

A CODELESS INTRODUCTION TO GPU PARALLELISM

Will Landau, Prof. Jarad Niemi

OUTLINE

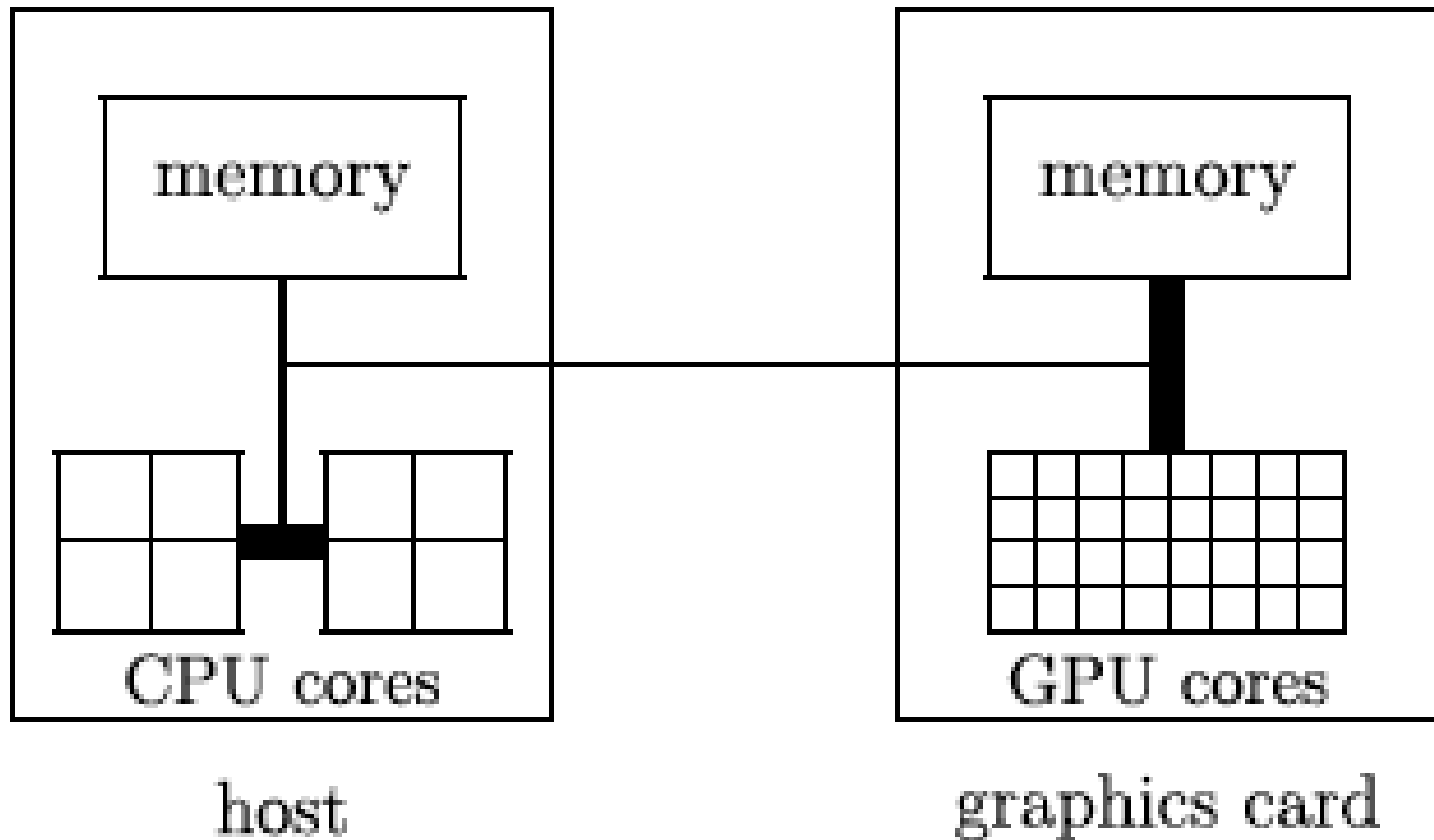
- A. A review of GPU parallelism
- B. How to GPU-parallelize the following:
 - 1. vector addition
 - 2. the pairwise (cascading) sum
 - 3. matrix multiplication

HOW THE CPU AND GPU WORK TOGETHER

A GPU can't run a whole computer on its own because it doesn't have access to all the computer's hardware.

