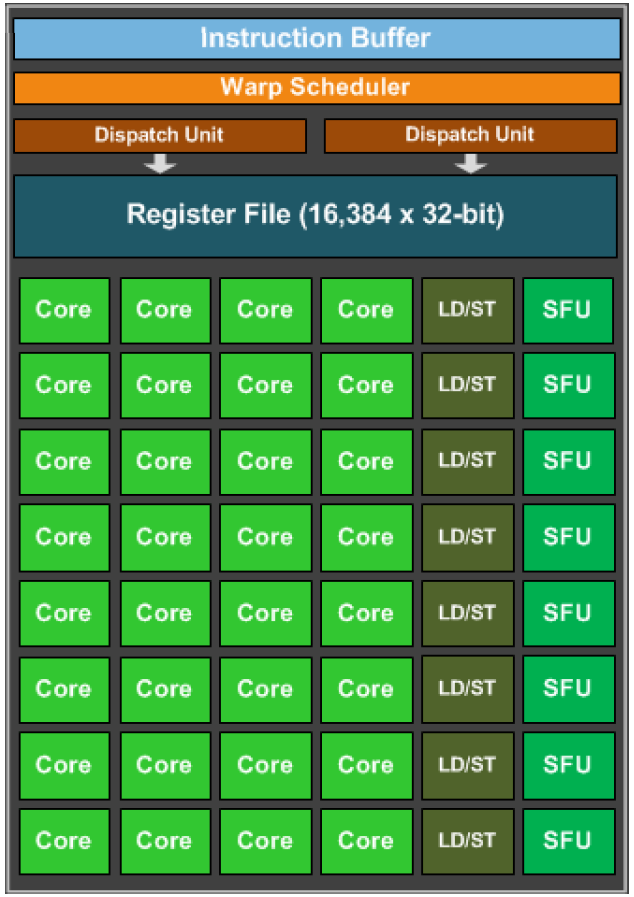
CSE113: Parallel Programming

- **Topics**:
  - GPUs continued



Announcements

- Last day to turn in HW 3 was last weekend, hope you got it in!
- HW 4 is already released. We will discuss it in class a little bit today.
- We will plan for HW 5 to be released on Nov 21.

Announcements

- Probably last day on GPUs.
- This is just the tip of the iceberg!
- Rest of quarter:
  - Memory models
  - Barriers
  - Concurrent Set
  - Schedulers (if time)

Previous quiz + Review

The host (CPU) will write a C++-like program that allocates and sets up memory on the GPU. The host will then call a GPU program called a kernel. Is this affirmation true?

- ◯ True
- ◯ False

Previous quiz + Review

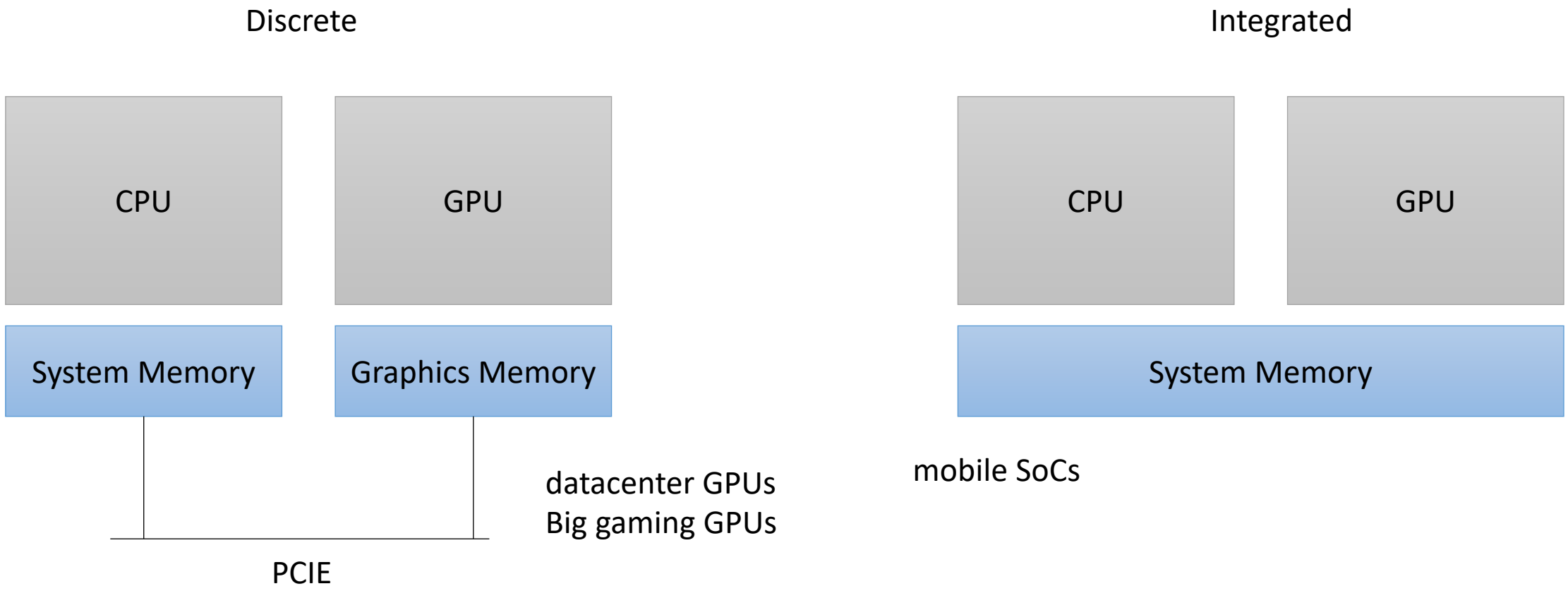
The host (CPU) will write a C++-like program that allocates and sets up memory on the GPU. The host will then call a GPU program called a kernel. Is this affirmation true?

-> ◯ True

◯ False

GPU set up

- GPUs come in two flavors

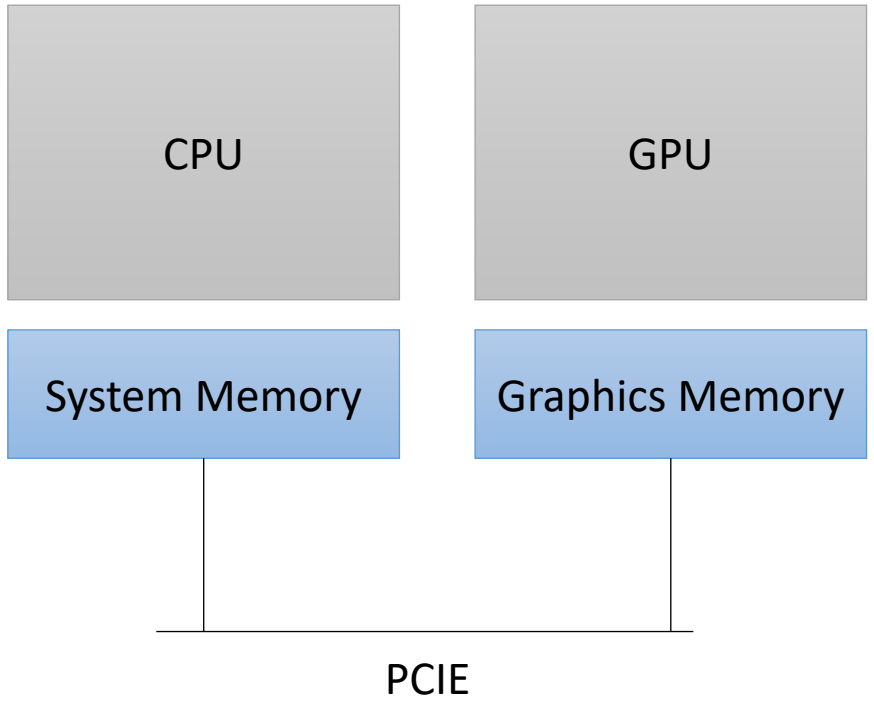


GPU set up

How do we allocate CPU memory on the host?

- Our heterogeneous, parallel, programming model

```
int *x = (int*) malloc(sizeof(int)*SIZE);
```

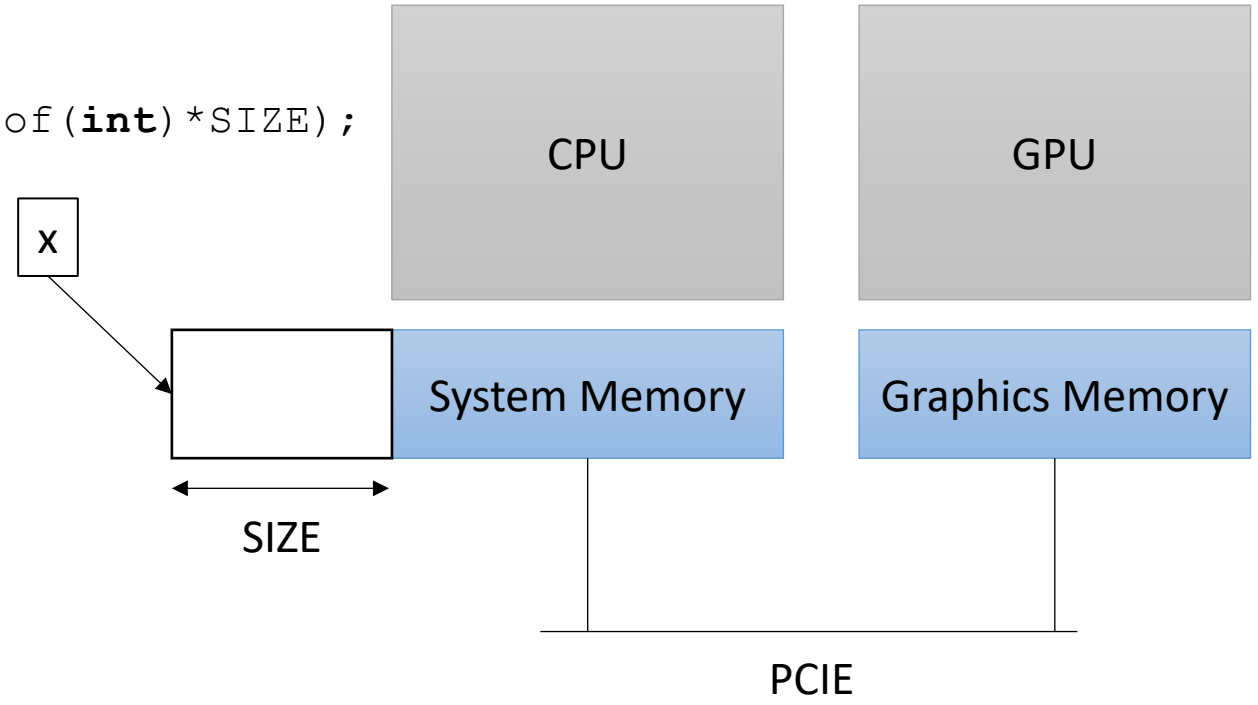


GPU set up

How do we allocate CPU memory on the host?

- Our heterogeneous, parallel, programming model

```
int *x = (int*) malloc(sizeof(int)*SIZE);
```

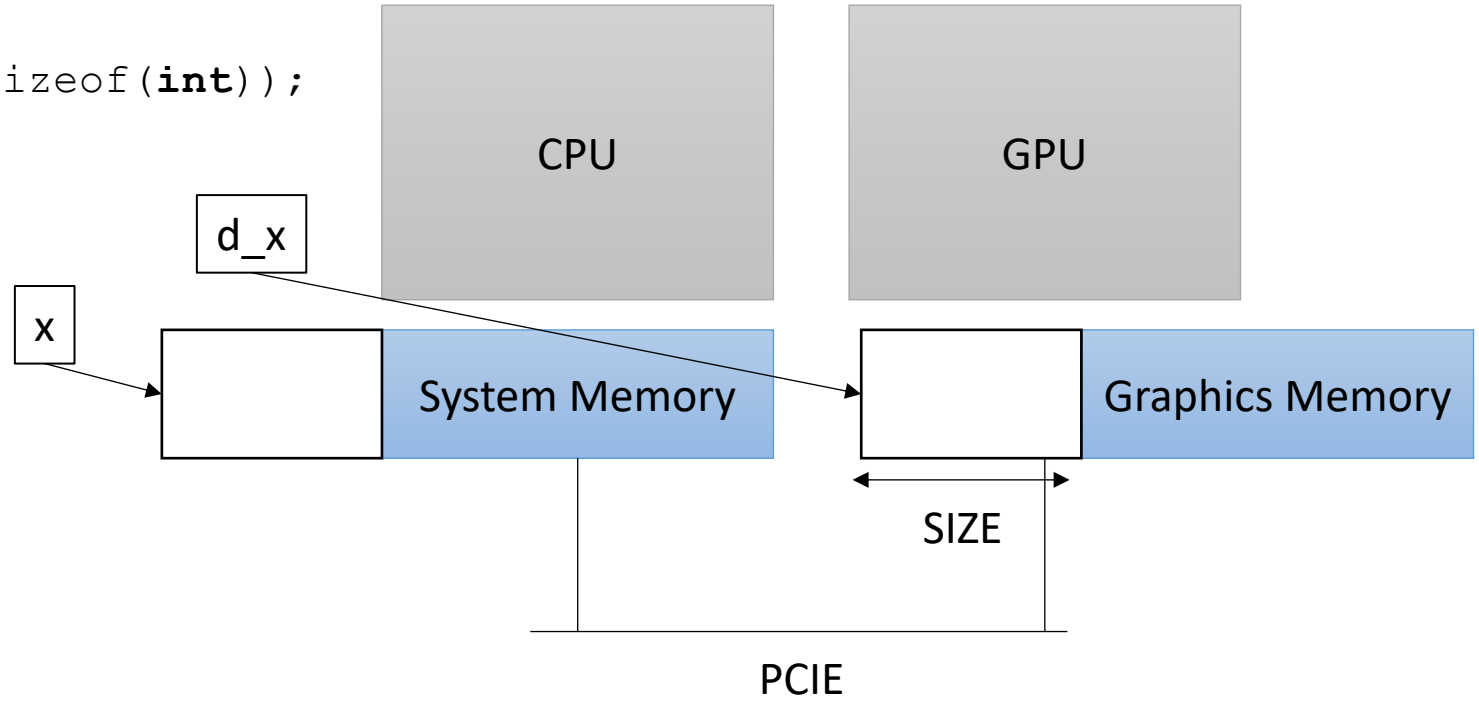


GPU set up

We need to allocate GPU memory on the host

- Our heterogeneous, parallel, programming model

```
int *d_x;
cudaMalloc(&d_x, SIZE*sizeof(int));
```

