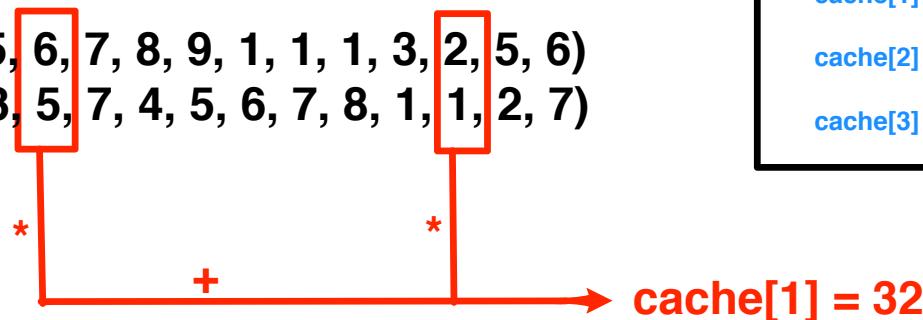
Block 0	Block 1
cache[0] = 47 cache[1] = 14 cache[2] = 22 cache[3] = 40	cache[0] = 18 cache[1] = cache[2] = cache[3] =

```
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)**

**threadIdx.x = 1
blockIdx.x = 1**



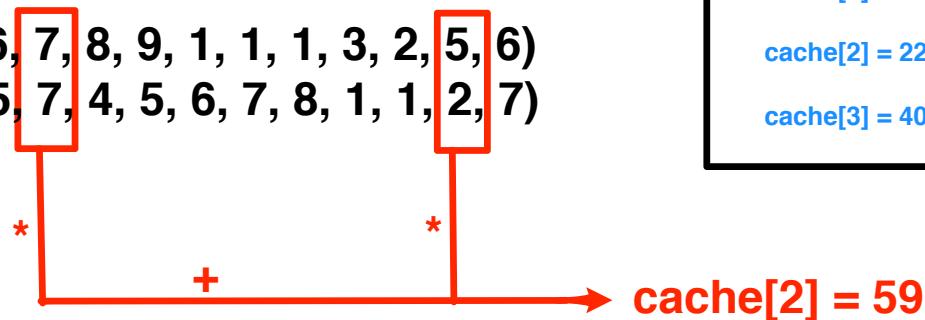
Block 0	Block 1
cache[0] = 47 cache[1] = 14 cache[2] = 22 cache[3] = 40	cache[0] = 18 cache[1] = 32 cache[2] = cache[3] =

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

```
blockDim.x = 4  
gridDim.x = 2
```

threadIdx.x = 2
blockIdx.x = 1

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)



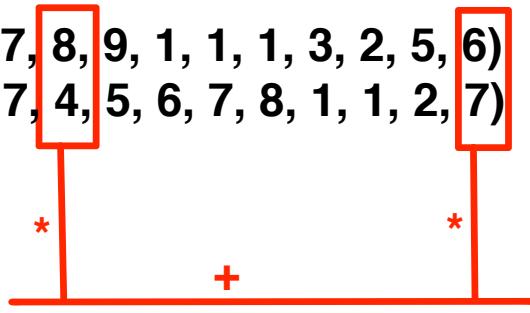
Block 0	Block 1
cache[0] = 47 cache[1] = 14 cache[2] = 22 cache[3] = 40	cache[0] = 18 cache[1] = 32 cache[2] = 59 cache[3] =

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

```
blockDim.x = 4  
gridDim.x = 2
```

threadIdx.x = 3
blockIdx.x = 1

a = (1, 2, 3, 4, 5, 6, 7, 8, 9, 1, 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] = 47	cache[0] = 18
cache[1] = 14	cache[1] = 32
cache[2] = 22	cache[2] = 59
cache[3] = 40	cache[3] = 74

We want to make sure that each block's copy of `cache` is filled up before we continue further.

Hence, the next line of code is:

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

NEXT, WE EXECUTE A PAIRWISE SUM ON cache FOR EACH BLOCK

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

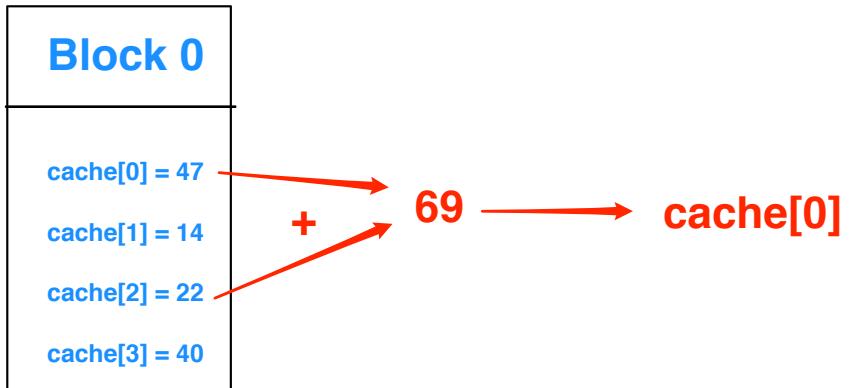
WHAT'S GOING ON IN OUR CALL TO

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

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

`blockDim.x = 4`
`gridDim.x = 2`

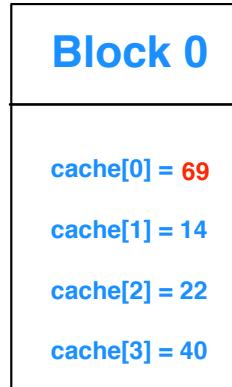
cachelIndex = threadIdx.x = 0
blockIdx.x = 0
i = 2



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