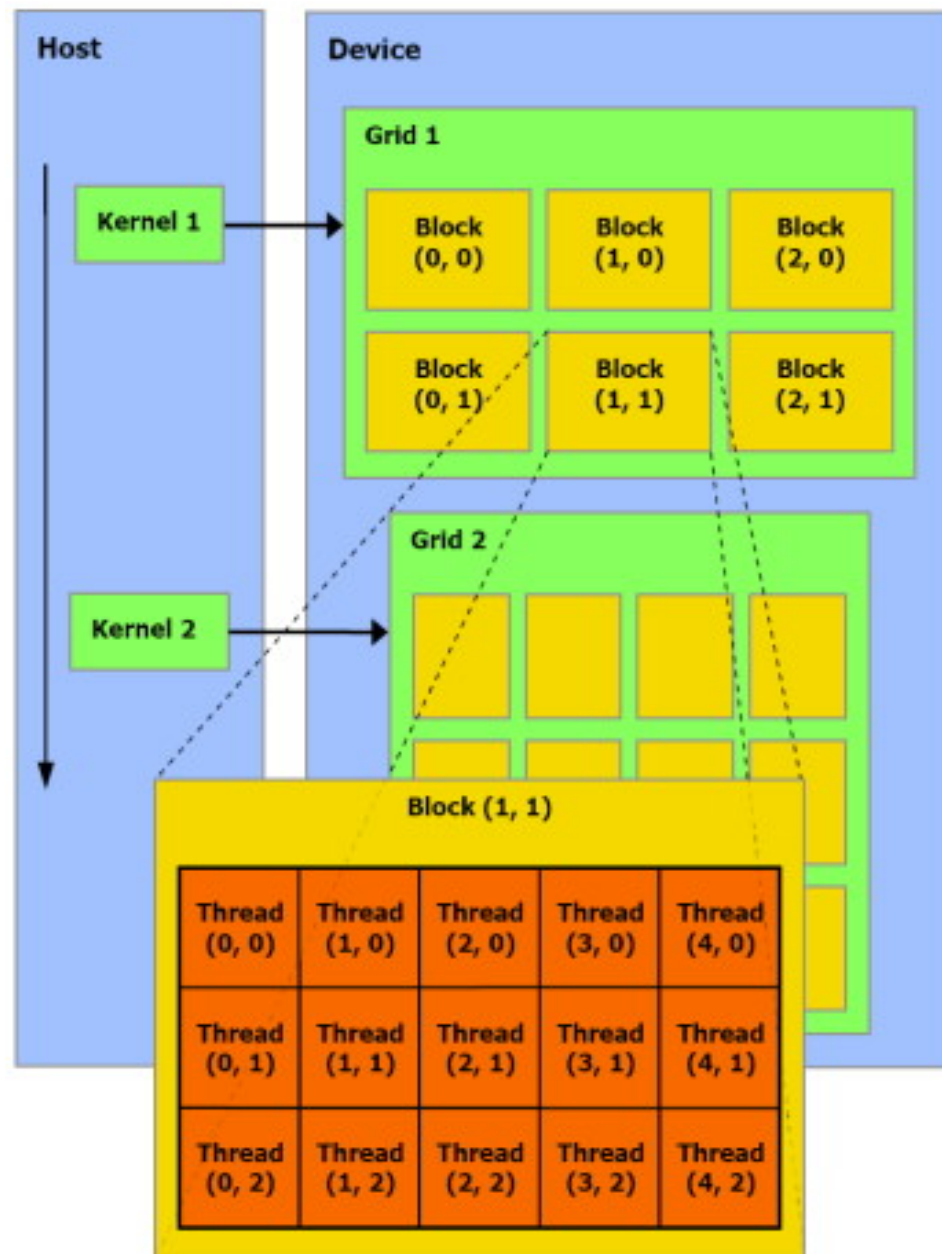
In a GPU-capable computer, the CPU is the main processor, and the GPU is an optional hardware add-on.

The CPU uses the GPU like a human would use a hand-held calculator: the CPU does all the main thinking and the GPU does the most cumbersome bits and pieces of number-crunching.



GPU PARALLELISM

1. The CPU sends a CPU-to-GPU command called a **kernel** to a single GPU core.
2. The GPU core multitasks to execute the command:
 - a. The GPU makes $B \cdot T$ **copies** of the kernel's code, and then runs all those copies simultaneously. Those parallel copies are called **threads**.
 - b. The $B \cdot T$ threads are partitioned into B groups, called **blocks**, of T threads each.
 - c. The sum total of all the threads from a kernel call is a **grid**.



WHEN TO PARALLELIZE

Calculations you want to parallelize:

- Highly repetitive floating point arithmetic procedures that can all be done simultaneously.

Calculations you don't want to parallelize:

- Inherently sequential calculations, such as recursions.
- Lengthy control flow: if-then statements, etc.
- CPU system routines, such as printing to the console.

EXAMPLES OF EASILY PARALLELIZABLE ALGORITHMS

Linear algebraic algorithms are particularly amenable to GPU computing because they involve a high volume of simple arithmetic.

I will showcase:

1. vector addition
2. the pairwise (cascading) sum
3. matrix multiplication

VECTOR ADDITION

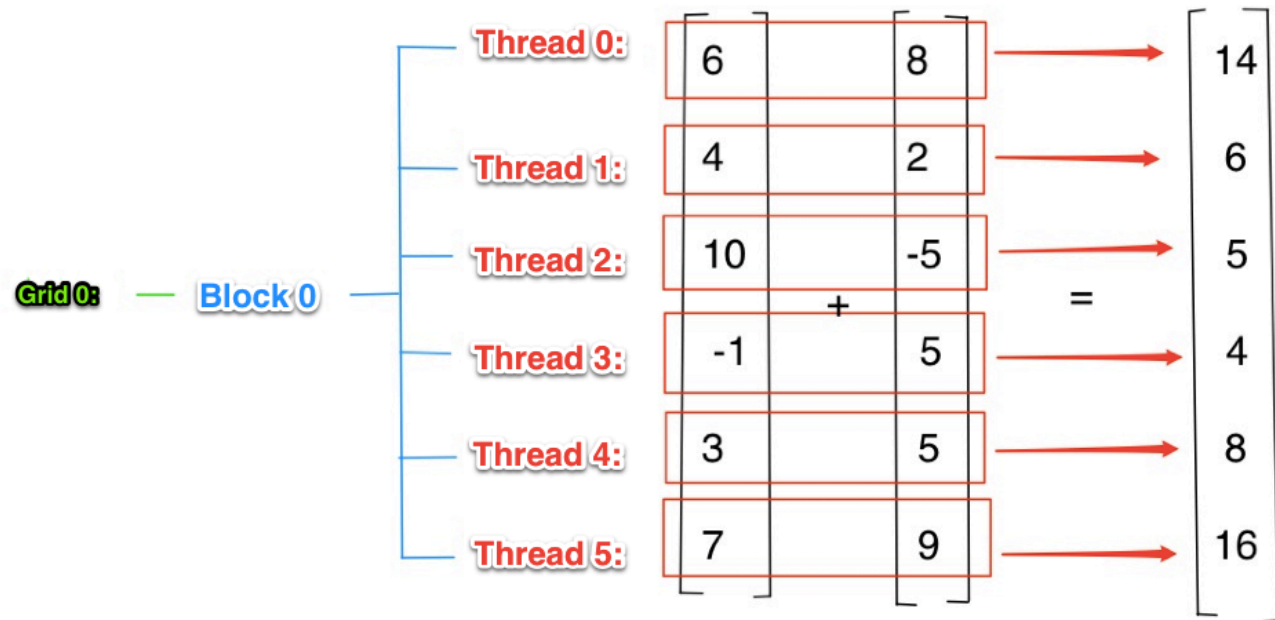
Say I have two vectors:

$$a = \begin{bmatrix} a_1 \\ a_2 \\ \vdots \\ a_n \end{bmatrix} \quad b = \begin{bmatrix} b_1 \\ b_2 \\ \vdots \\ b_n \end{bmatrix}$$

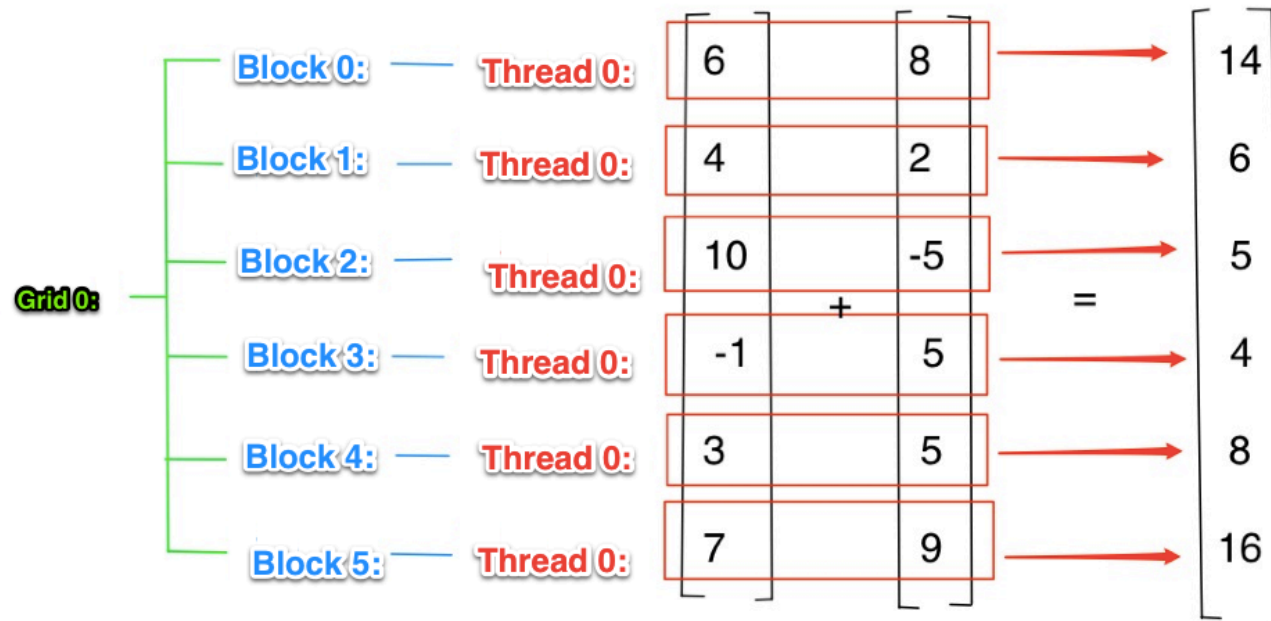
I compute their sum, $c = a + b$, by:

$$c = \begin{bmatrix} c_1 \\ c_2 \\ \vdots \\ c_n \end{bmatrix} = \begin{bmatrix} a_1 + b_1 \\ a_2 + b_2 \\ \vdots \\ a_n + b_n \end{bmatrix}$$