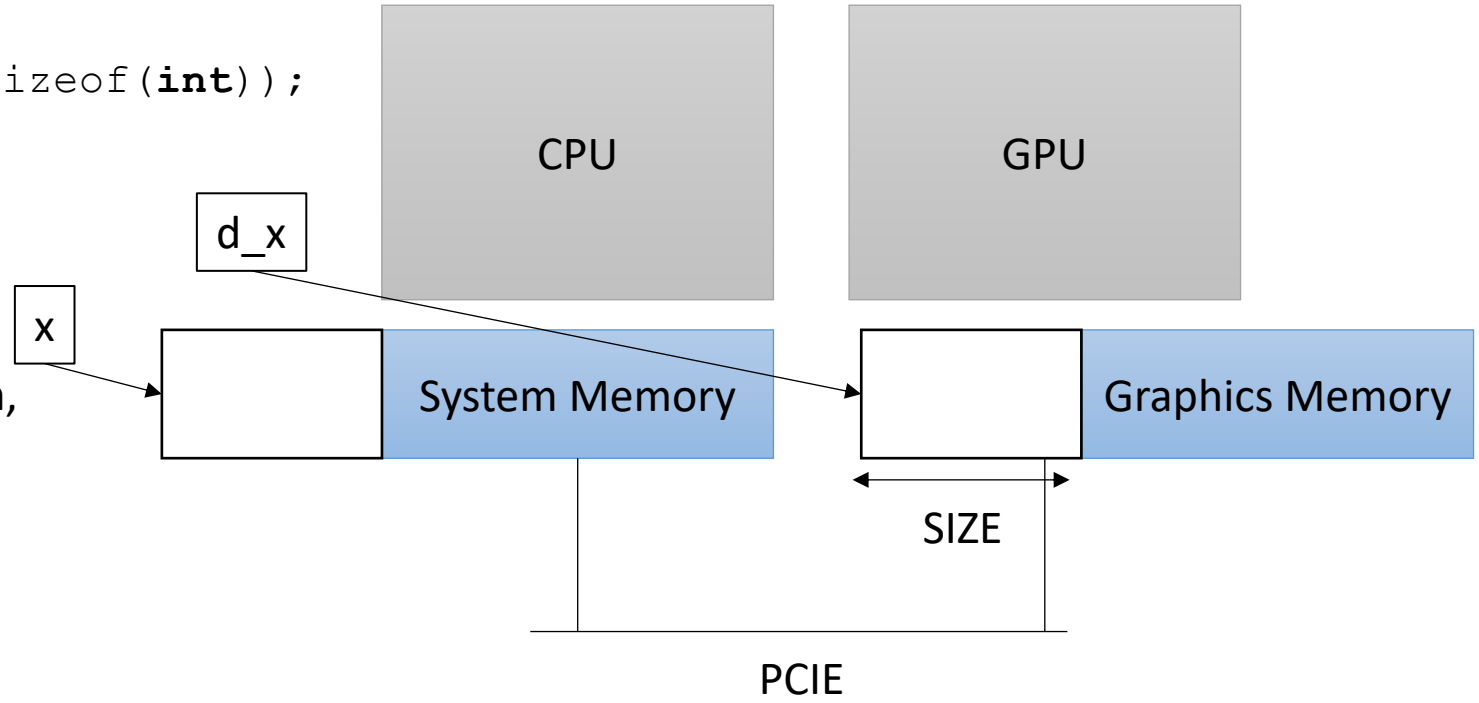


GPU set up

We need to allocate GPU memory on the host

- Our heterogeneous, parallel, programming model

```
int *d_x;
cudaMalloc(&d_x, SIZE*sizeof(int));
```



`d_x` is a pointer, in the CPU program, that points to memory on the GPU.

We can pass the pointer around, but the CPU cannot access the data i.e. `d_x[0]` gives an error!

Previous quiz + Review

How do we initialize memory for a variable we aim to use in the GPU computation?

- ◯ Using cudaMemcpy
- ◯ Using memcpy from C++
- ◯ Just declaring a new variable

Previous quiz + Review

How do we initialize memory for a variable we aim to use in the GPU computation?

-> ◯ Using cudaMemcpy

◯ Using memcpy from C++

◯ Just declaring a new variable

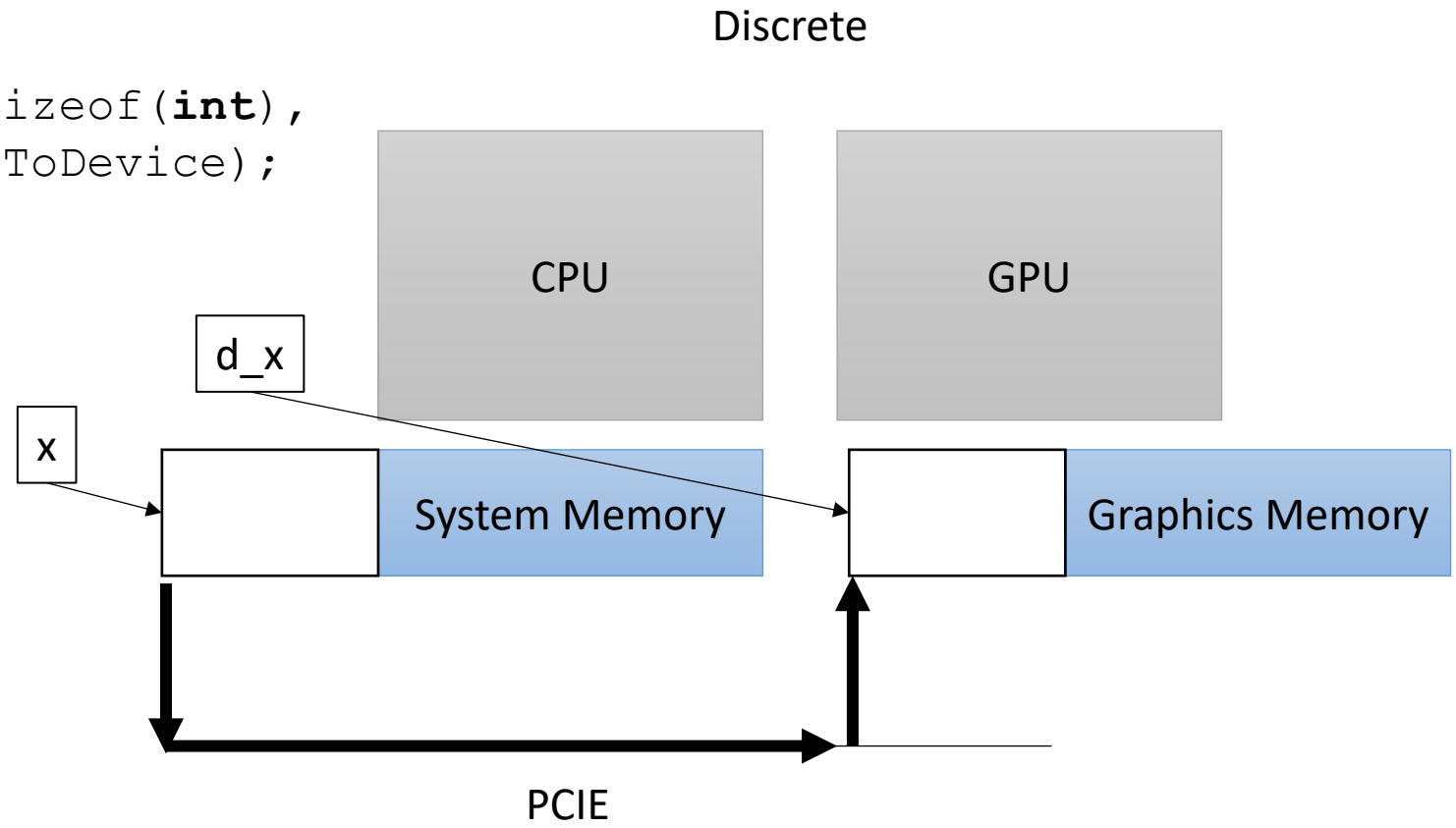
GPU set up

- Our heterogeneous, parallel, programming model

If we can't access d_x on the CPU, how do we initialize the memory?

GPU has no access to input devices e.g. disk

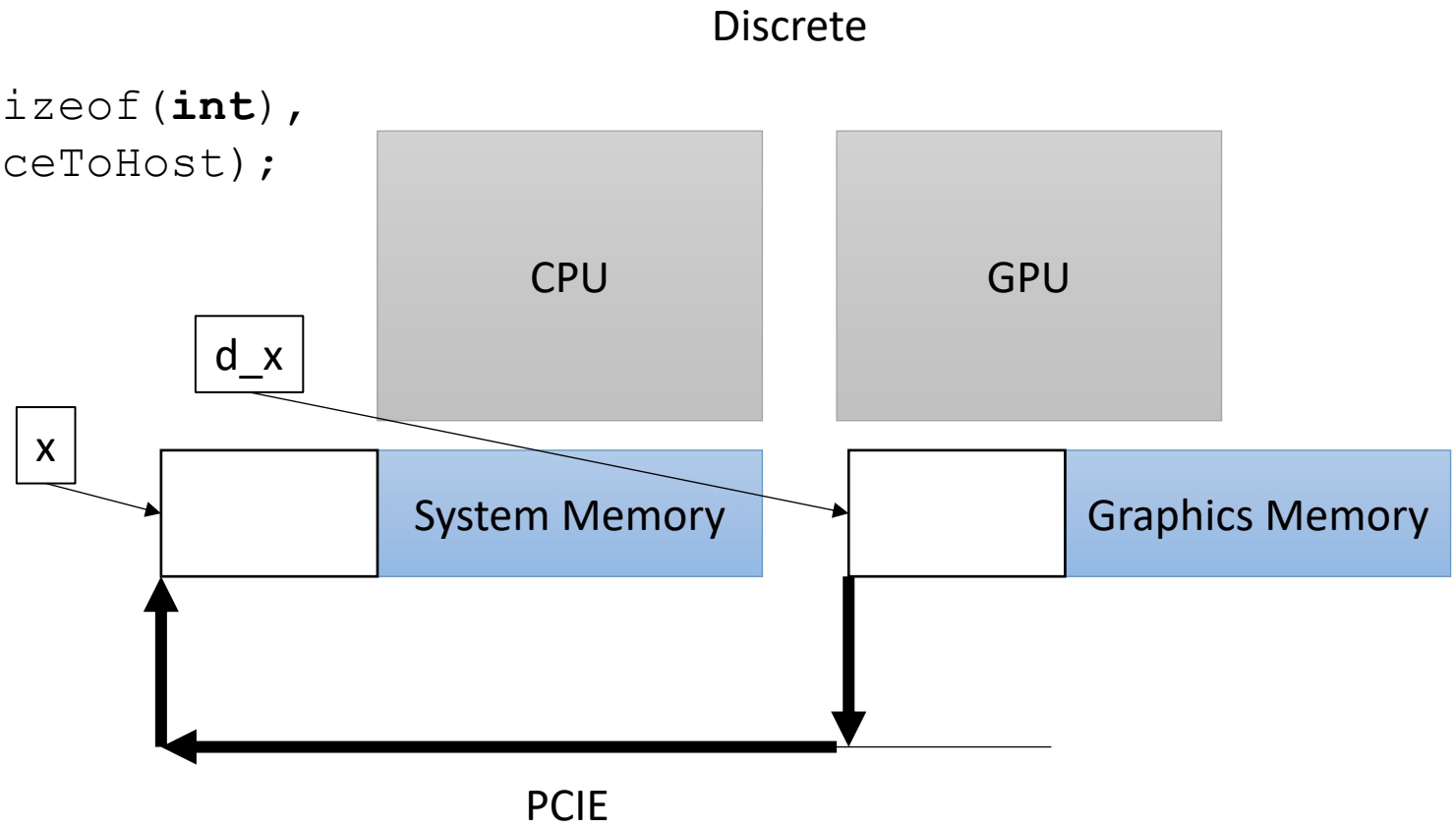
```
//initialize x on host
cudaMemcpy(d_x, x, SIZE*sizeof(int),
           cudaMemcpyHostToDevice);
```



GPU set up

- Our heterogeneous, parallel, programming model

```
//initialize x on host
cudaMemcpy(x, d_x, SIZE*sizeof(int),
           cudaMemcpyDeviceToHost);
```



Previous quiz + Review

What keyword do we need to include for a function to be executed on the GPU using CUDA?

- ○ __kernel__
- ○ __global__
- ○ __this__
- ○ __gpu__

Previous quiz + Review

What keyword do we need to include for a function to be executed on the GPU using CUDA?

- ○ __kernel__
- -> ○ __global__
- ○ __this__
- ○ __gpu__

The GPU Program

```
__global__ void vector_add(int * a, int * b, int * c, int size) {
    for (int i = 0; i < size; i++) {
      a[i] = b[i] + c[i];
   }
}
```

First parallelization attempt

```
__global__ void vector_add(int * d_a, int * d_b, int * d_c, int size) {
    int chunk_size = size/blockDim.x;
    int start = chunk_size * threadIdx.x;
    int end = start + end;
    for (int i = start; i < end; i++) {
      d_a[i] = d_b[i] + d_c[i];
   }
}
```

calling the function

```
vector_add<<<1,32>>>(d_a, d_b, d_c, size);
```

number of threads
thread id

Kernel constraints

- What can and can’t you do in a GPU kernel?

Kernel constraints

- What can and can’t you do in a GPU kernel?
  - Print?
  - File I/O?
  - C++ standard library? E.g. vectors?
  - Memory allocation?
  - Atomics?

Previous quiz + Review

Using a few sentences, give examples of workloads that benefit from GPU parallelism.

Previous quiz + Review

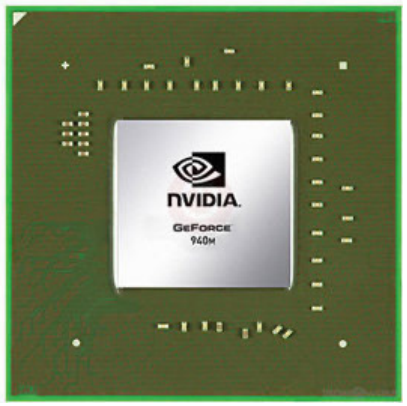
Using a few sentences, give examples of workloads that benefit from GPU parallelism.

Data Parallelism

Recalling where we left off

Programming a GPU

Tiny GPU in an embedded system



Nvidia Jetson Nano (whole chip, CPU + GPU)
2 Billion transistors
10 TDP
Est. $99

Fight!

The CPU in my research workstation

Intel i7-9700K
2.16 Billion transistors
95 TDP
Est. $316

https://www.techpowerup.com/gpu-specs/geforce-940m.c2648
https://www.alibaba.com/product-detail/Intel-Core-i7-9700K-8-Cores_62512430487.html
https://www.prolast.com/prolast-elevated-boxing-rings-22-x-22/

