

MORE PROGRAMMING IN CUDA C: PERFORMANCE MEASUREMENT AND ATOMICS

Will Landau, Prof. Jarad Niemi

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.

```
int main(){
    float    elapsedTime;
    cudaEvent_t start, stop;

    cudaEventCreate(&start);
    cudaEventCreate(&stop);
    cudaEventRecord( start, 0 );

    // SOME GPU KERNEL YOU WANT TIMED HERE

    cudaEventRecord( stop, 0 );
    cudaEventSynchronize( stop );
    cudaEventElapsedTime( &elapsedTime, start, stop );

    cudaEventDestroy( start );
    cudaEventDestroy( stop );

    printf("GPU Time elapsed: %f\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.

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);
}
```

ATOMICS

Consider the following GPU operation on integer **x**:

x++;

which tells the GPU to do 3 things...

`x++;`

1. Read the value stored in x.
2. Add 1 to the value read in step 1.
3. Write the result back to x.

Say we need threads A and B to increment x. We want:

STEP	EXAMPLE
1. Thread A reads the value in x.	A reads 7 from x.
2. Thread A adds 1 to the value it read.	A computes 8.
3. Thread A writes the result back to x.	x <- 8.
4. Thread B reads the value in x.	B reads 8 from x.
5. Thread B adds 1 to the value it read.	B computes 9.
6. Thread B writes the result back to x.	x <- 9.

but we might get:

STEP	EXAMPLE
Thread A reads the value in x.	A reads 7 from x.
Thread B reads the value in x.	B reads 7 from x.
Thread A adds 1 to the value it read.	A computes 8.
Thread B adds 1 to the value it read.	B computes 8.
Thread A writes the result back to x.	<code>x <- 8.</code>
Thread B writes the result back to x.	<code>x <- 8.</code>

Race Condition: A computational hazard that arises when the results of a program depend on the timing of uncontrollable events, such as threads.

Atomic Operation: A command that is executed one thread at a time, thus avoiding a race condition.

To avoid the race condition in our example, we atomically add 1 to x:

```
atomicAdd( &x, 1 );
```

instead of using `x++;`

LIST OF CUDA C BUILT-IN ATOMICS

atomicAdd()

atomicSub()

atomicMin()

atomicMax()

atomicInc()

atomicDec()

atomicExch()

atomicCAS()

```
int atomicAdd(int* address, int val);
unsigned int atomicAdd(unsigned int* address,
                       unsigned int val);
unsigned long long int atomicAdd(unsigned long long int* address,
                                unsigned long long int val);
float atomicAdd(float* address, float val);
```

reads the 32-bit or 64-bit word **old** located at the address **address** in global or shared memory, computes **(old + val)**, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

```
int atomicSub(int* address, int val);
```

```
unsigned int atomicSub(unsigned int* address,  
                        unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes **(old - val)**, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

```
int atomicExch(int* address, int val);
unsigned int atomicExch(unsigned int* address,
                        unsigned int val);
unsigned long long int atomicExch(unsigned long long int* address,
                                unsigned long long int val);
float atomicExch(float* address, float val);
```

reads the 32-bit or 64-bit word **old** located at the address **address** in global or shared memory and stores **val** back to memory at the same address. These two operations are performed in one atomic transaction. The function returns **old**.

```
--  
int atomicMin(int* address, int val);  
unsigned int atomicMin(unsigned int* address,  
                        unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes the minimum of **old** and **val**, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

```
int atomicMax(int* address, int val);  
unsigned int atomicMax(unsigned int* address,  
                        unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes the maximum of **old** and **val**, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.


```
--  
unsigned int atomicInc(unsigned int* address,  
                        unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes $((\text{old} \geq \text{val}) ? 0 : (\text{old} + 1))$, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

```
unsigned int atomicDec(unsigned int* address,  
                        unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes $((\mathbf{old} == 0) \mid (\mathbf{old} > \mathbf{val})) ? \mathbf{val} : (\mathbf{old}-1)$, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

```
int atomicCAS(int* address, int compare, int val);
unsigned int atomicCAS(unsigned int* address,
                      unsigned int compare,
                      unsigned int val);
unsigned long long int atomicCAS(unsigned long long int* address,
                                unsigned long long int compare,
                                unsigned long long int val);
```

reads the 32-bit or 64-bit word **old** located at the address **address** in global or shared memory, computes (**old == compare ? val : old**), and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old** (Compare And Swap).