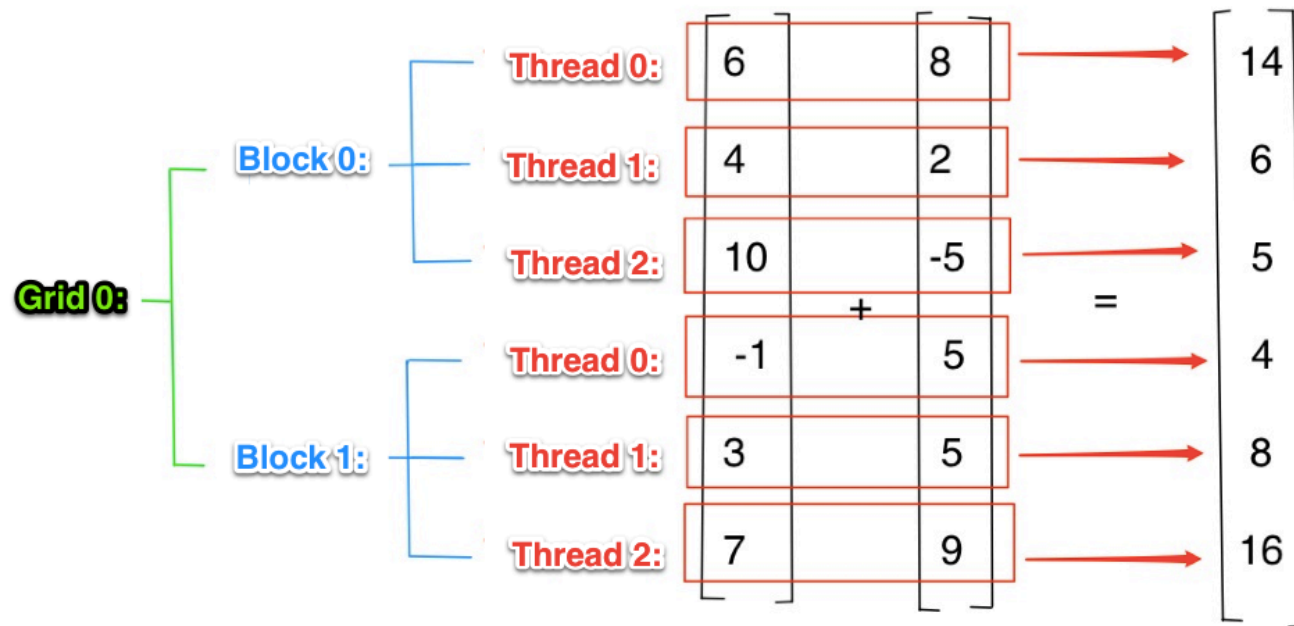
PARALLELIZING VECTOR ADDITION: METHOD 1 OF 3



PARALLELIZING VECTOR ADDITION: METHOD 2 OF 3



PARALLELIZING VECTOR ADDITION: METHOD 3 OF 3

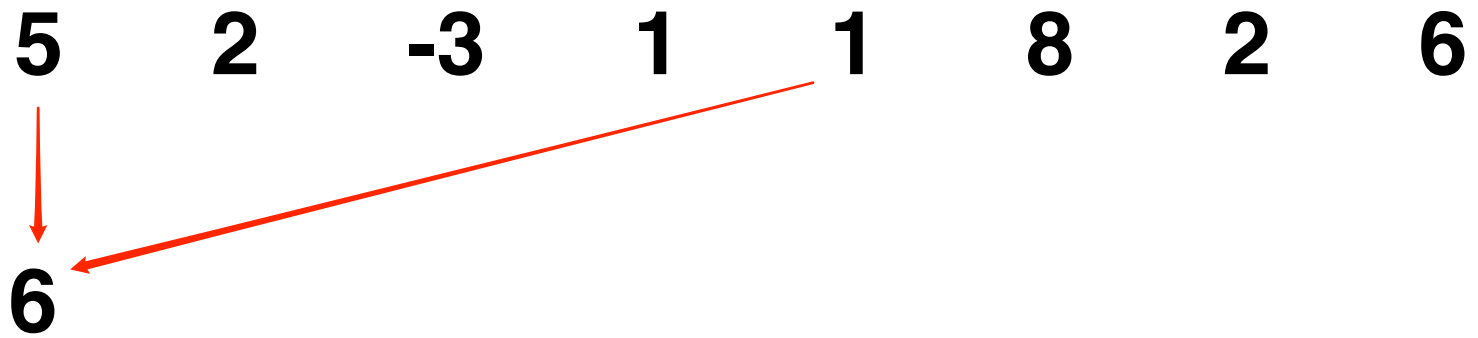


THE PAIRWISE SUM

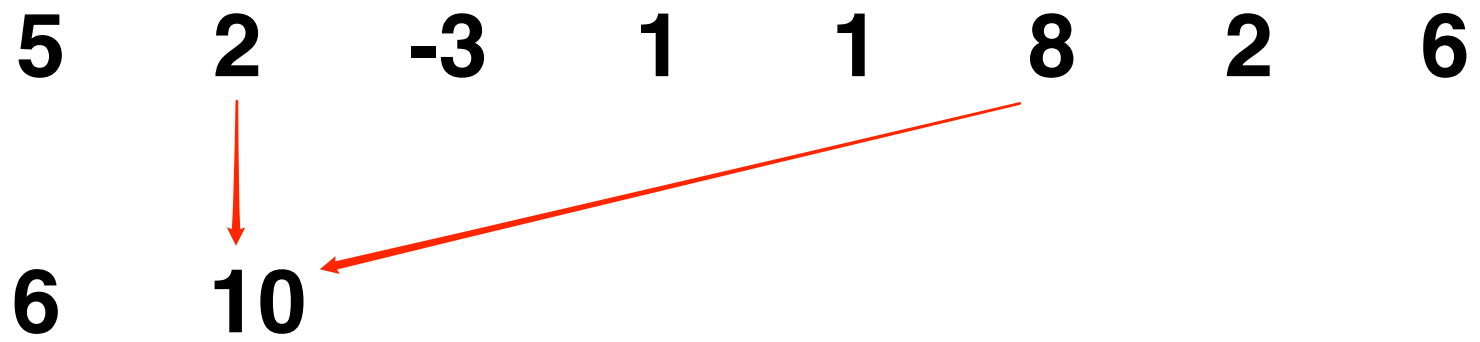
Let's take the pairwise sum of the vector:

$$(5, 2, -3, 1, 1, 8, 2, 6)$$

Using one block of 4 threads.