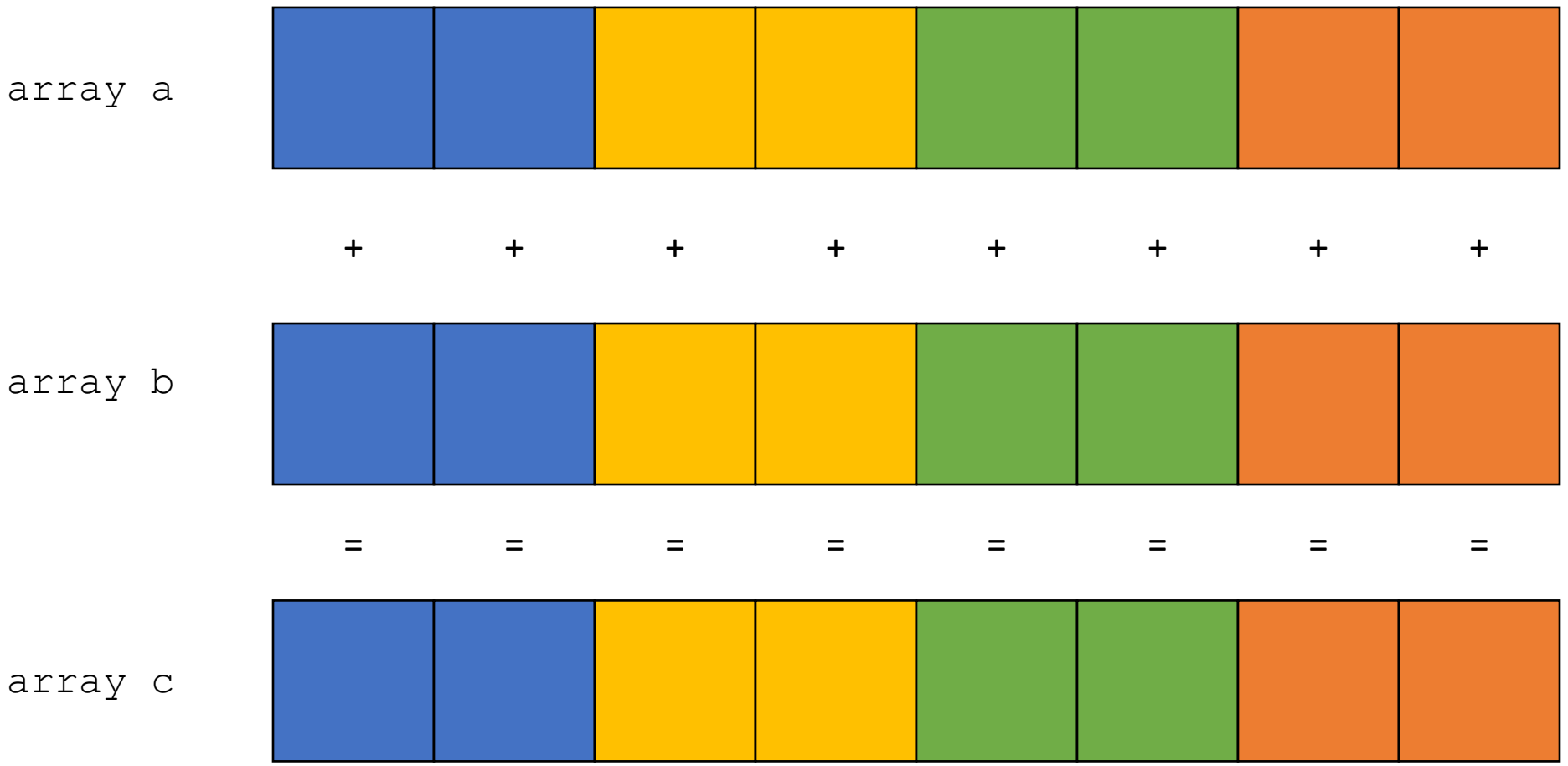
Programming a GPU

- The problem: Vector addition

Parallel Schedules

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange



Lets set up the CPU

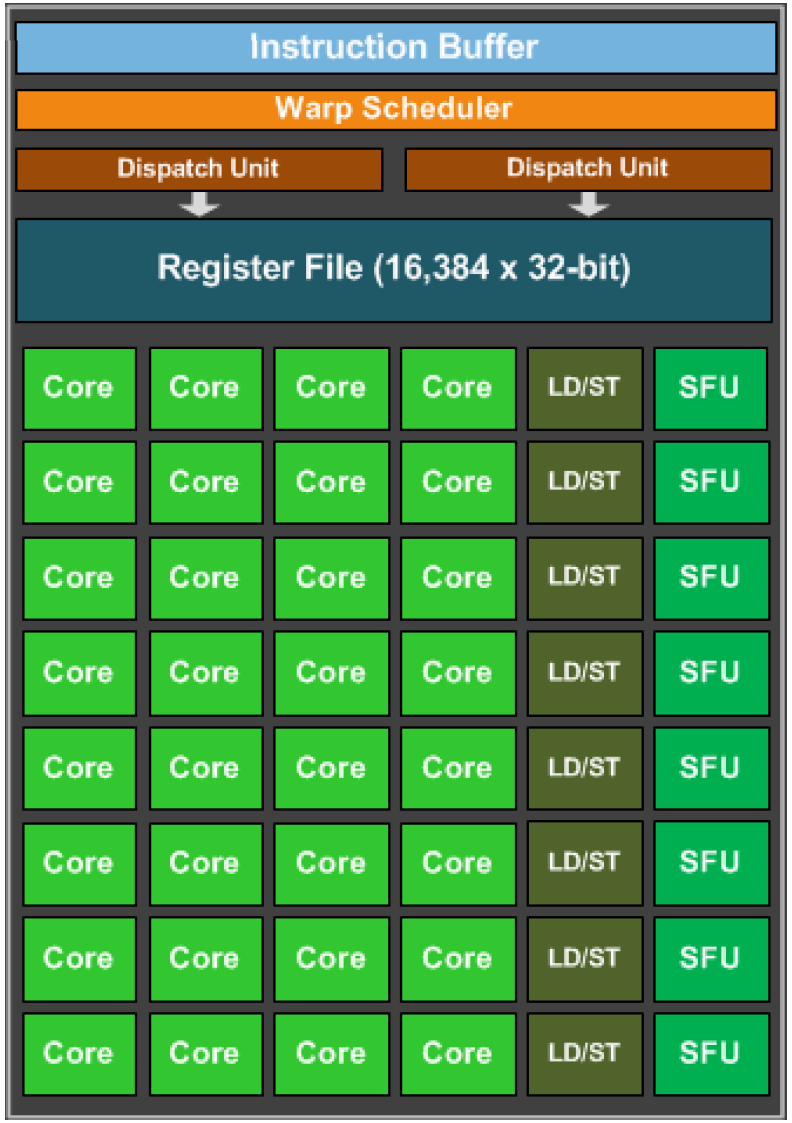
- CPU code

First GPU attempt

- Basic sequential GPU program
  - Issues?
  - Key insights?

woah, 32 cores!

We should parallelize our application!



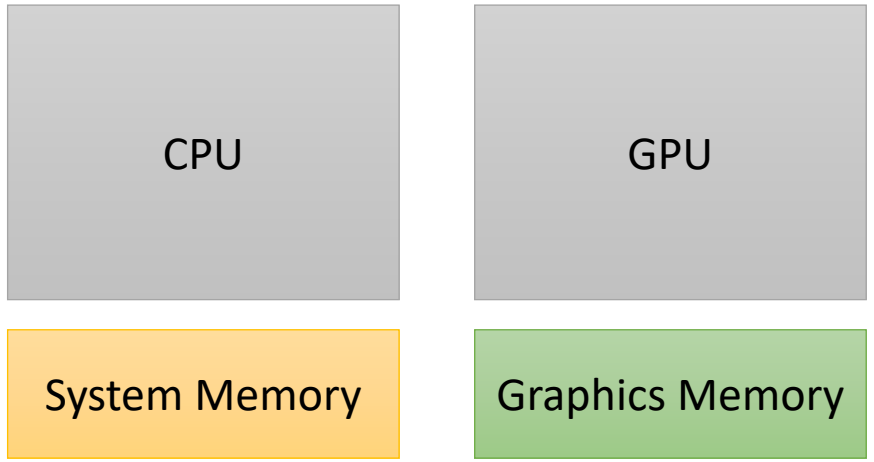
https://www.techpowerup.com/gpu-specs/docs/nvidia-gtx-980.pdf

Second GPU attempt

- Use 32 cores
  - Issues?
  - Key insights?

GPU Memory

CPU Memory:
Fast: Low Latency
Easily saturated: Low Bandwidth
Scales well: up to 1 TB
DDR



GPU Memory:
slow: High Latency
hard to saturate: High Bandwidth
doesn't scale: 32 GB
GDDR, HBM

2-lane straight highway driven on by sports cars

Different technologies

16-lane highway on a windy road driven by semi trucks

Preemption and concurrency?

memory access
600 cycles

warp 1

GPU

Graphics Memory

warp 2

warp 0

preempt warp 1
and put warp 2 on

We can hide latency through preemption and concurrency!

Go back to our program

```
__global__ void vector_add(int * d_a, int * d_b, int * d_c, int size) {
    int chunk_size = size/blockDim.x;
    int start = chunk_size * threadIdx.x;
    int end = start + end;
    for (int i = start; i < end; i++) {
      d_a[i] = d_b[i] + d_c[i];
   }
}
```

calling the function

Lets launch with 32 warps

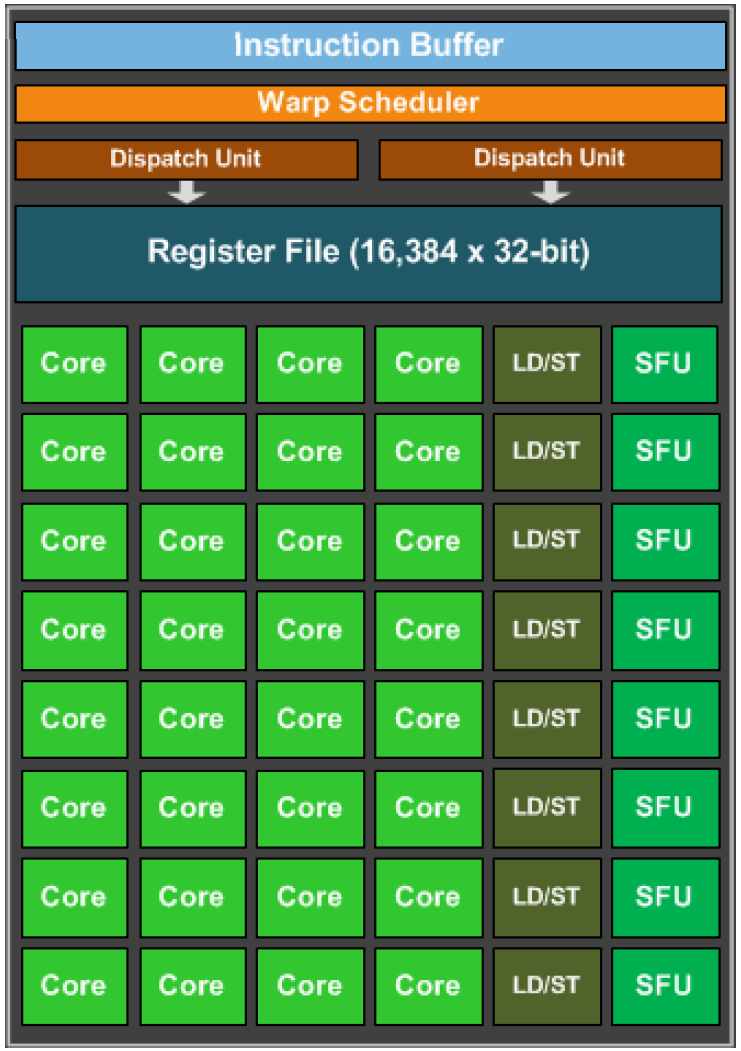
```
vector_add<<<1,1024>>>(d_a, d_b, d_c, size);
```

Concurrent warps

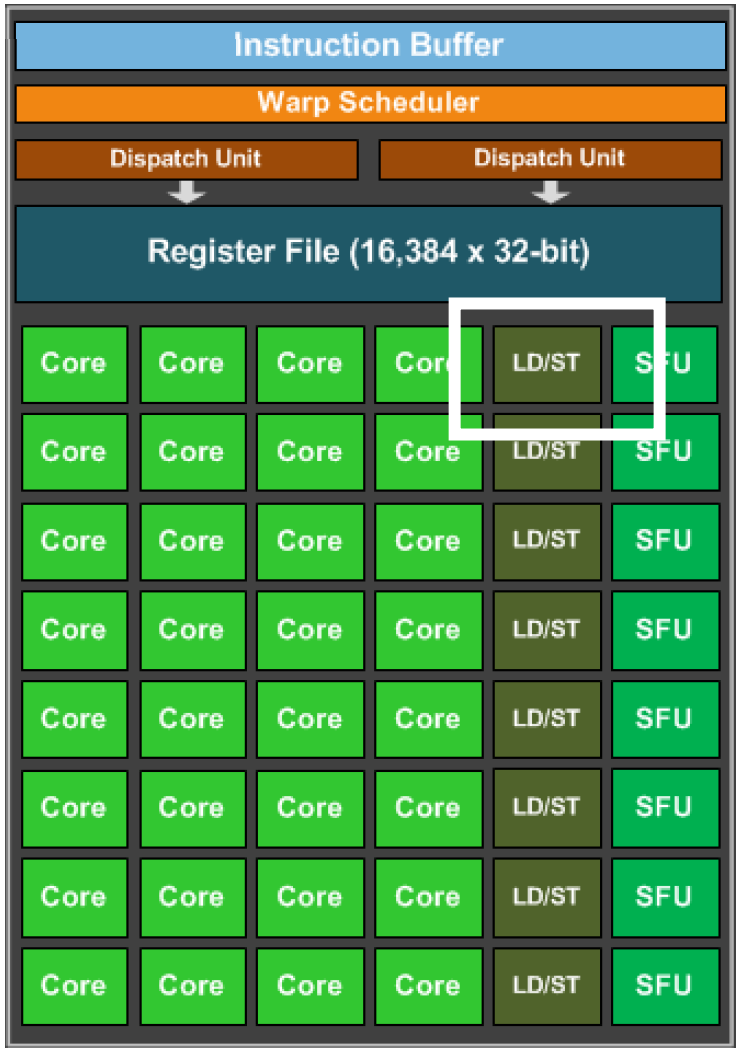
This is about 2x faster.

Getting better!

Optimizing memory accesses

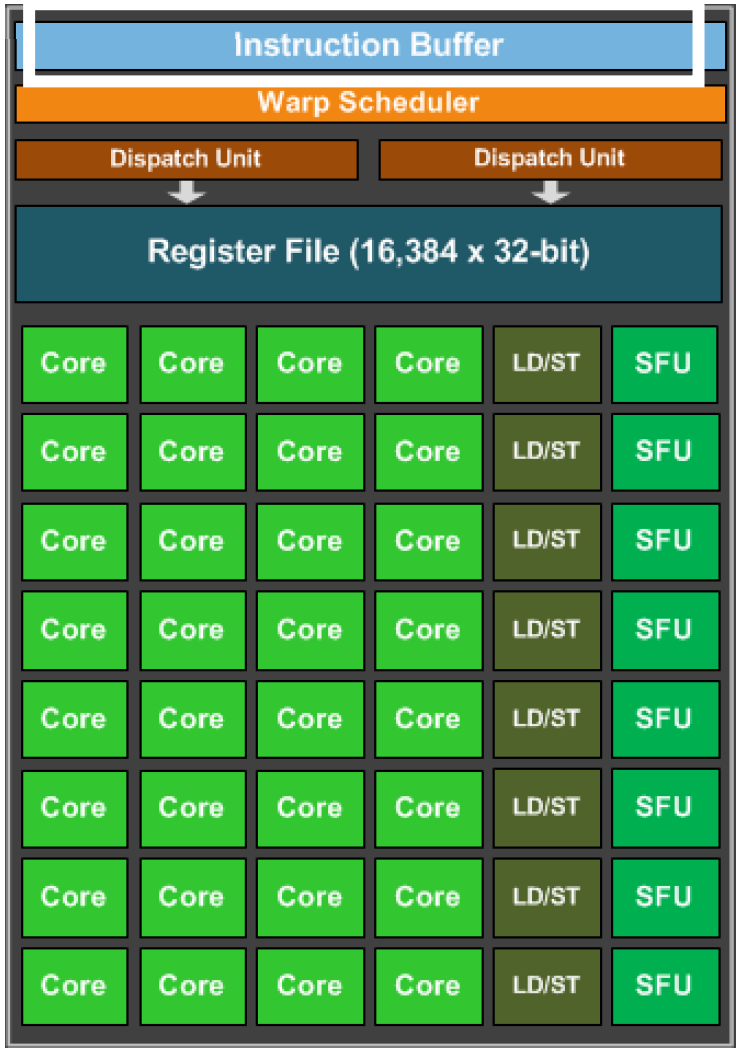


Optimizing memory accesses



This is the load/store unit. The hardware component responsible for issuing loads and stores.
Shared between 4 cores.