```
int atomicAnd(int* address, int val);  
unsigned int atomicAnd(unsigned int* address,  
                        unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes (**old & val**), and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

```
int atomicOr(int* address, int val);  
unsigned int atomicOr(unsigned int* address,  
                      unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes **(old | val)**, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

```
int atomicXor(int* address, int val);  
unsigned int atomicXor(unsigned int* address,  
                        unsigned int val);
```

reads the 32-bit word **old** located at the address **address** in global or shared memory, computes **(old ^ val)**, and stores the result back to memory at the same address. These three operations are performed in one atomic transaction. The function returns **old**.

NOTE: If you're using any of the above functions in your code, compile with the flag, **-arch sm_20**

Example:

```
nvcc dot_product_atomic.cu -arch sm_20  
    -o dot_product_atomic
```

LOCKS

Lock: a mechanism in parallel computing that forces a block of code to be executed atomically.

mutex: short for “mutual exclusion”, the idea behind locks: while a thread is running code inside a lock, it blocks all other threads from running the code.

lock.h:

```
struct Lock {
    int *mutex;
    Lock( void ) {
        int state = 0;
        HANDLE_ERROR( cudaMalloc( (void**)& mutex,
                                   sizeof(int) ) );
        HANDLE_ERROR( cudaMemcpy( mutex, &state, sizeof(int),
                                   cudaMemcpyHostToDevice ) );
    }

    ~Lock( void ) {
        cudaFree( mutex );
    }

    __device__ void lock( void ) {
        while( atomicCAS( mutex, 0, 1 ) != 0 );
    }

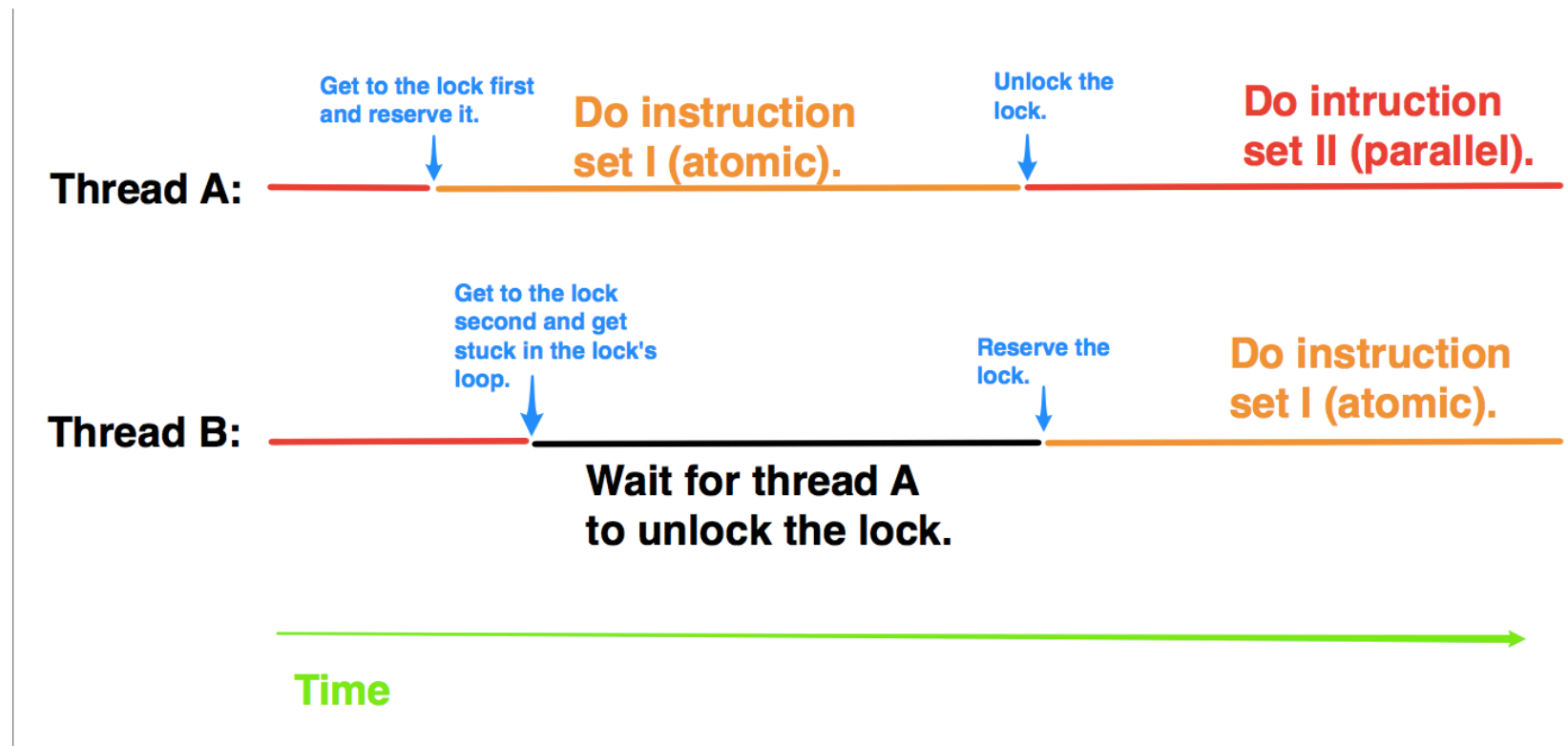
    __device__ void unlock( void ) {
        atomicExch( mutex, 0 );
    }
};
```

Now, let's look at the lock function:

```
__device__ void lock( void ) {  
    while( atomicCAS( mutex, 0, 1 ) != 0 );  
}
```

In pseudo-code:

```
__device__ void lock( void ) {  
    repeat{  
        do atomically{  
  
            if(mutex == 0){  
                mutex = 1;  
                return_value = 0;  
            }  
  
            else if(mutex == 1){  
                return_value = 1;  
            }  
  
        } // do atomically  
  
        if(return_value = 0)  
            exit loop;  
  
    } // repeat  
} // lock
```



Compare these two kernels, both of which attempt to count the number of spawned blocks:

```
--global__ void blockCounterUnlocked( int *nblocks ){
    if(threadIdx.x == 0){
        *nblocks = *nblocks + 1;
    }
}
```

```
--global__ void blockCounter1( Lock lock, int *nblocks ){
    if(threadIdx.x == 0){
        lock.lock();
        *nblocks = *nblocks + 1;
        lock.unlock();
    }
}
```

Which one gives us the correct answer?

Which one is faster?

blockCounter.cu

```
#include "../common/lock.h"
#define NBLOCKS_TRUE 512
#define NTHREADS_TRUE 512 * 2

__global__ void blockCounterUnlocked( int *nblocks ){
    if(threadIdx.x == 0){
        *nblocks = *nblocks + 1;
    }
}

__global__ void blockCounter1( Lock lock, int *nblocks ){
    if(threadIdx.x == 0){
        lock.lock();
        *nblocks = *nblocks + 1;
        lock.unlock();
    }
}
```

```

int main(){
    int nblocks_host, *nblocks_dev;
    Lock lock;
    float elapsedTime;
    cudaEvent_t start, stop;

    cudaMalloc((void**) &nblocks_dev, sizeof(int));

    //blockCounterUnlocked:

    nblocks_host = 0;
    cudaMemcpy( nblocks_dev, &nblocks_host, sizeof(int), cudaMemcpyHostToDevice );

    cudaEventCreate(&start);
    cudaEventCreate(&stop);
    cudaEventRecord( start, 0 );

    blockCounterUnlocked<<<NBLOCKS_TRUE, NTHREADS_TRUE>>>(nblocks_dev);

    cudaEventRecord( stop, 0 );
    cudaEventSynchronize( stop );
    cudaEventElapsedTime( &elapsedTime, start, stop );

```

```

cudaEventDestroy( start );
cudaEventDestroy( stop );

cudaMemcpy( &nblocks_host, nblocks_dev, sizeof(int), cudaMemcpyDeviceToHost );
printf("blockCounterUnlocked <<< %d, %d >>> () counted %d blocks in %f ms.\n",
      NBLOCKS_TRUE,
      NTHREADS_TRUE,
      nblocks_host,
      elapsedTime);