Thread 0

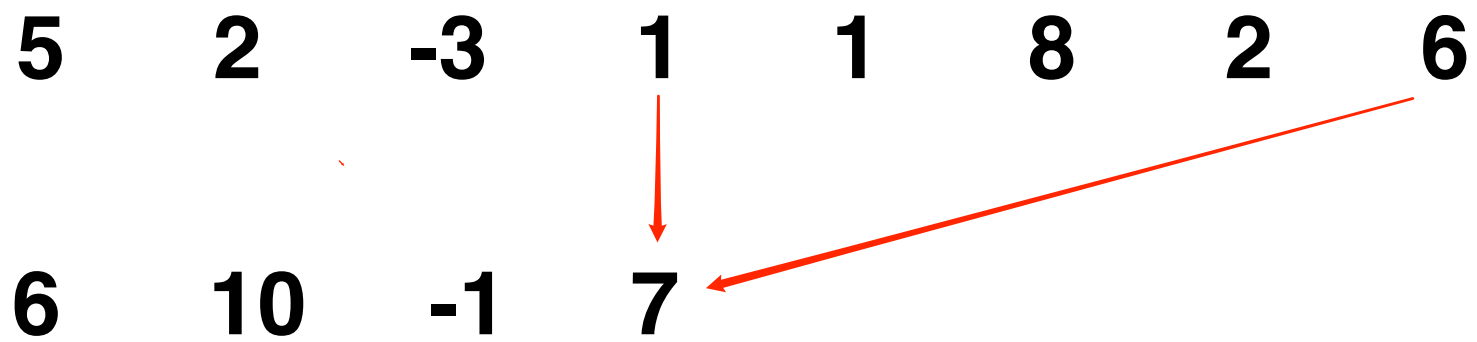


Thread 1

5	2	-3	1	1	8	2	6
6	10	-1					

Diagram illustrating a sequence of numbers arranged in two rows. The top row contains the numbers 5, 2, -3, 1, 1, 8, 2, 6. The bottom row contains the numbers 6, 10, -1. A red arrow points from the -3 in the top row down to the -1 in the bottom row. Another red arrow points from the 2 in the top row down to the -1 in the bottom row.

Thread 2



Thread 3

5 2 -3 1 1 8 2 6

6 10 -1 7

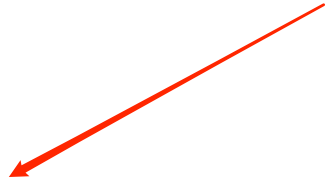
Synchronize threads

5 2 -3 1 1 8 2 6

6 10 -1 7



5



Thread 0

5 2 -3 1 1 8 2 6

6 10 -1 7

5 17

Thread 1

5 2 -3 1 1 8 2 6

6 10 -1 7

5 17

Synchronize Threads

5 2 -3 1 1 8 2 6

6 10 -1 7

5 17
↓ ↙
22

Thread 0

AN ASIDE: SYNCHRONIZING THREADS

Synchronization: Waiting for all parallel tasks to reach a checkpoint before allowing any of them to proceed.

- Threads from the same block can be synchronized easily.
- In general, do not try to synchronize threads from different blocks. It's possible, but extremely inefficient.

A RIGOROUS DESCRIPTION OF THE PAIRWISE SUM

Suppose you have a vector $X_0 = (x_{(0,0)}, x_{(0,2)}, \dots, x_{(0,n-1)})$, where $n = 2^m$ for some $m > 0$.

Compute $\sum_{i=1}^n x_{(0,i)}$ in the following way:

1. Create a new vector:

$$X_1 = (\underbrace{x_{(0,0)} + x_{(0,n/2)}}_{x_{(1,0)}}, \underbrace{x_{(0,1)} + x_{(0,n/2+1)}}_{x_{(1,1)}}, \dots, \underbrace{x_{(0,n/2-1)} + x_{(0,n-1)}}_{x_{(1,n/2-1)})$$

2. Create another new vector:

$$X_2 = (\underbrace{x_{(1,0)} + x_{(1,n/4)}}_{x_{(2,0)}}, \underbrace{x_{(1,1)} + x_{(1,n/4+1)}}_{x_{(2,1)}}, \dots, \underbrace{x_{(1,n/4-1)} + x_{(1,n/2-1)}}_{x_{(2,n/4-1)})$$

3. Continue this process until you get a singleton vector:

$$X_m = (\underbrace{x_{(m-1,0)} + x_{(m-1,1)}}_{x_{(m,0)}})$$

Notice: $\sum_{i=1}^n x_{(0,i)} = x_{(m,0)}$

PARALLELIZING THE PAIRWISE SUM

Spawn one grid with a single block and $n/2$ threads ($n = 2^m$). Starting with $i = 1$, do the following:

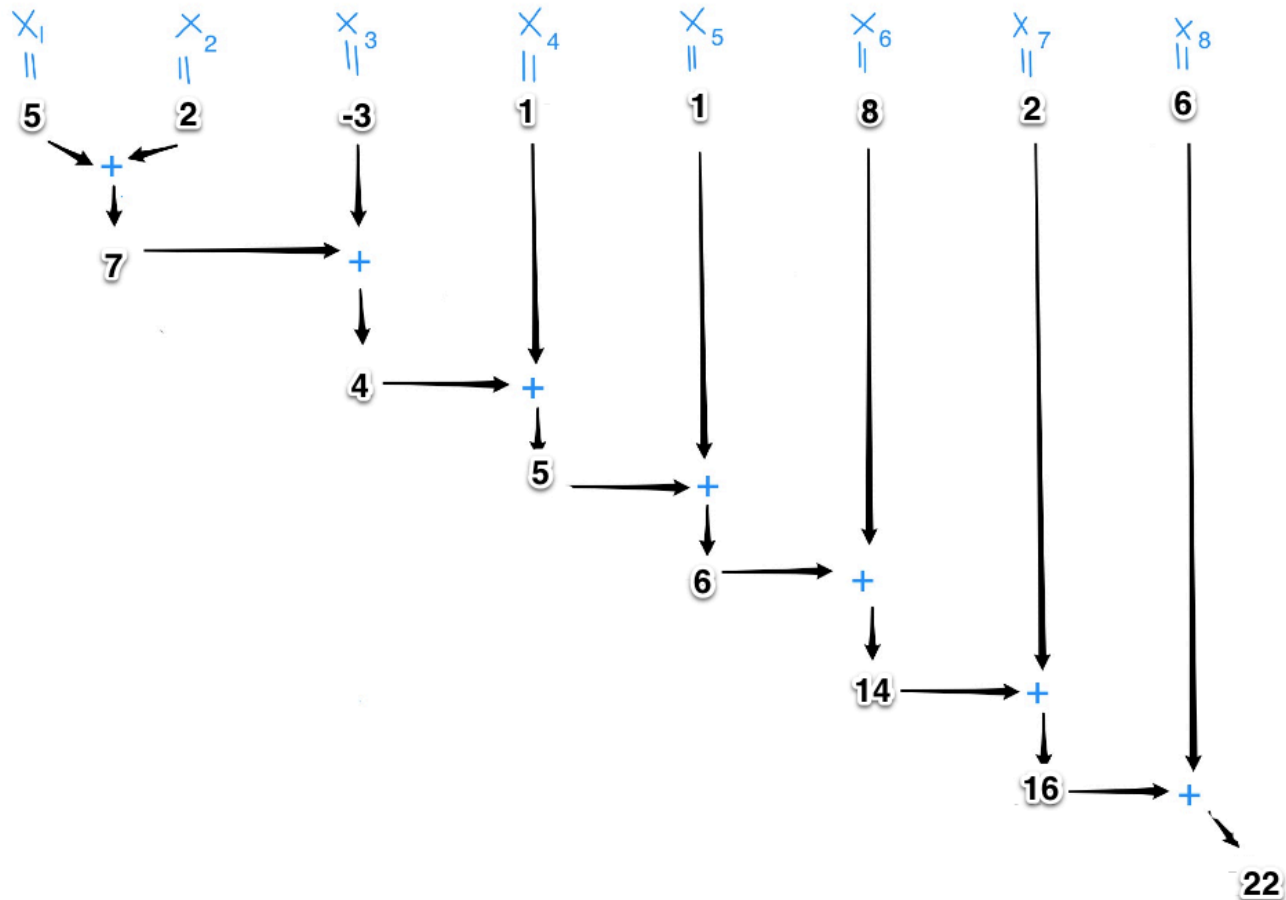
1. Set $\text{offset} = n/2^i$.
2. Assign thread j to compute:

$$x_{(i,j)} = x_{(i-1, j)} + x_{(i-1, j+\text{offset})}$$

for $j = 0, 2, \dots, \text{offset} - 1$.

3. Wait until all the above $\frac{n}{2^i}$ threads have completed step 2.
4. Integer divide offset by 2. Repeat if $\text{offset} > 0$.

ASIDE: COMPARE TO THE SEQUENTIAL VERSION



The pairwise sum requires only $\log_2(n)$ sequential steps, whereas the sequential sum requires $n - 1$ steps.

3. MATRIX MULTIPLICATION

Consider an $m \times n$ matrix, $A = (a_{ij})$, and an $n \times p$ matrix, $B = (b_{ij})$. Compute $A \cdot B$:

1. Break apart A into its rows: $A = \begin{bmatrix} a_{1.} \\ a_{2.} \\ \vdots \\ a_{m.} \end{bmatrix}$, where each $a_{i.} = [a_{i1} \ a_{i2} \ \cdots \ a_{in}]$

2. Break apart B into its columns: $B = [b_{.1} \ b_{.2} \ \cdots \ b_{.p}]$, where each $b_{.j} = \begin{bmatrix} b_{1j} \\ b_{2j} \\ \vdots \\ b_{nj} \end{bmatrix}$

3. Compute $C = A \cdot B$ elementwise, using the usual matrix multiplication rules to find each $a_{i.} \cdot b_{.j}$:

$$C = A \cdot B = \begin{bmatrix} (a_{1.} \cdot b_{.1}) & (a_{1.} \cdot b_{.2}) & \cdots & (a_{1.} \cdot b_{.p}) \\ (a_{2.} \cdot b_{.1}) & (a_{2.} \cdot b_{.2}) & & (a_{2.} \cdot b_{.p}) \\ \vdots & & \ddots & \vdots \\ (a_{m.} \cdot b_{.1}) & (a_{m.} \cdot b_{.2}) & \cdots & (a_{m.} \cdot b_{.p}) \end{bmatrix}$$

i.e.:

$$C_{(i,j)} = a_{i.} \cdot b_{.j}$$

PARALLELIZING MATRIX MULTIPLICATION

Spawn one grid with $m \cdot p$ blocks. Assign block (i, j) to compute $C_{(i,j)} = a_{i.} \cdot b_{.j}$. Within each block:

1. Spawn n threads.
2. Tell the k 'th thread to compute $c_{ijk} = a_{ik}b_{kj}$.
3. Synchronize the n threads to make sure we have finished calculating all of $c_{ij1}, c_{ij2}, \dots, c_{ijn}$ before proceeding.
4. Compute $C_{(i,j)} = \sum_{k=1}^n c_{ijk}$ as a pairwise sum.