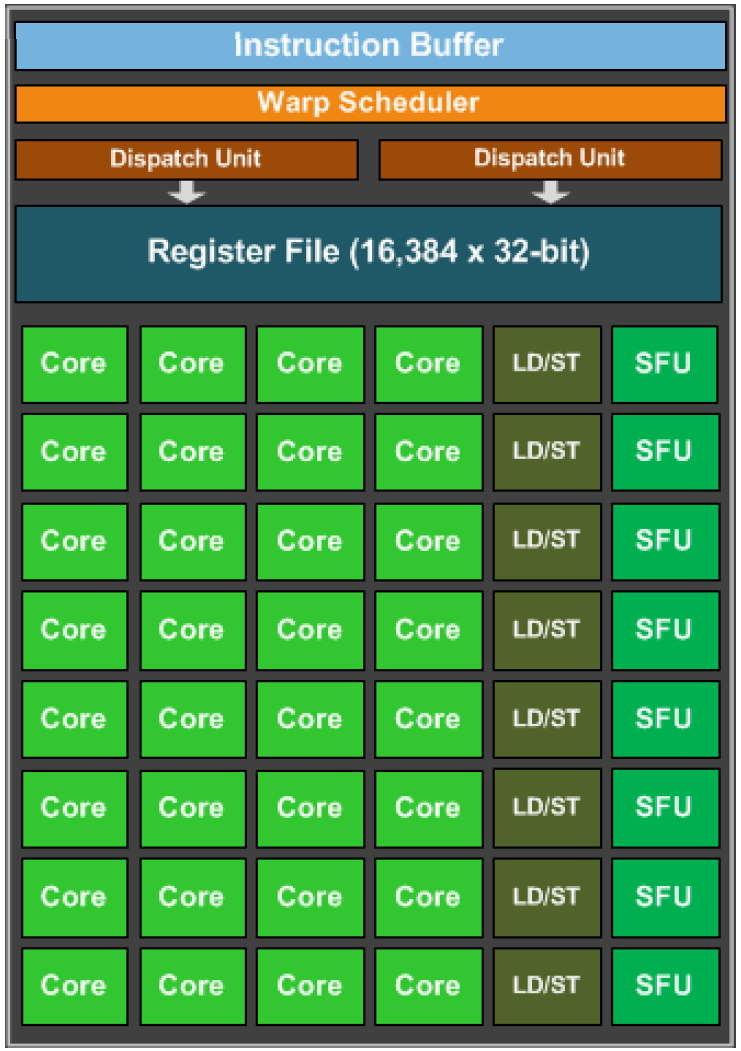
Optimizing memory accesses



This is the instruction cache
Shared between all cores of the warp.

This is the load/store unit. The hardware component responsible for issuing loads and stores.
Shared between 4 cores.

Warp execution



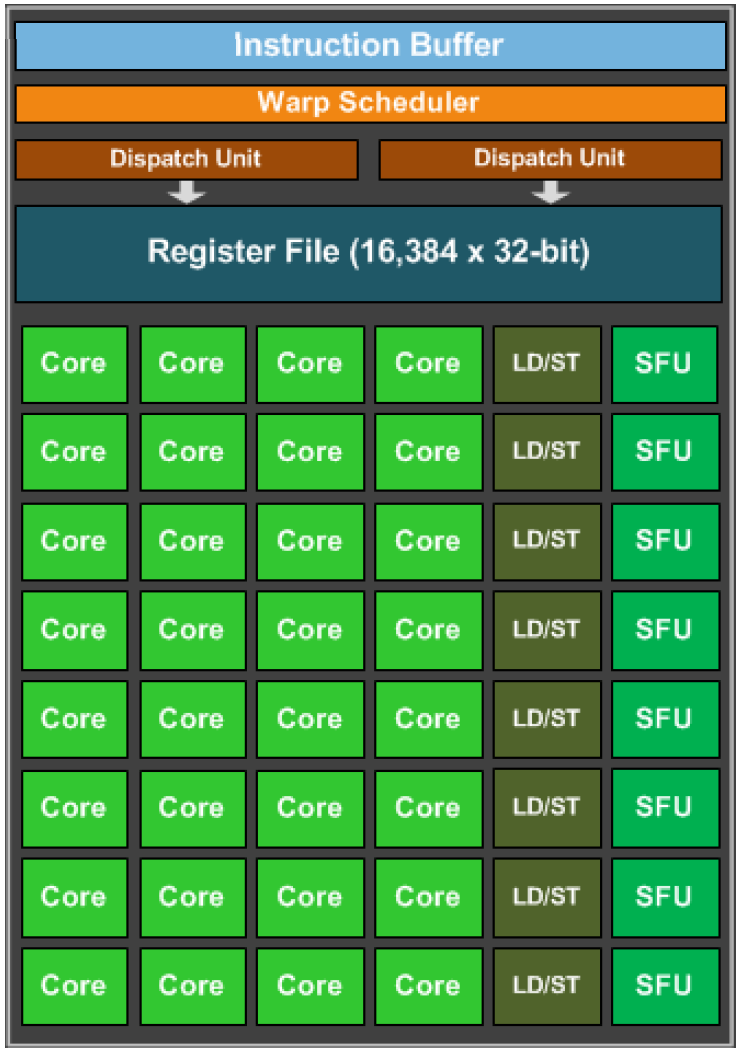
Groups of 32 threads are called a “warp”

They are executed in lock-step, i.e. they all execute the same instruction at the same time

Warp execution

Groups of 32 threads are called a “warp”

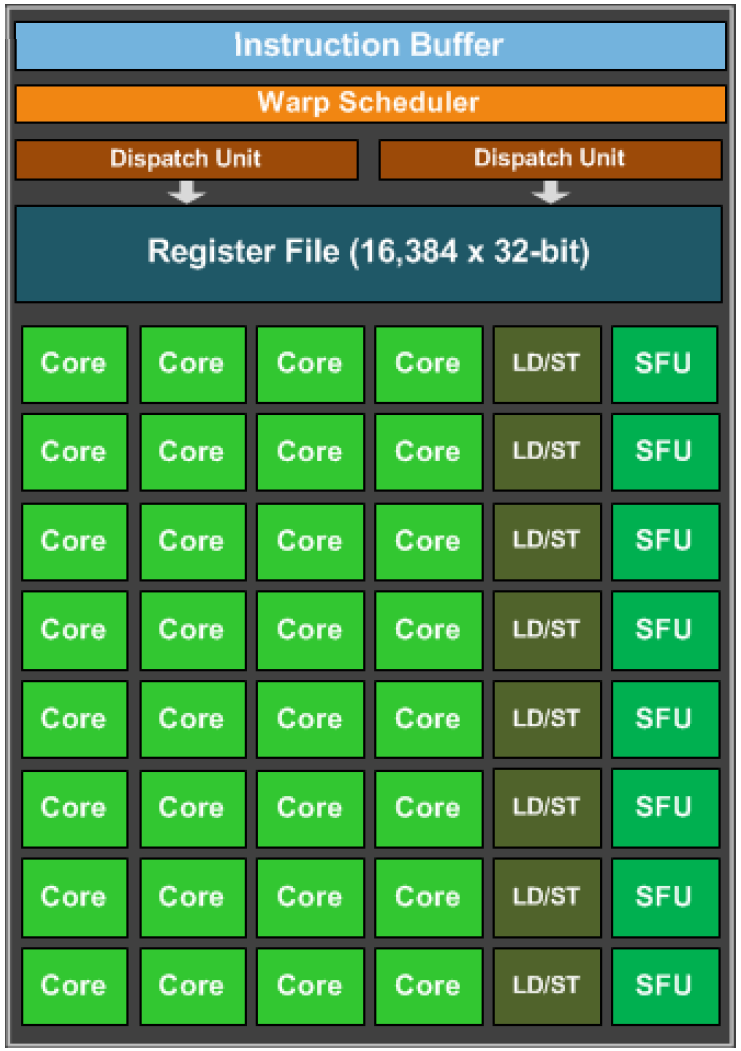
They are executed in lock-step, i.e. they all execute the same instruction at the same time



Program:

```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

Warp execution



Groups of 32 threads are called a “warp”

They are executed in lock-step, i.e. they all execute the same instruction at the same time

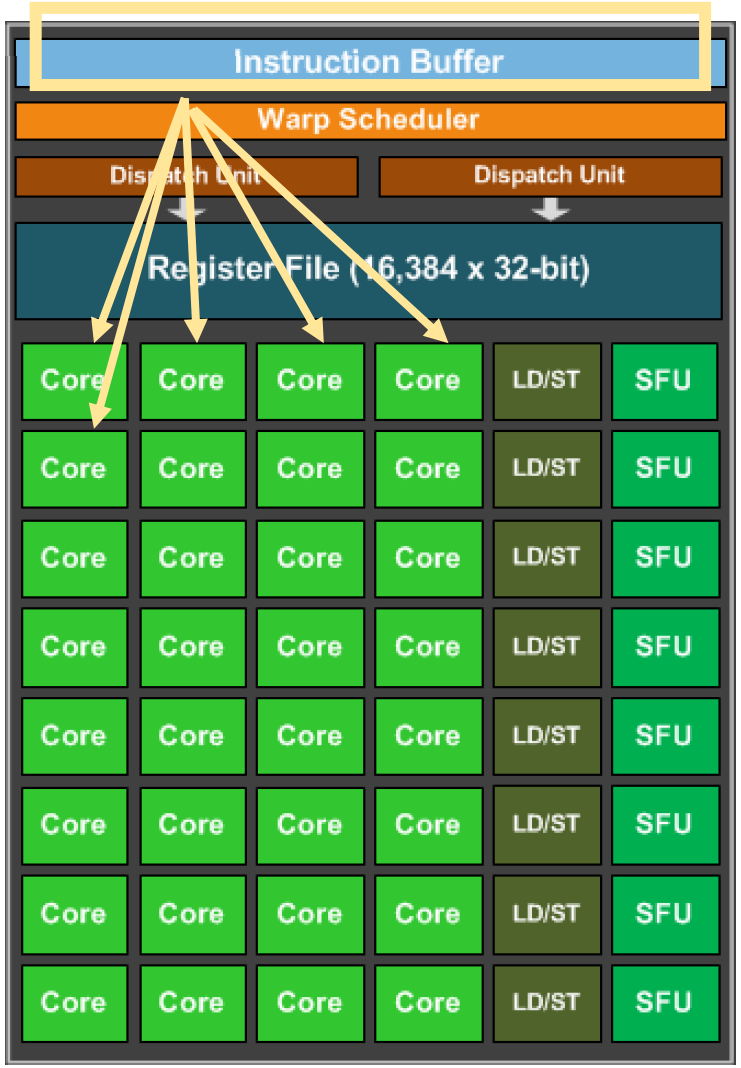
Program:

```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

Warp execution

Groups of 32 threads are called a “warp”

They are executed in lock-step, i.e. they all execute the same instruction at the same time



instruction is fetched from the buffer and distributed to all the cores.

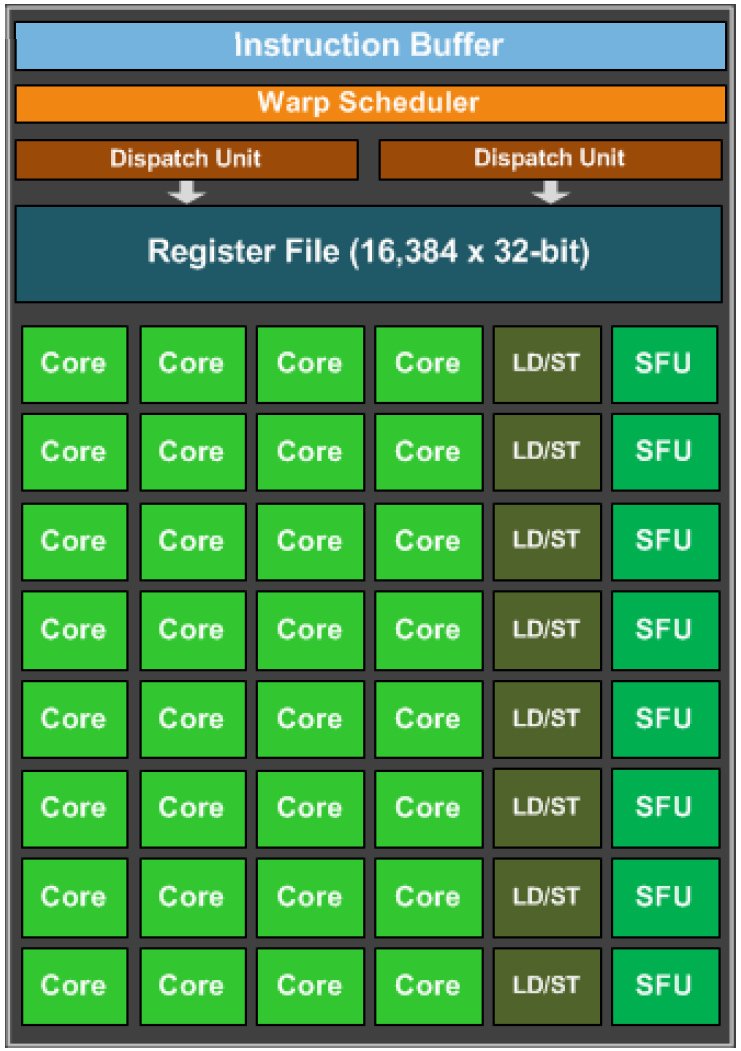
Program:

```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

Warp execution

Groups of 32 threads are called a “warp”

They are executed in lock-step, i.e. they all execute the same instruction at the same time



All cores need to wait until all cores finish the first instruction

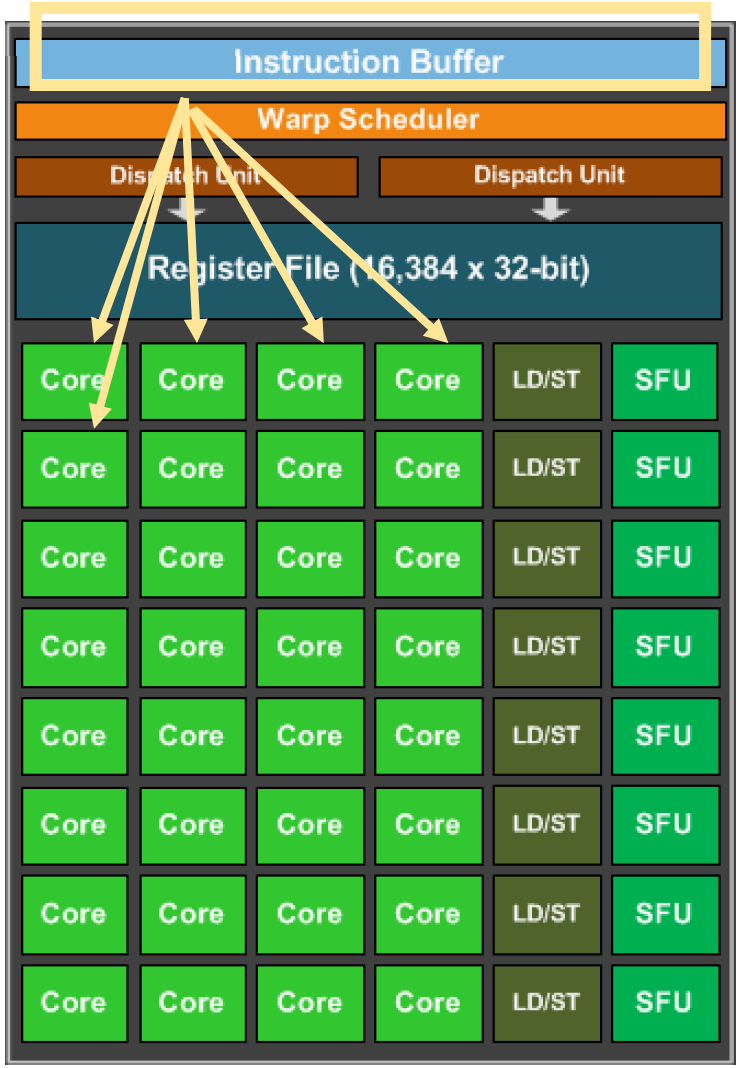
Program:

```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

Warp execution

Groups of 32 threads are called a “warp”

They are executed in lock-step, i.e. they all execute the same instruction at the same time



Start the next instruction.