```
blockDim.x = 4  
gridDim.x = 2
```

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



```
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

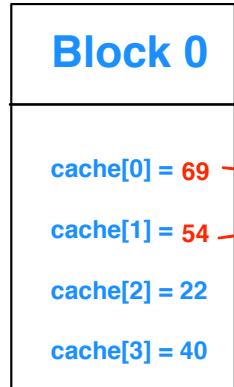
**cachelIndex = threadIdx.x = 1
blockIdx.x = 0
i = 2**

__syncthreads();

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

```
blockDim.x = 4  
gridDim.x = 2
```

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



$$\text{cache}[0] = 69 + \text{cache}[1] = 54 = 123 \rightarrow \text{cache}[0]$$

```
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

**cachelIndex = threadIdx.x = 0
blockIdx.x = 0
i = 1**

__syncthreads();

```
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

cachelIndex = threadIdx.x = 0
blockIdx.x = 0
i = 0

i = 0, so end the pairwise sum.

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

Similarly, cache[0] for block 1 is 183.

Next:

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

So now, **partial_c[0]** = 123 and **partial_c[1]** is 183.

We return from the kernel, `dot()`, and compute the linear sum of the elements of `partial_c`:

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

Now, `partial_c[0]` is the final answer.

COMPLETE CODE

```
#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;

// synchronize threads in this block
__syncthreads();

// for reductions, threadsPerBlock must be a power of 2 //
// because of the following code
int i = blockDim.x/2;
while (i != 0) {
    if (cacheIndex < i)
        cache[cacheIndex] += cache[cacheIndex + i];
    __syncthreads();      i /= 2;
}

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

int main( void ) {
    float *a, *b, c, *partial_c;
    float *dev_a, *dev_b, *dev_partial_c;

```

```

// allocate memory on the CPU side
a = (float *)malloc( N*sizeof(float) );
b = (float *)malloc( N*sizeof(float) );
partial_c = (float *)malloc( blocksPerGrid*sizeof(float) );

// allocate the memory on the GPU
HANDLEERROR( cudaMalloc( (void**)&dev_a , N*sizeof(float) ) );
HANDLEERROR( cudaMalloc( (void**)&dev_b , N*sizeof(float) ) );
HANDLEERROR( cudaMalloc( (void**)&dev_partial_c , blocksPerGrid
    *sizeof(float) ) );

// fill in the host memory with data
for (int i=0; i<N; i++) {
    a[i] = i;
    b[i] = i*2;
}

// copy the arrays a and b to the GPU
HANDLEERROR( cudaMemcpy( dev_a , a , N*sizeof(float) ,
    cudaMemcpyHostToDevice ) );
HANDLEERROR( cudaMemcpy( dev_b , b , N*sizeof(float) ,
    cudaMemcpyHostToDevice ) );

dot<<<blocksPerGrid , threadsPerBlock>>>( dev_a , dev_b ,

```

```

    dev_partial_c ) ;

// copy the array 'c' back from the GPU to the CPU
HANDLEERROR( 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 ];
}

#define sum_squares(x)( x * (x + 1) * (2 * x + 1) / 6 )

printf("Does GPU value %.6g = %.6g?\n" , c , 2 * sum_squares( (
float )(N - 1) ) ) ;

// free memory on the GPU side
cudaFree( dev_a );
cudaFree( dev_b );
cudaFree( dev_partial_c );
// free memory on the CPU side
free( a );

```

```
    free( b );
    free( partial_c );
}
```

OUTPUT

```
[landau@impact1 dot_product]$ nvcc dot_product.cu -o dot_product
[landau@impact1 dot_product]$ ./dot_product
Does GPU value 2.57236e+13 = 2.57236e+13?
[landau@impact1 dot_product]$
```

OUTLINE

- Measuring GPU performance
- Global memory vs. shared memory vs. local memory and registers
- Implementing the dot product

LECTURE SERIES MATERIALS

These lecture slides, a tentative syllabus for the whole lecture series, and code are available at:

<https://github.com/wlandau/gpu>.

After logging into you home directory on impact1, type:

```
git clone https://github.com/wlandau/gpu
```

into the command line to download all the course materials.

REFERENCES

David B. Kirk and Wen-mei W. Hwu. “Programming Massively Parallel Processors: a Hands-on Approach.” Morgan Kaufman, 2010.

J. Sanders and E. Kandrot. *CUDA by Example*. Addison-Wesley, 2010.

Michael Romero and Rodrigo Urra. ”CUDA Programming.” Rochester Institute of Technology.
http://cuda.ce.rit.edu/cuda_overview/cuda_overview.html