EXAMPLE

Say I want to compute $A \cdot B$, where:

$$A = \begin{bmatrix} 1 & 2 \\ -1 & 5 \\ 7 & -9 \end{bmatrix} \quad B = \begin{bmatrix} 8 & 8 & 7 \\ 3 & 5 & 2 \end{bmatrix}$$

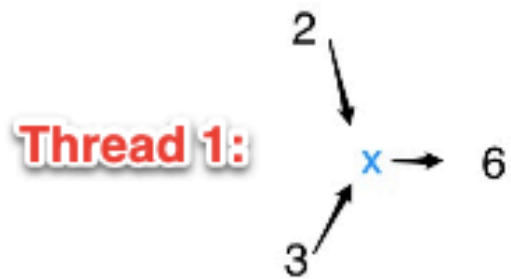
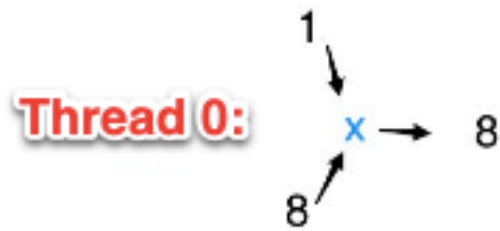
which I'm setting up as:

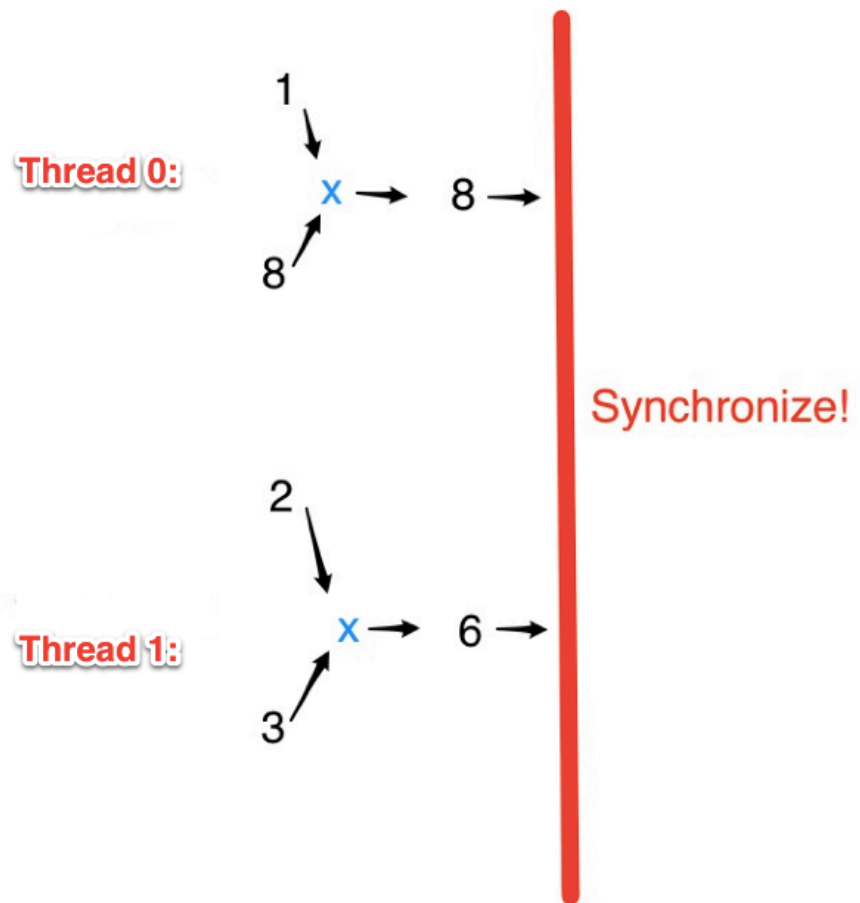
$$C = A \cdot B = \begin{bmatrix} \left(\begin{bmatrix} 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 3 \end{bmatrix} \right) & \left(\begin{bmatrix} 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 5 \end{bmatrix} \right) & \left(\begin{bmatrix} 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 7 \\ 2 \end{bmatrix} \right) \\ \left(\begin{bmatrix} -1 & 5 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 3 \end{bmatrix} \right) & \left(\begin{bmatrix} -1 & 5 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 5 \end{bmatrix} \right) & \left(\begin{bmatrix} -1 & 5 \end{bmatrix} \cdot \begin{bmatrix} 7 \\ 2 \end{bmatrix} \right) \\ \left(\begin{bmatrix} 7 & -9 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 3 \end{bmatrix} \right) & \left(\begin{bmatrix} 7 & -9 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 5 \end{bmatrix} \right) & \left(\begin{bmatrix} 7 & -9 \end{bmatrix} \cdot \begin{bmatrix} 7 \\ 2 \end{bmatrix} \right) \end{bmatrix}$$