Program:

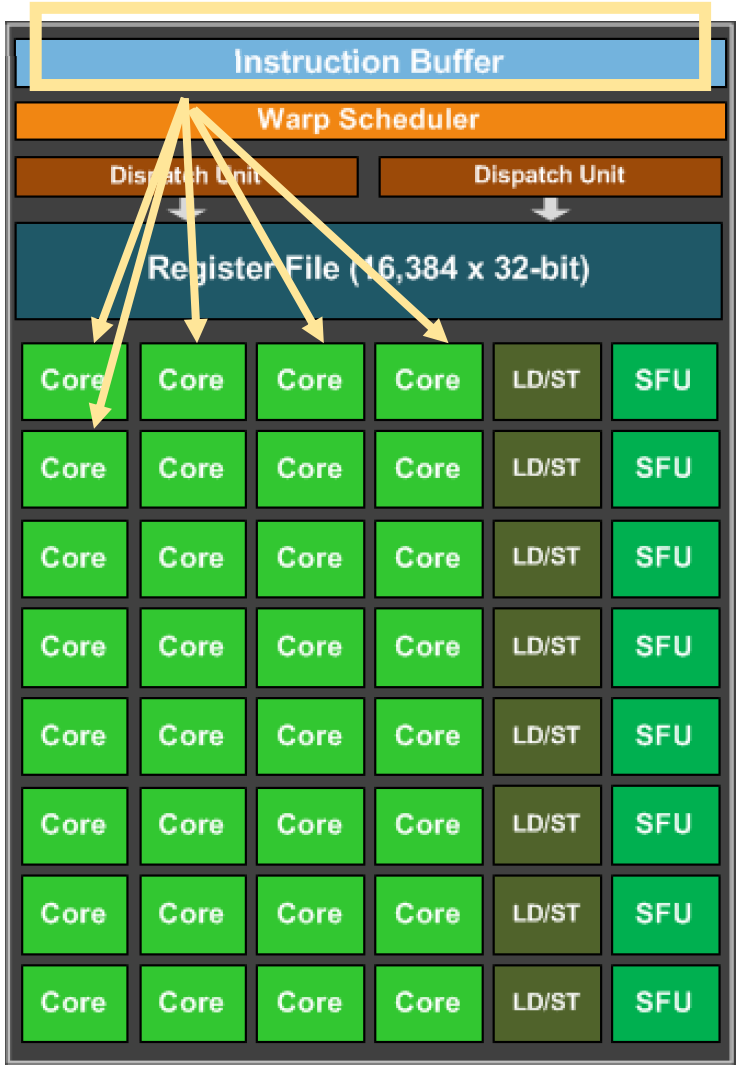
```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

Why would we have a programming model like this?

Warp execution

Groups of 32 threads are called a “warp”

They are executed in lock-step, i.e. they all execute the same instruction at the same time



Start the next instruction.

Program:

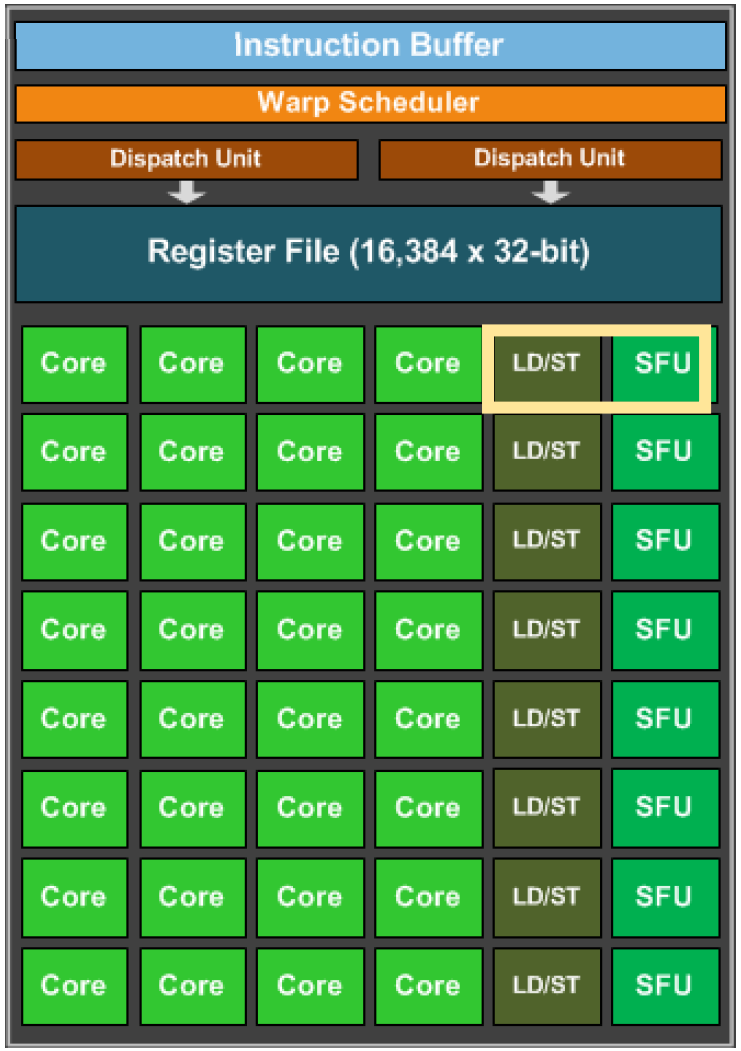
```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

Why would we have a programming model like this?
More cores (share program counters)
Can be efficient to share hardware resources

Warp execution

Groups of 32 threads are called a “warp”

They are executed in lock-step, i.e. they all execute the same instruction at the same time



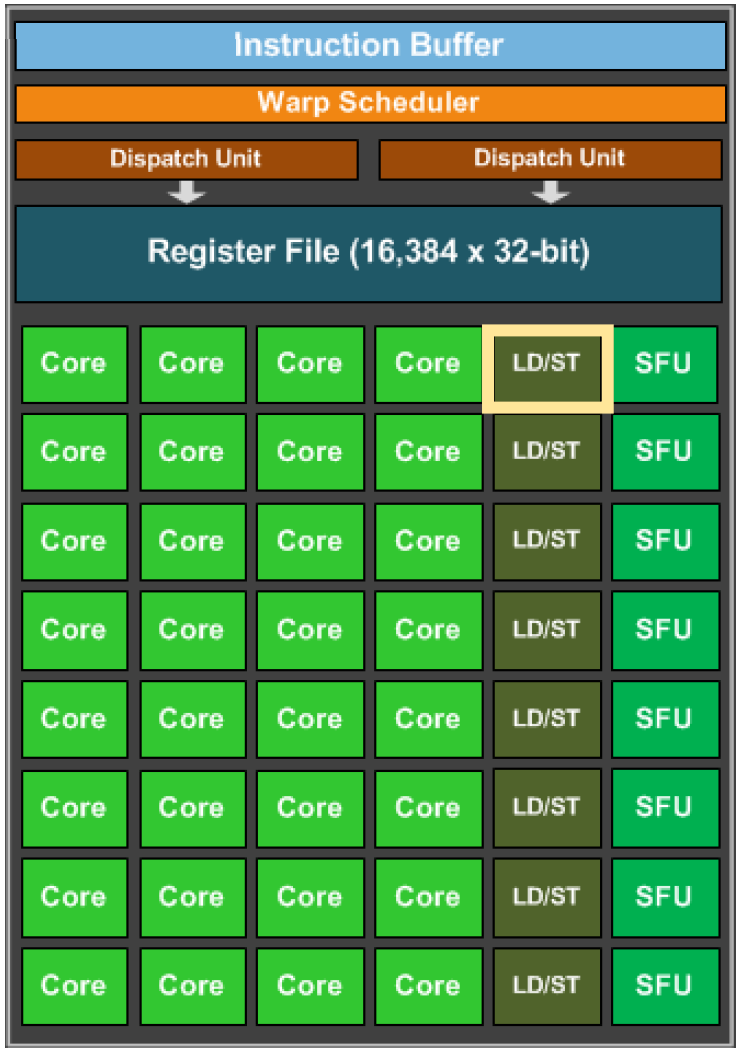
Cores share expensive HW units (load/store and special functions)

Program:

```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

Warp execution

Lets look closer at memory

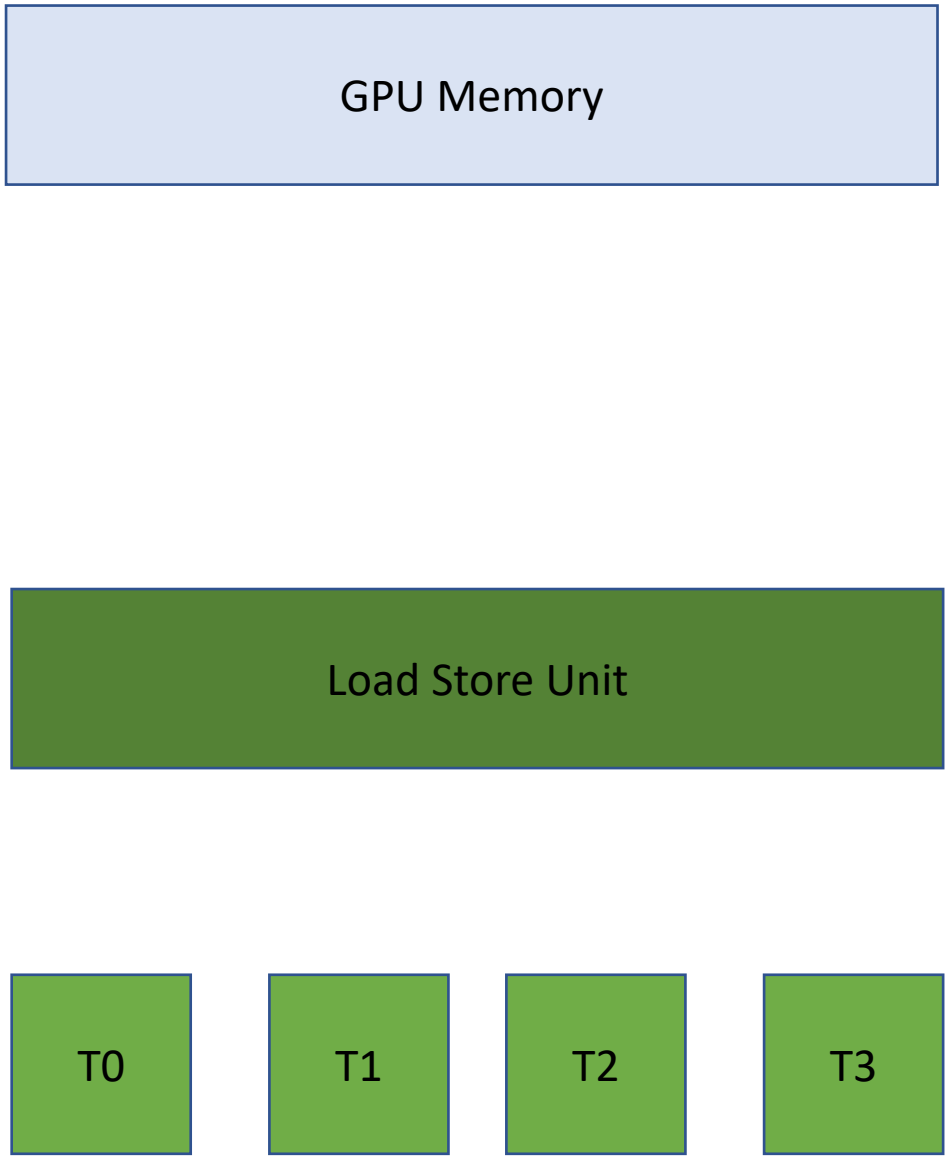


Program:

```
int variable1 = b[0];
int variable2 = c[0];
int variable3 = variable1 + variable2;
a[0] = variable3;
```

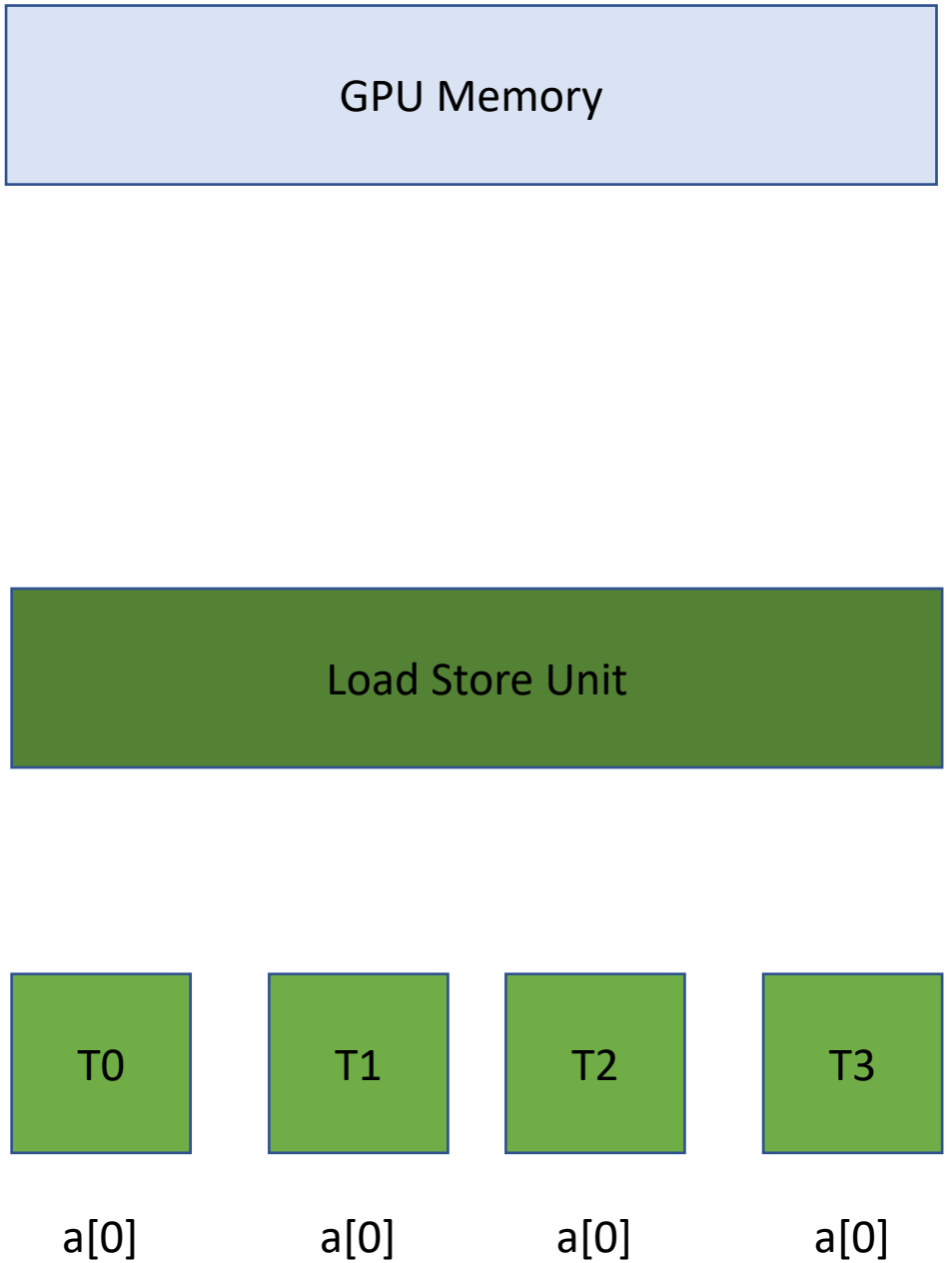
4 cores are accessing memory. what happens if they access the same value?

4 cores are accessing memory. What can happen



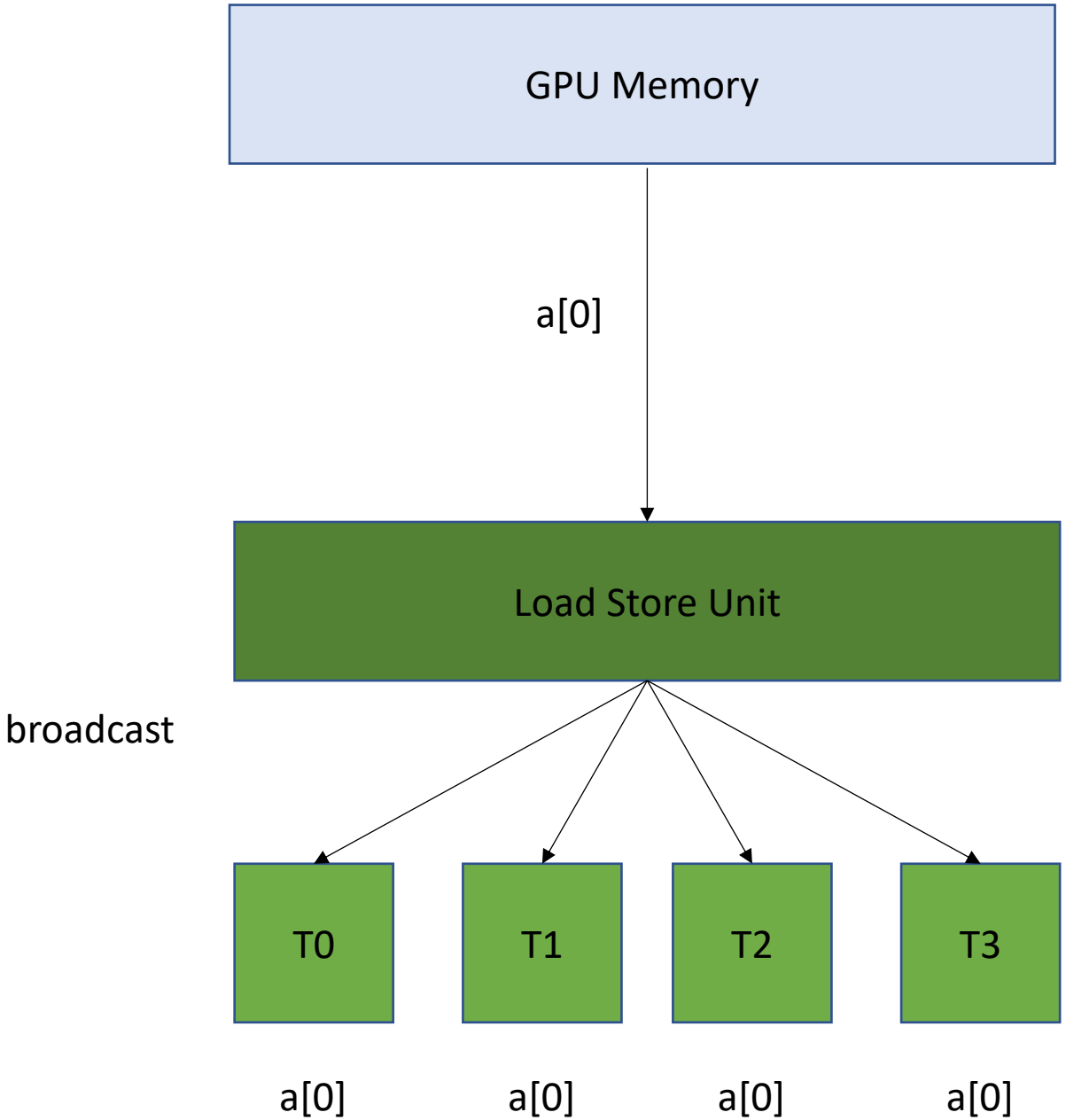
4 cores are accessing memory. What can happen

All read the same value



4 cores are accessing memory. What can happen

All read the same value
This is efficient: the load store unit can ask for the value and then broadcast it to all cores.

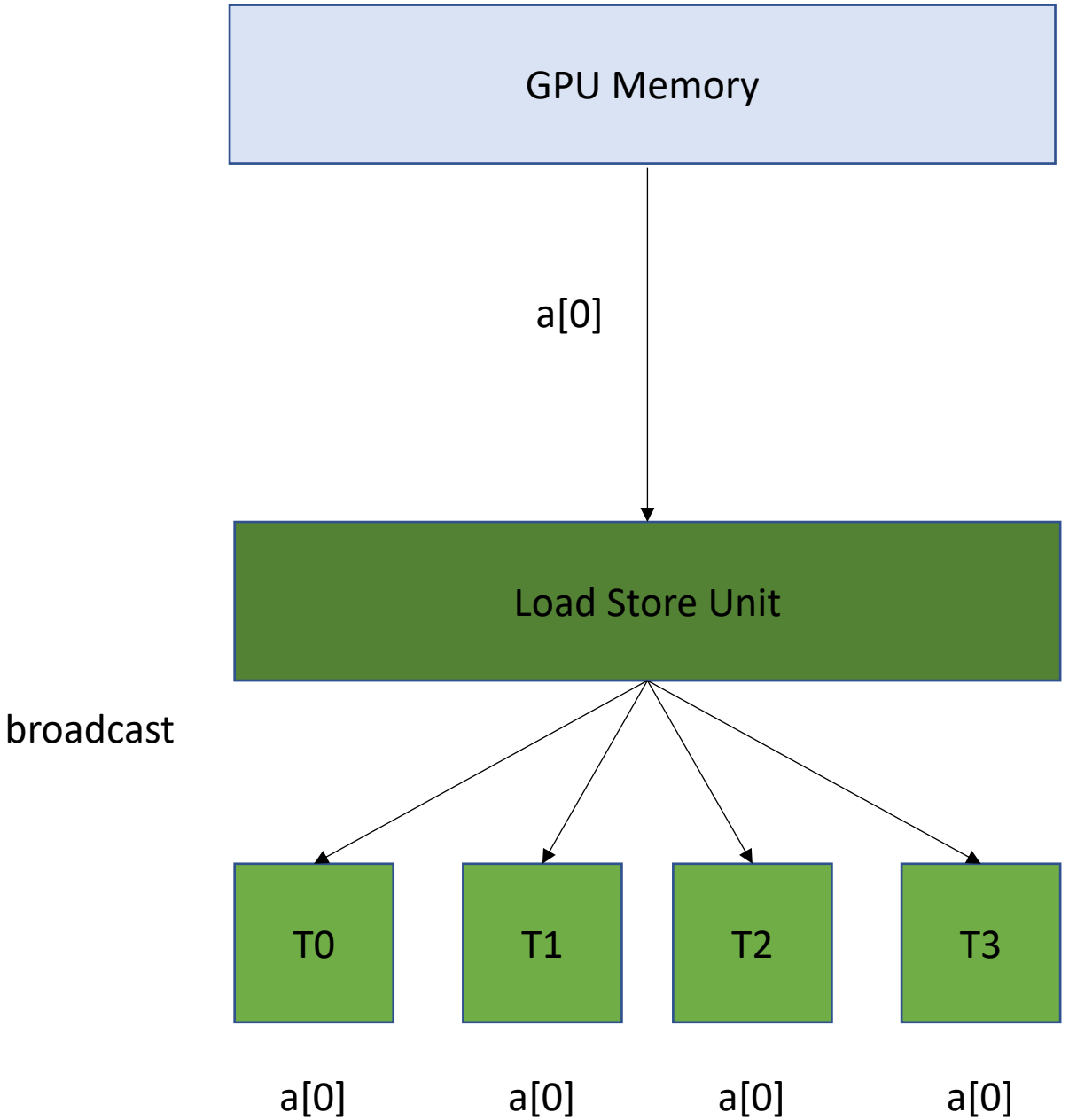


4 cores are accessing memory. What can happen

All read the same value
This is efficient: the load store unit can ask for the value and then broadcast it to all cores.

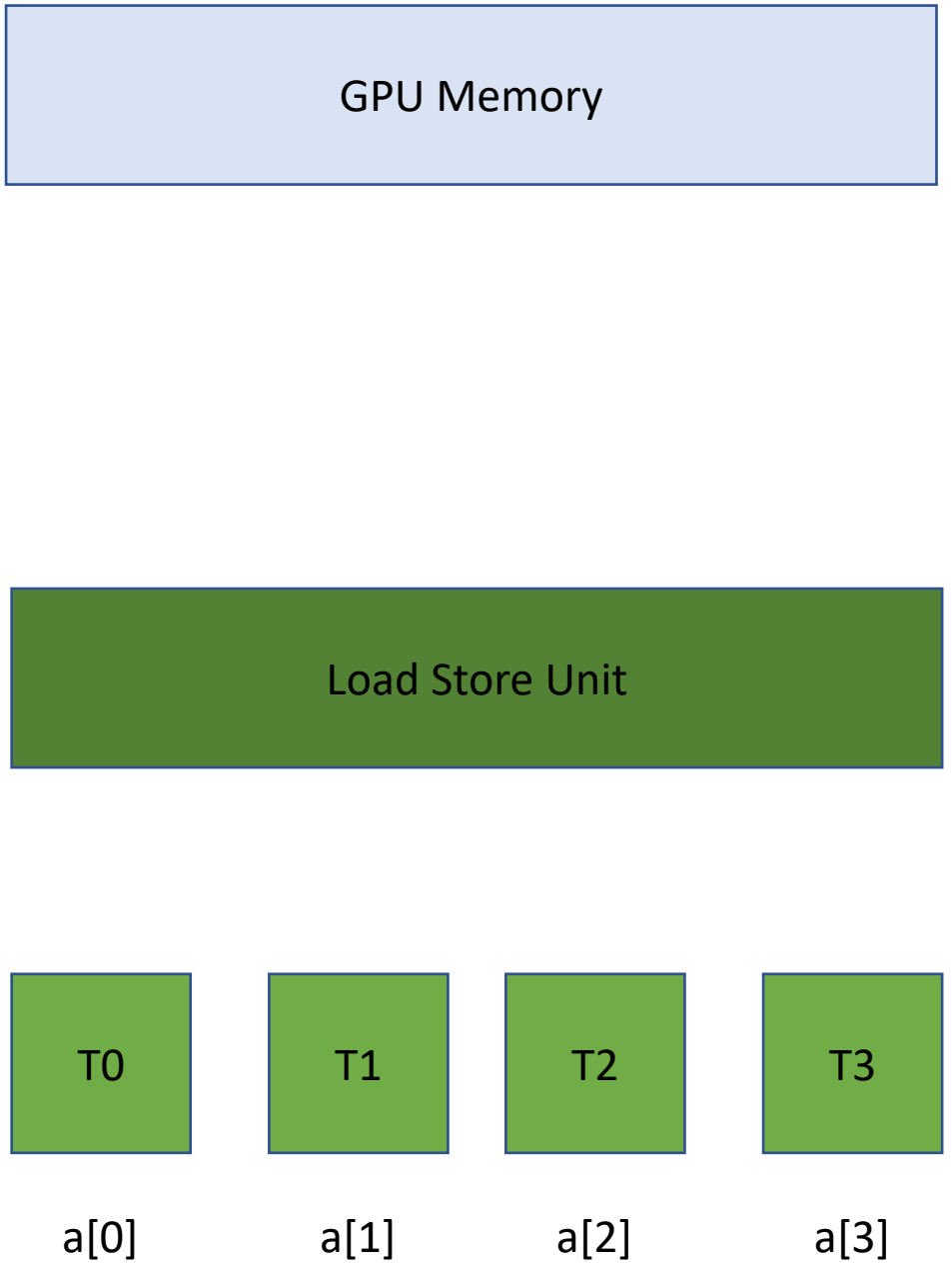
1 request to GPU memory

Efficient, but probably not too common.



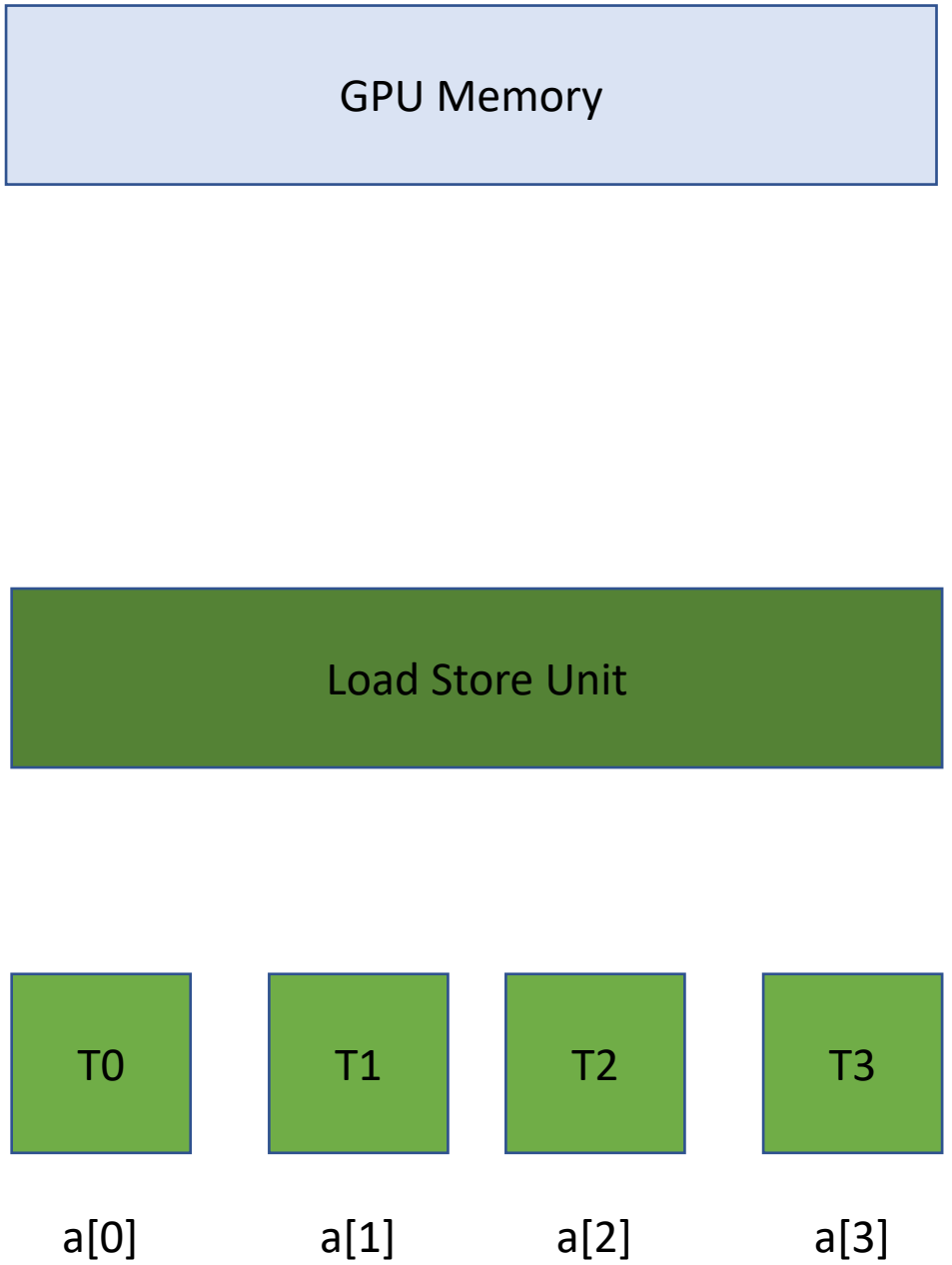
4 cores are accessing memory. What can happen

Read contiguous values



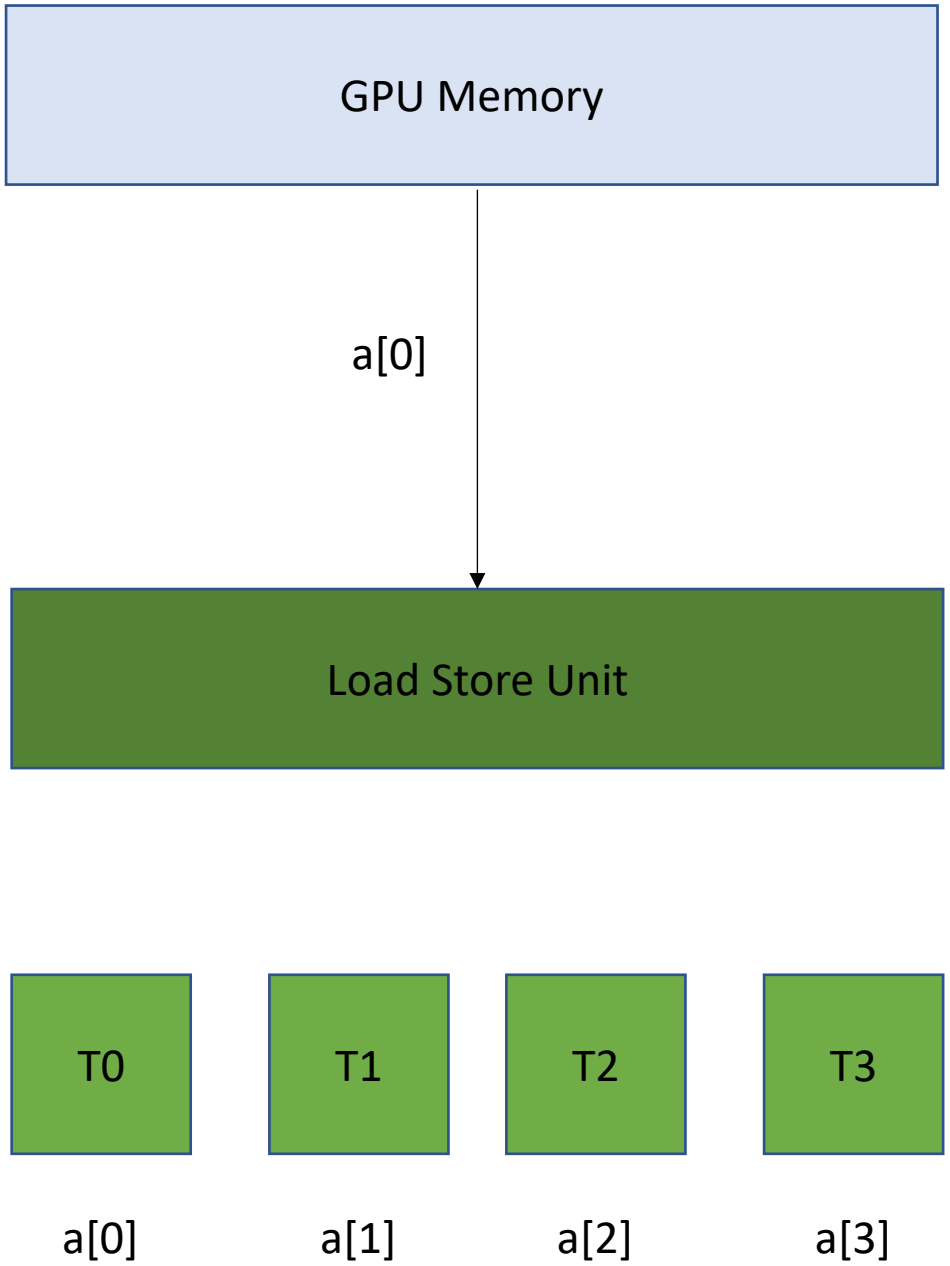