//blockCounter1:

nblocks_host = 0;
cudaMemcpy( nblocks_dev, &nblocks_host, sizeof(int), cudaMemcpyHostToDevice );

cudaEventCreate(&start);
cudaEventCreate(&stop);
cudaEventRecord( start, 0 );

blockCounter1<<<NBLOCKS_TRUE, NTHREADS_TRUE>>>(lock, nblocks_dev);

cudaEventRecord( stop, 0 );
cudaEventSynchronize( stop );

```

```

    cudaEventElapsedTime( &elapsedTime, start, stop );

    cudaEventDestroy( start );
    cudaEventDestroy( stop );

    cudaMemcpy( &nblocks_host, nblocks_dev, sizeof(int), cudaMemcpyDeviceToHost );
    printf("blockCounter1 <<< %d, %d >>> () counted %d blocks in %f ms.\n",
        NBLOCKS_TRUE,
        NTHREADS_TRUE,
        nblocks_host,
        elapsedTime);

    cudaFree(nblocks_dev);
}

```



```
[landau@impact1 blockCounter]$ nvcc blockCounter.cu -arch sm_20 -o blockCounter
[landau@impact1 blockCounter]$ ./blockCounter
blockCounterUnlocked <<< 512, 1024 >>> () counted 47 blocks in 0.057920 ms.
blockCounter1 <<< 512, 1024 >>> () counted 512 blocks in 0.636064 ms.
[landau@impact1 blockCounter]$
[landau@impact1 blockCounter]$ ./blockCounter
blockCounterUnlocked <<< 512, 1024 >>> () counted 51 blocks in 0.052288 ms.
blockCounter1 <<< 512, 1024 >>> () counted 512 blocks in 0.638304 ms.
[landau@impact1 blockCounter]$
[landau@impact1 blockCounter]$ ./blockCounter
blockCounterUnlocked <<< 512, 1024 >>> () counted 47 blocks in 0.052096 ms.
blockCounter1 <<< 512, 1024 >>> () counted 512 blocks in 0.640768 ms.
[landau@impact1 blockCounter]$ |
```

**WITH MORE THAN 1 THREAD PER
BLOCK, THIS KERNEL WILL MAKE
YOUR PROGRAM STALL OUT**