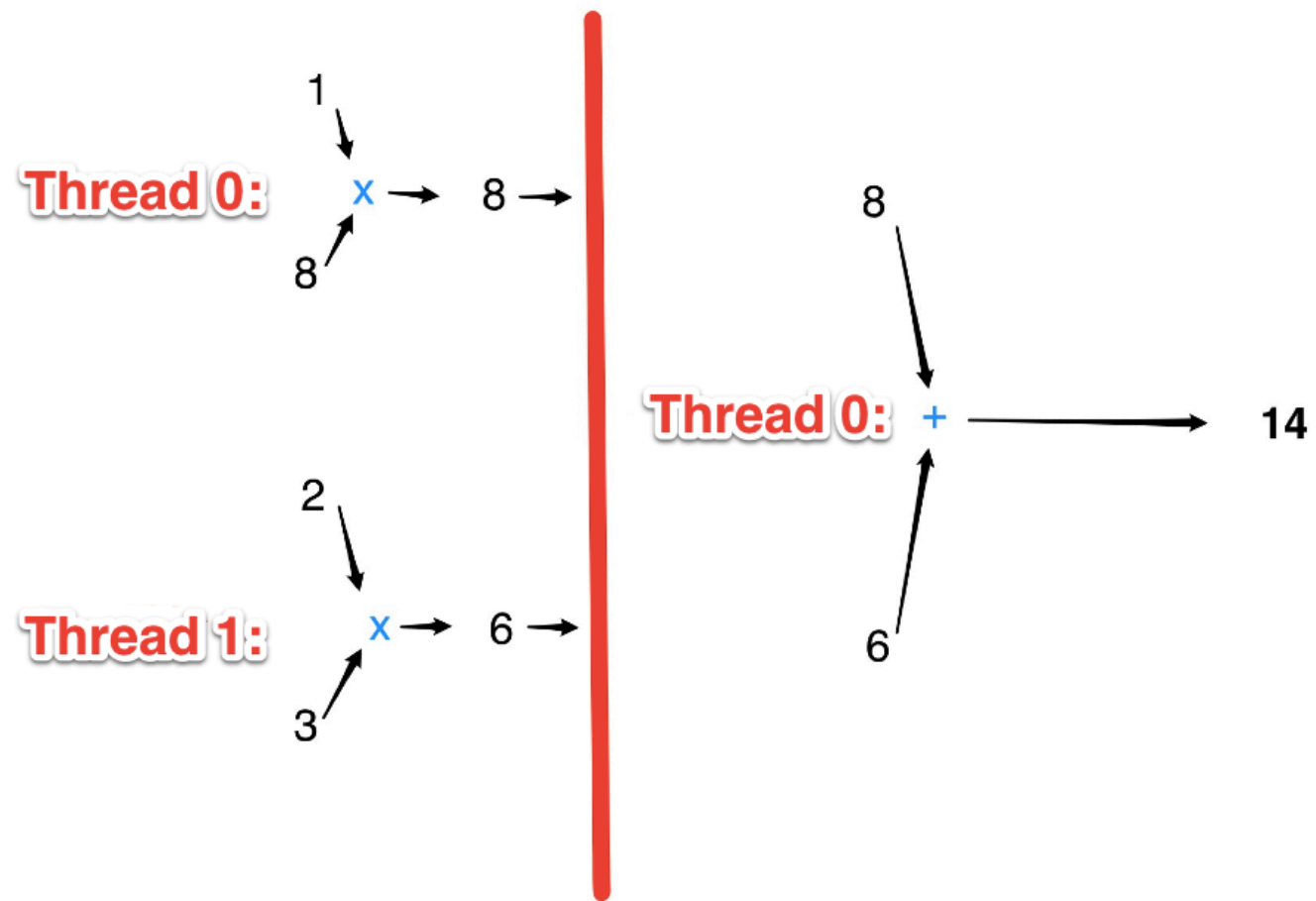
$$\begin{bmatrix}
 \text{Block (0, 0)} & \text{Block (1, 0)} & \text{Block (2, 0)} \\
 \left(\begin{bmatrix} 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 3 \end{bmatrix} \right) & \left(\begin{bmatrix} 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 5 \end{bmatrix} \right) & \left(\begin{bmatrix} 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 7 \\ 2 \end{bmatrix} \right) \\
 \text{Block (0, 1)} & \text{Block (1, 1)} & \text{Block (2, 1)} \\
 \left(\begin{bmatrix} -1 & 5 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 3 \end{bmatrix} \right) & \left(\begin{bmatrix} -1 & 5 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 5 \end{bmatrix} \right) & \left(\begin{bmatrix} -1 & 5 \end{bmatrix} \cdot \begin{bmatrix} 7 \\ 2 \end{bmatrix} \right) \\
 \text{Block (0, 2)} & \text{Block (1, 2)} & \text{Block (2, 2)} \\
 \left(\begin{bmatrix} 7 & -9 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 3 \end{bmatrix} \right) & \left(\begin{bmatrix} 7 & -9 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 5 \end{bmatrix} \right) & \left(\begin{bmatrix} 7 & -9 \end{bmatrix} \cdot \begin{bmatrix} 7 \\ 2 \end{bmatrix} \right)
 \end{bmatrix}$$

We don't need to synchronize the blocks because they can do their jobs independently.

Consider Block (0,0), which computes $\begin{bmatrix} 1 & 2 \end{bmatrix} \cdot \begin{bmatrix} 8 \\ 3 \end{bmatrix}$:







OUTLINE

- A. A review of GPU parallelism
- B. How to GPU-parallelize the following:
 - 1. vector addition
 - 2. the pairwise (cascading) sum
 - 3. matrix multiplication

PREVIEW: skeleton.cu, A BARE BONES CUDA C WORKFLOW

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

__global__ void some_kernel(...){...}

int main (void){
    // Declare all variables.
    ...
    // Dynamically allocate host memory.
    ...
    // Dynamically allocate device memory.
    ...
    // Write to host memory.
    ...
    // Copy host memory to device memory.
    ...
    // Execute kernel on the device.
    some_kernel<<< num_blocks, num_threads_per_block >>>(...);

    // Write device memory back to host memory.
    ...
    // Free dynamically-allocated host memory
    ...
    // Free dynamically-allocated device memory
    ...
}
```

MATERIALS

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

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

After logging into your home directory on impact1, type:

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

into the command line to download all the materials.

REFERENCES

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