4 cores are accessing memory. What can happen

Read contiguous values
Like the CPU cache, the Load/Store Unit reads in memory in chunks. 16 bytes



4 cores are accessing memory. What can happen

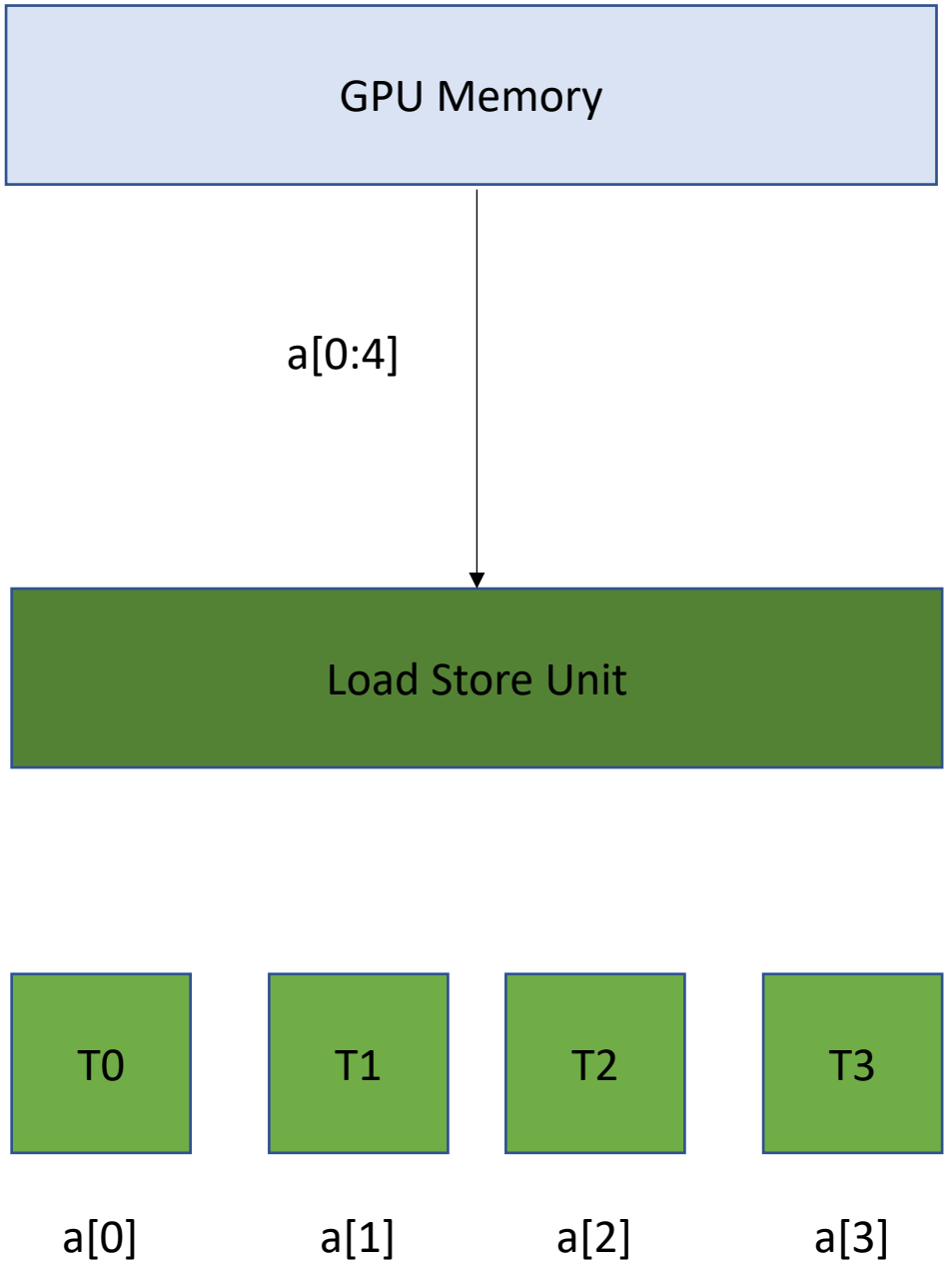
Read contiguous values
Like the CPU cache, the Load/Store Unit reads in memory in chunks. 16 bytes



4 cores are accessing memory. What can happen

Read contiguous values
Like the CPU cache, the Load/Store Unit reads in memory in chunks. 16 bytes

Can easily distribute the values to the threads

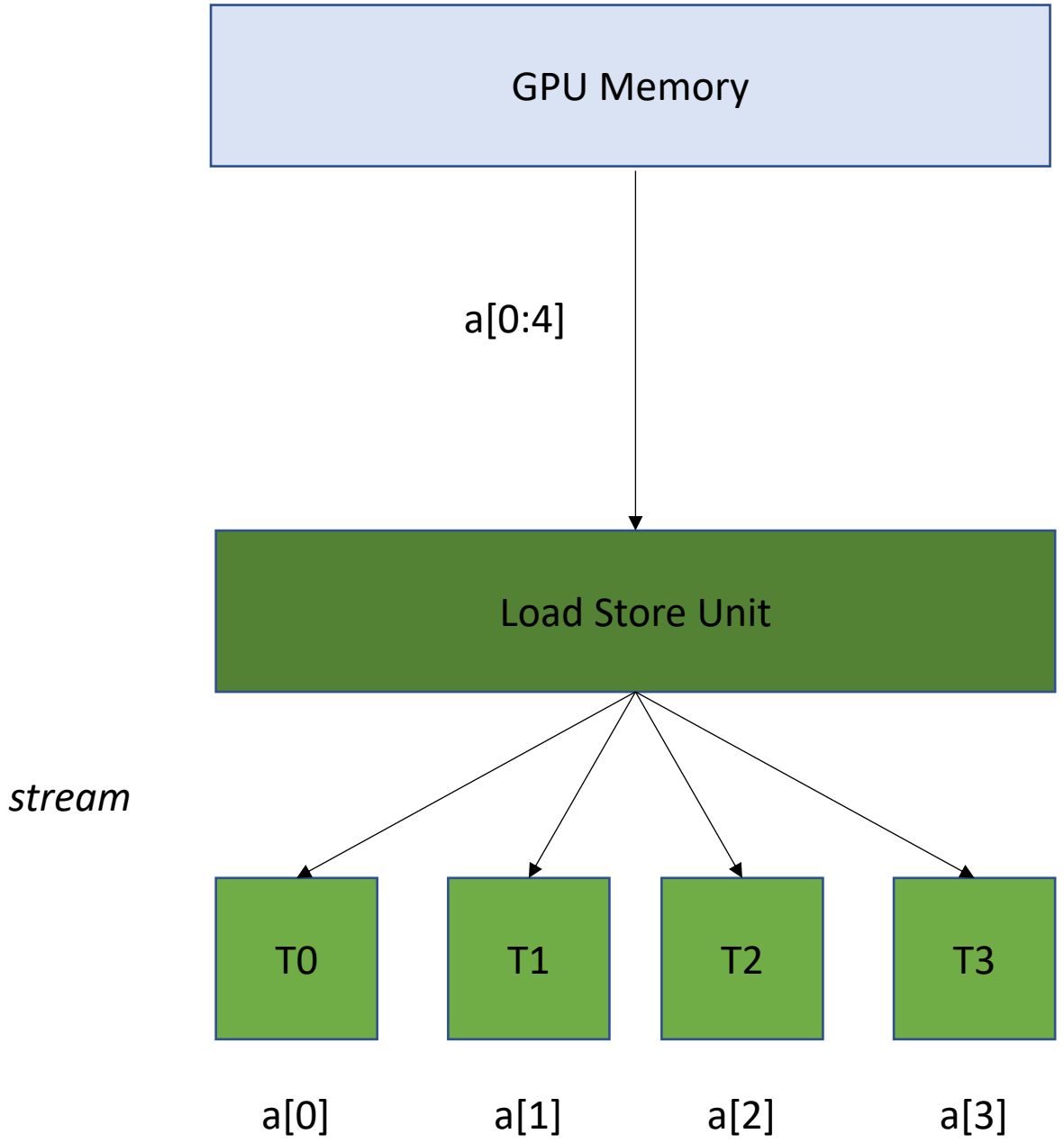


4 cores are accessing memory. What can happen

Read contiguous values
Like the CPU cache, the Load/Store Unit reads in memory in chunks. 16 bytes

Can easily distribute the values to the threads

1 request to GPU memory

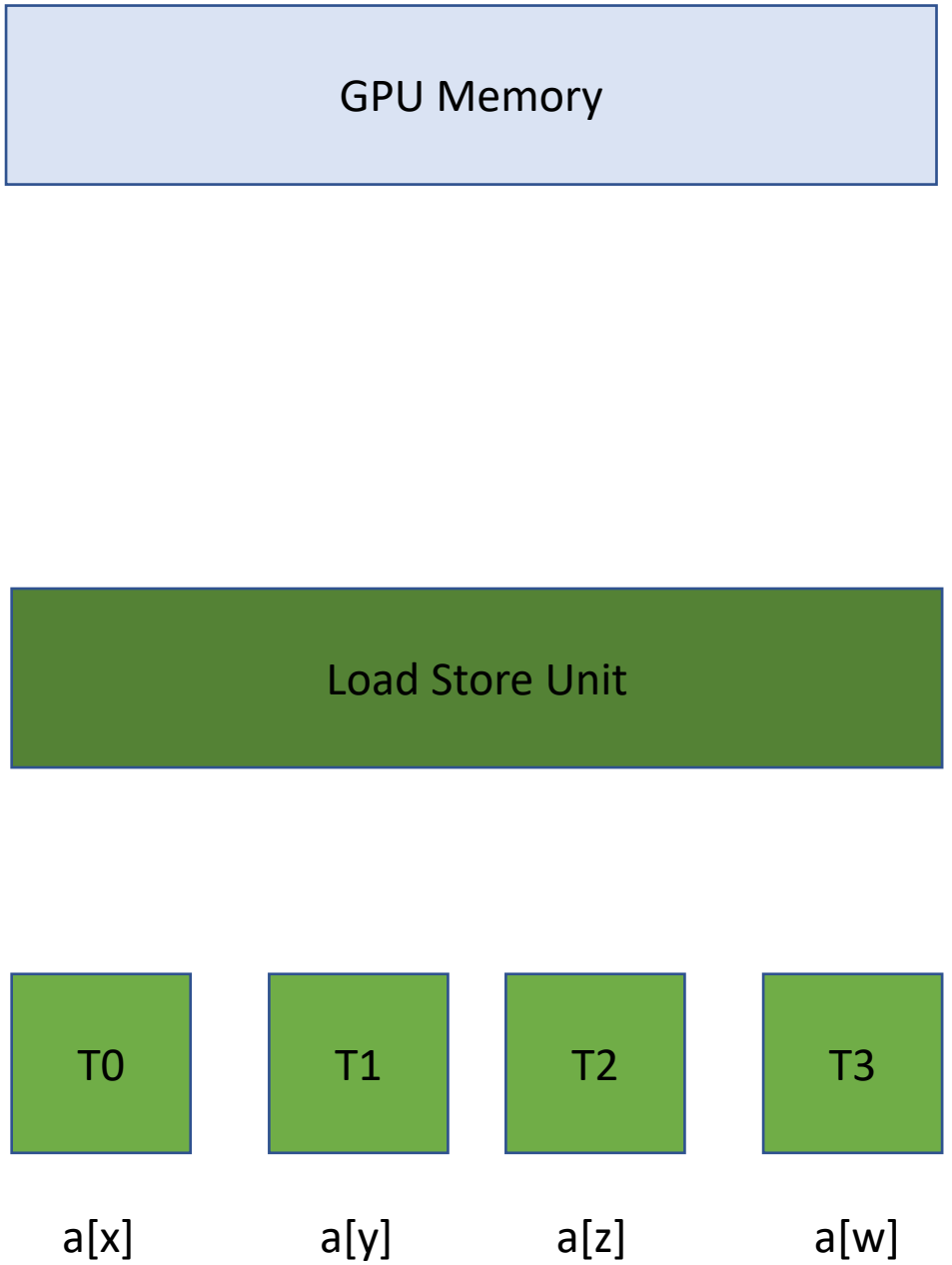


4 cores are accessing memory. What can happen

Read non-contiguous values

Not good!

Accesses are Serialized.
You need 4 requests to GPU memory

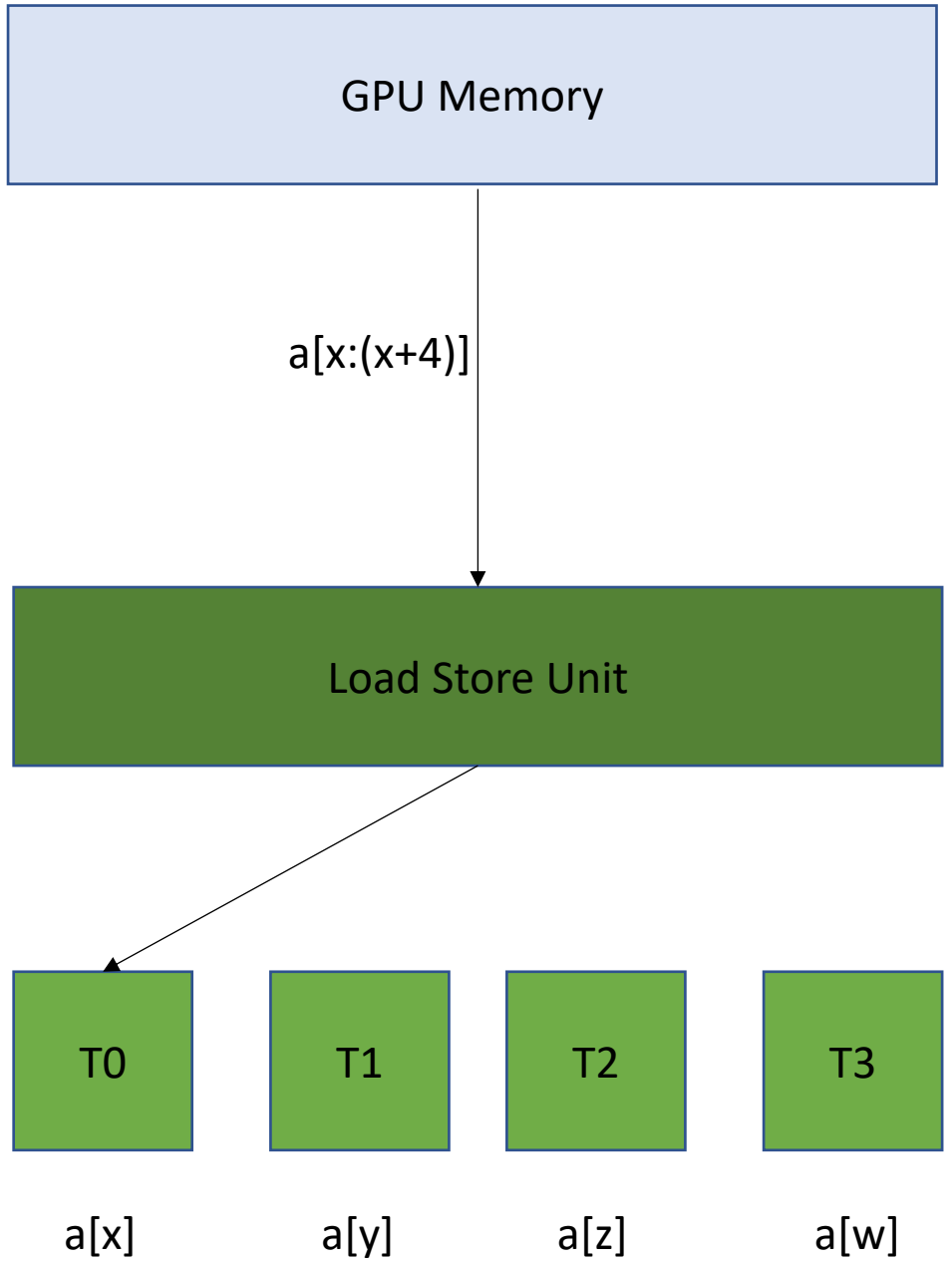