```
__global__ void blockCounter2( Lock lock, int *nblocks ){  
    lock.lock();  
    if(threadIdx.x == 0){  
        *nblocks = *nblocks + 1 ;  
    }  
    lock.unlock();  
}
```

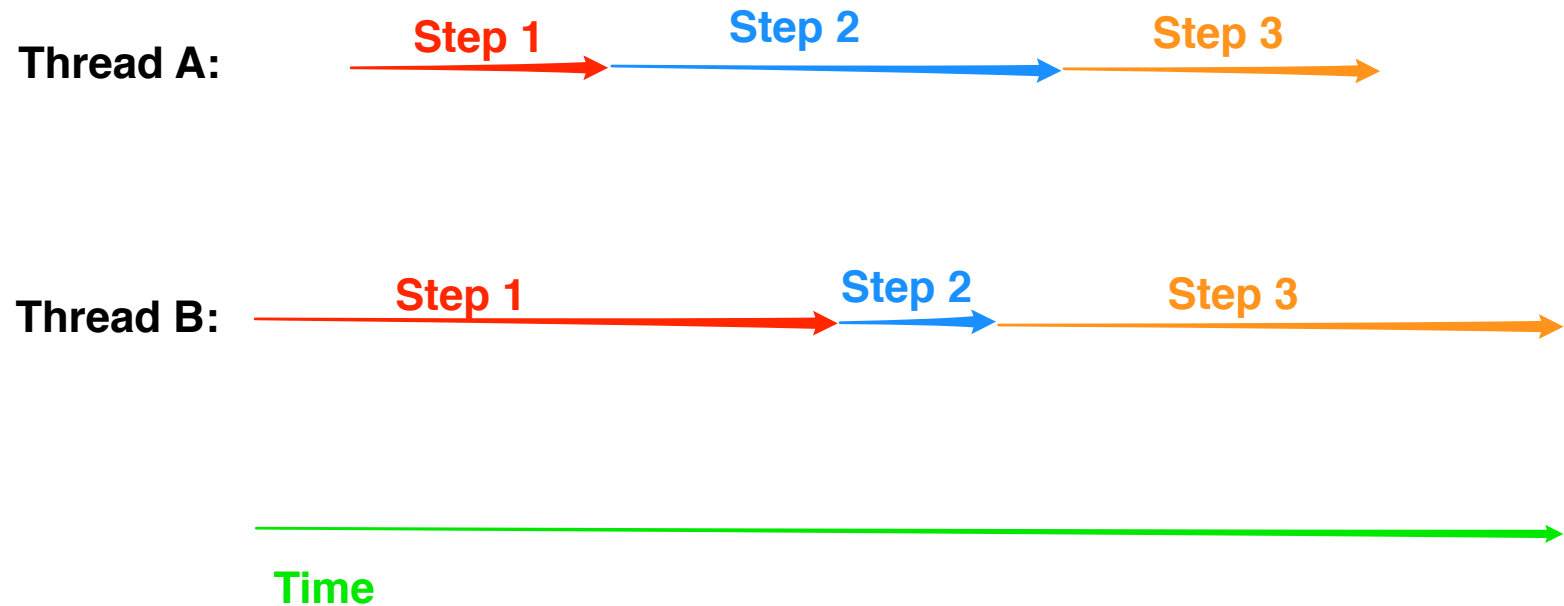
WHY? BECAUSE OF WARPS!

Each block is divided into groups of 32 threads called warps.

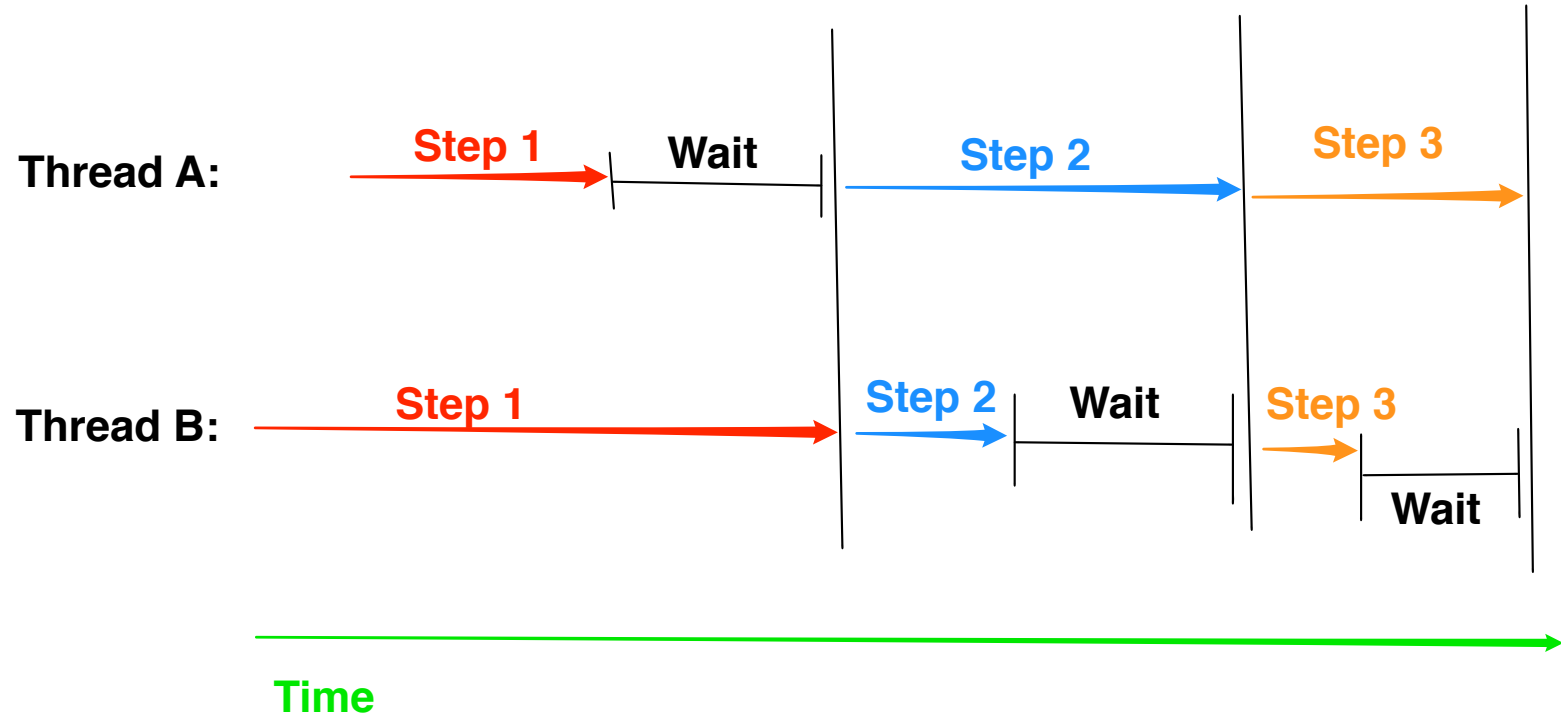
Warp: a group of 32 threads that execute together in lockstep: that is, all threads in the warp synchronize after every single step.

Imagine that a warp is saturated with calls to `__syncthreads()`.

Threads in different warps:



Threads in the same warp:



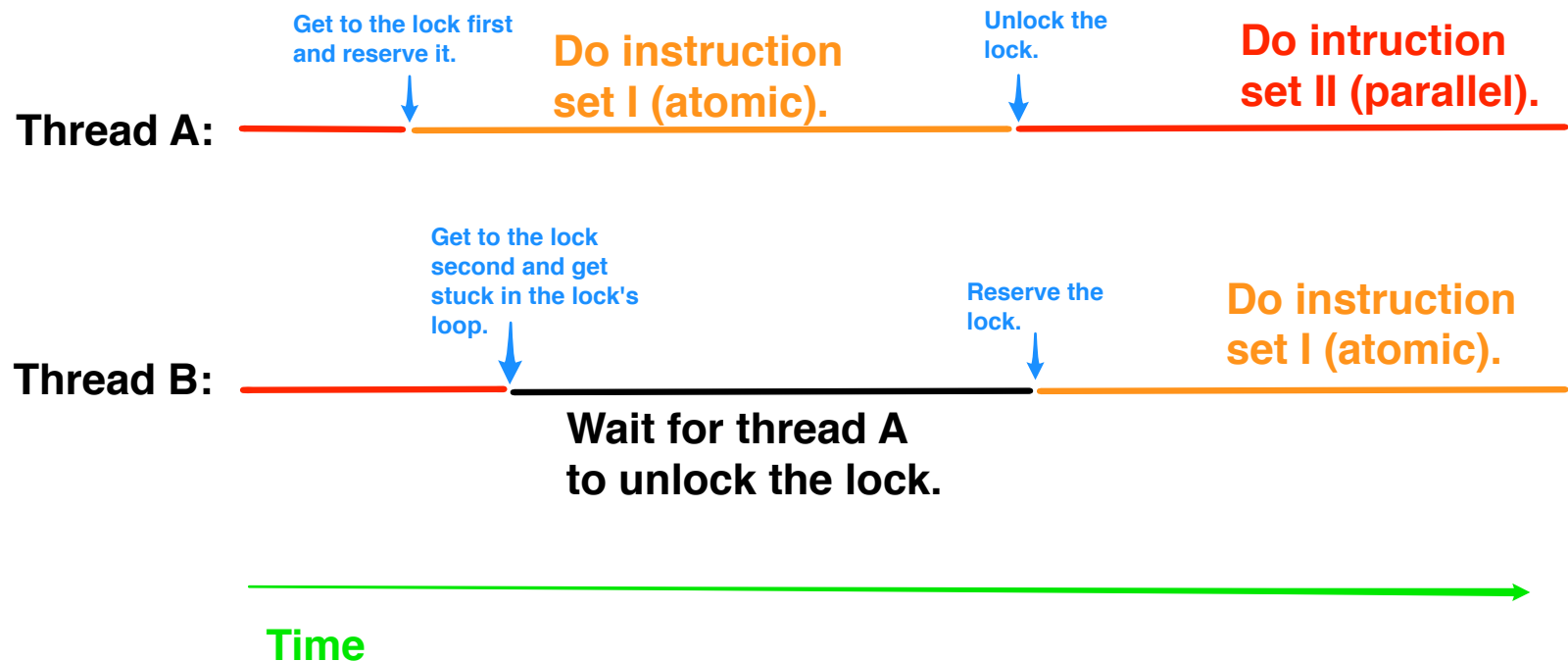
Now, let's look at the lock function again:

```
__device__ void lock( void ) {  
    while( atomicCAS( mutex, 0, 1 ) != 0 );  
}
```

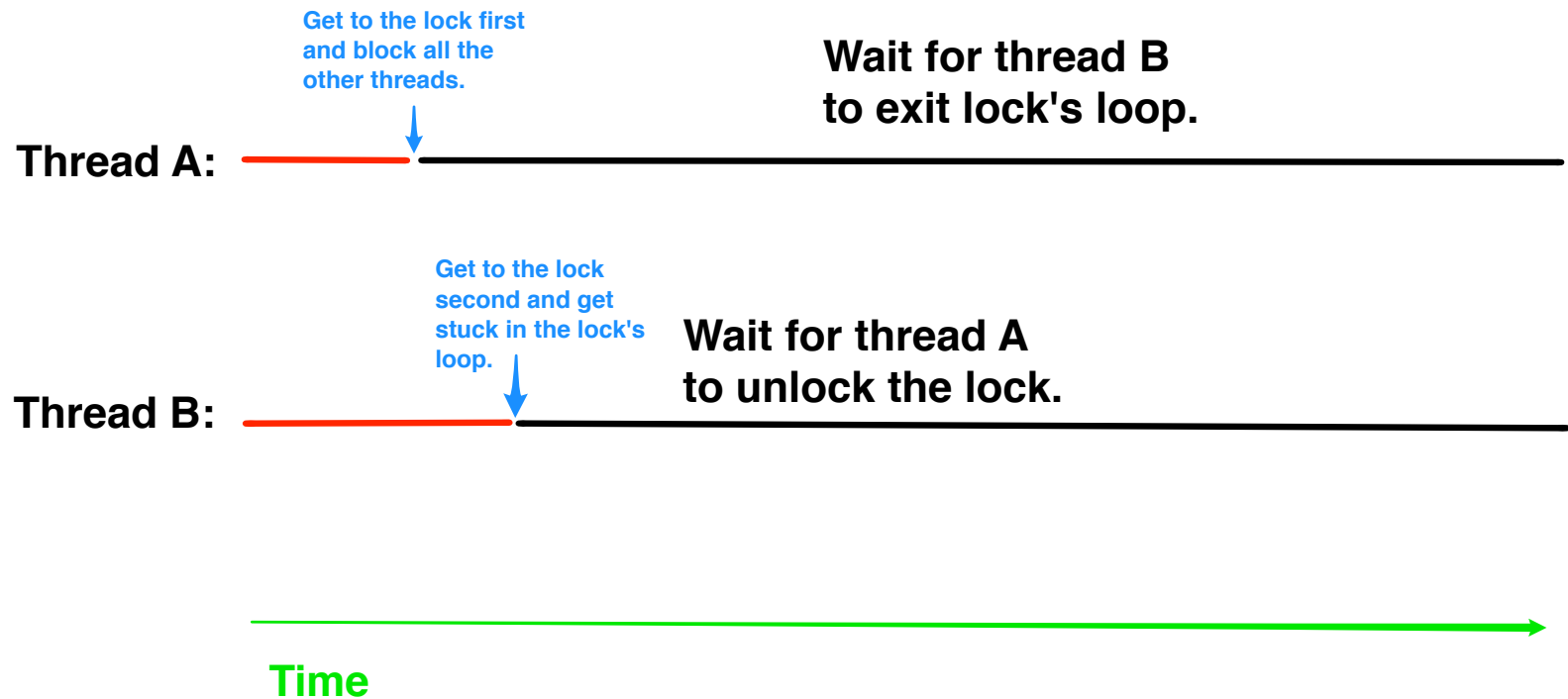
In pseudo-code:

```
__device__ void lock( void ) {  
    repeat{  
        do atomically{  
  
            if(mutex == 0){  
                mutex = 1;  
                return_value = 0;  
            }  
  
            else if(mutex == 1){  
                return_value = 1;  
            }  
  
        } // do atomically  
  
        if(return_value = 0)  
            exit loop;  
  
    } // repeat  
} // lock
```

Threads in different warps:



Threads in the same warp:



BEWARE THE CATCH-22!

LECTURE SERIES MATERIALS

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

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

REFERENCES

NVIDIA CUDA C Programming Guide. Version 3.2.
2010.

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