4 cores are accessing memory. What can happen

Read non-contiguous values

Not good!

Accesses are Serialized.
You need 4 requests to GPU memory

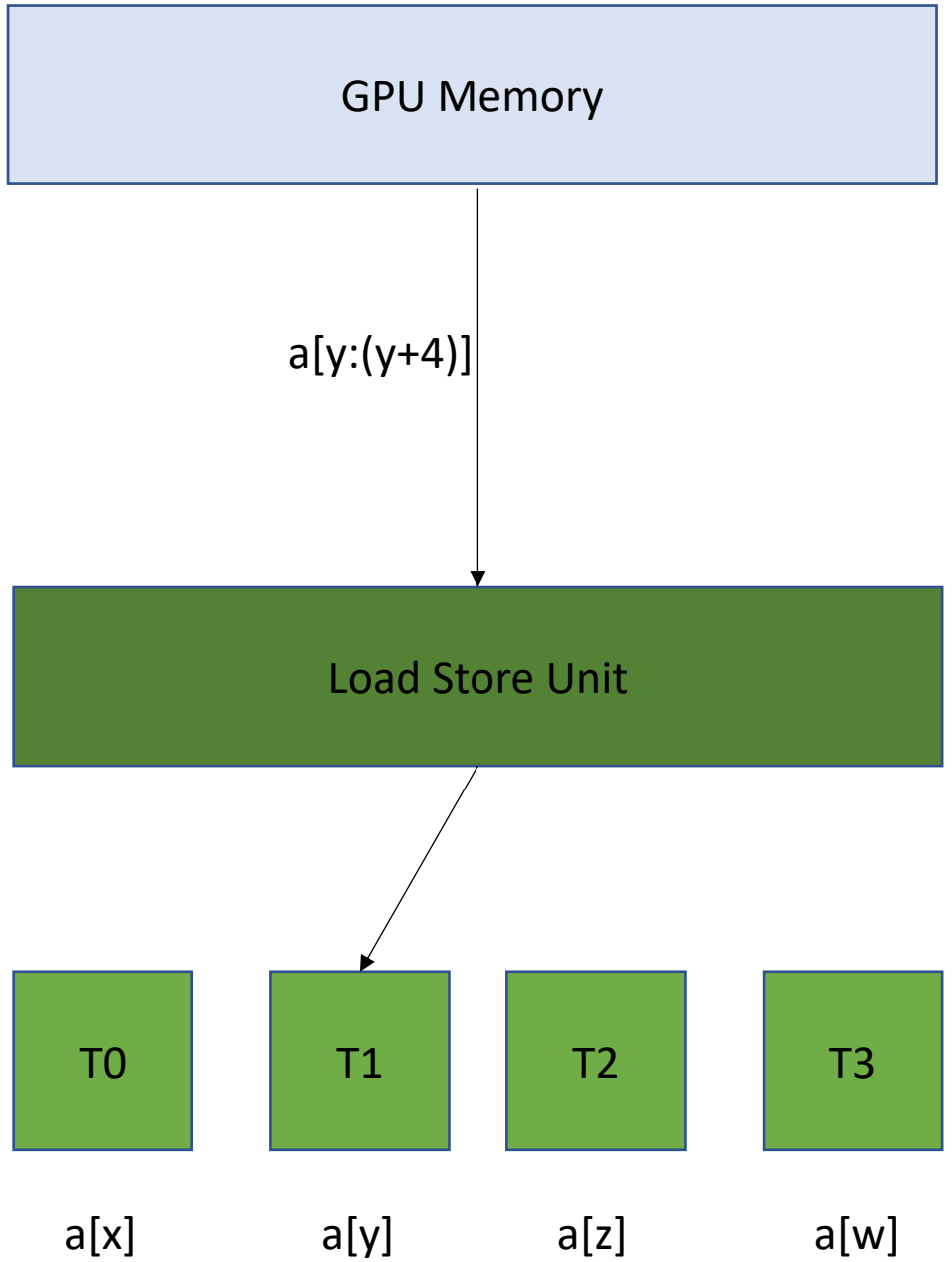


4 cores are accessing memory. What can happen

Read non-contiguous values

Not good!

Accesses are Serialized.
You need 4 requests to GPU memory

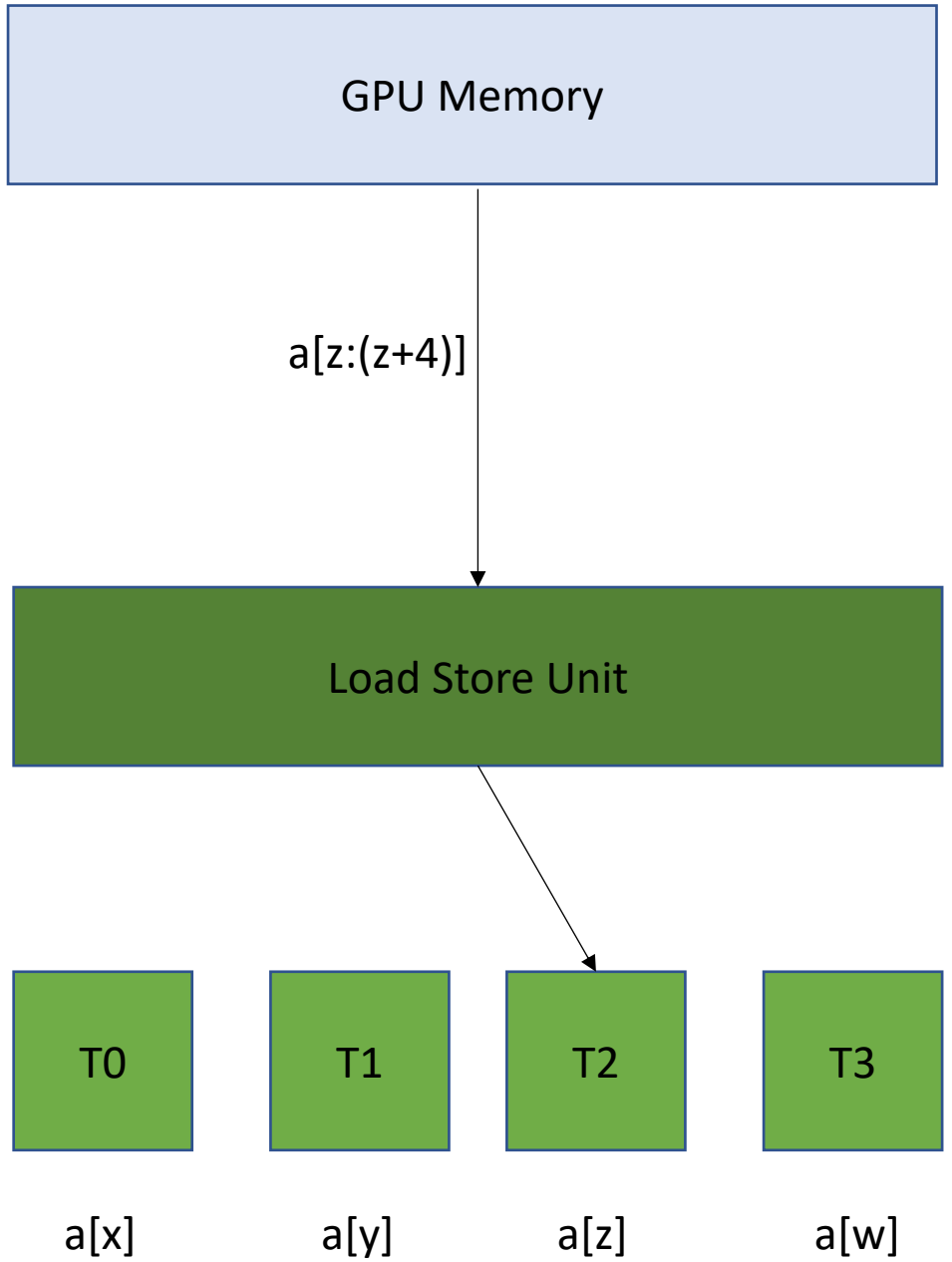


4 cores are accessing memory. What can happen

Read non-contiguous values

Not good!

Accesses are Serialized.
You need 4 requests to GPU memory

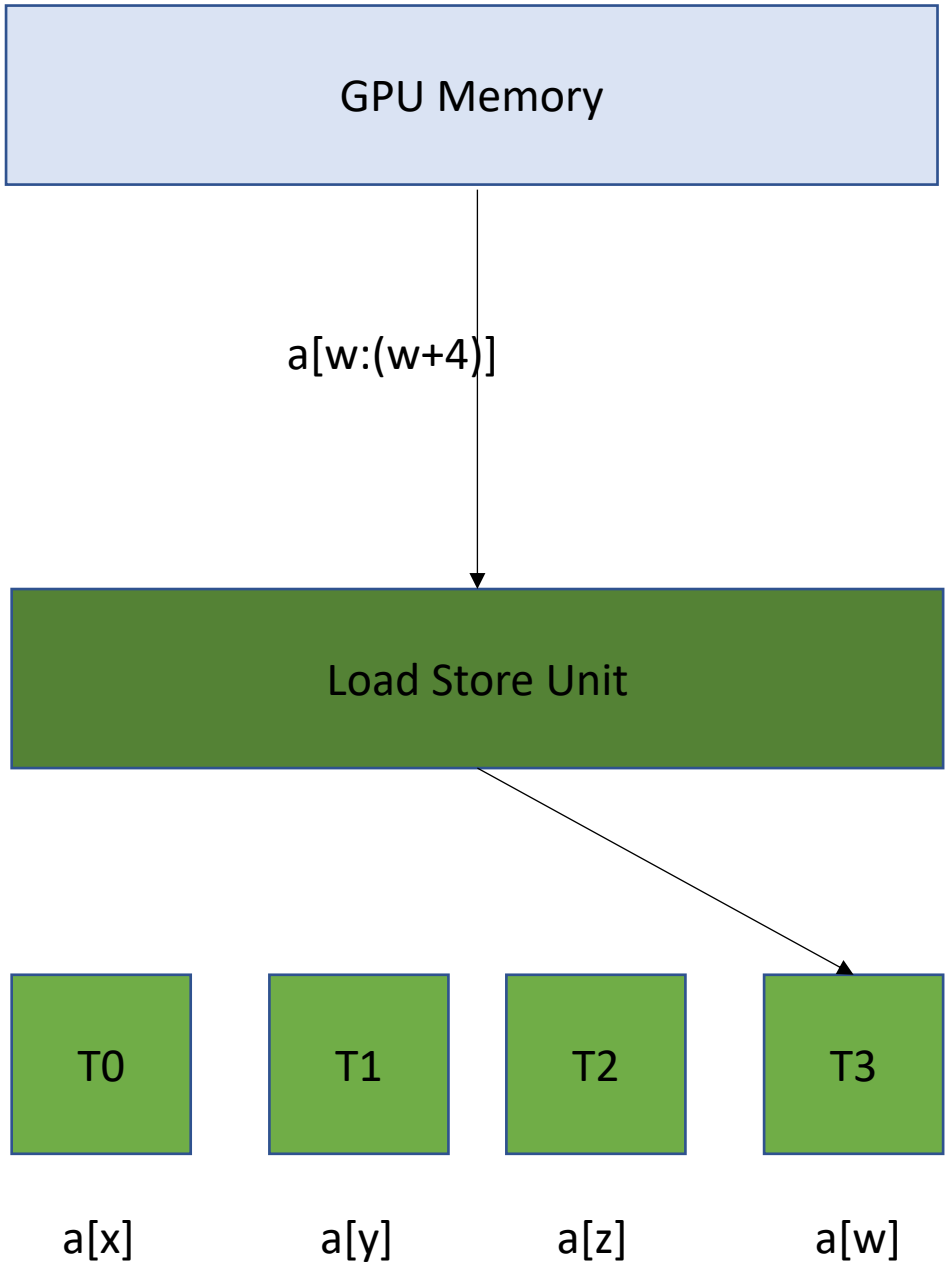


4 cores are accessing memory. What can happen

Read non-contiguous values

Not good!

Accesses are Serialized.
You need 4 requests to GPU memory



Go back to our program

```
__global__ void vector_add(int * d_a, int * d_b, int * d_c, int size) {
    int chunk_size = size/blockDim.x;
    int start = chunk_size * threadIdx.x;
    int end = start + end;
    for (int i = start; i < end; i++) {
      d_a[i] = d_b[i] + d_c[i];
   }
}
```

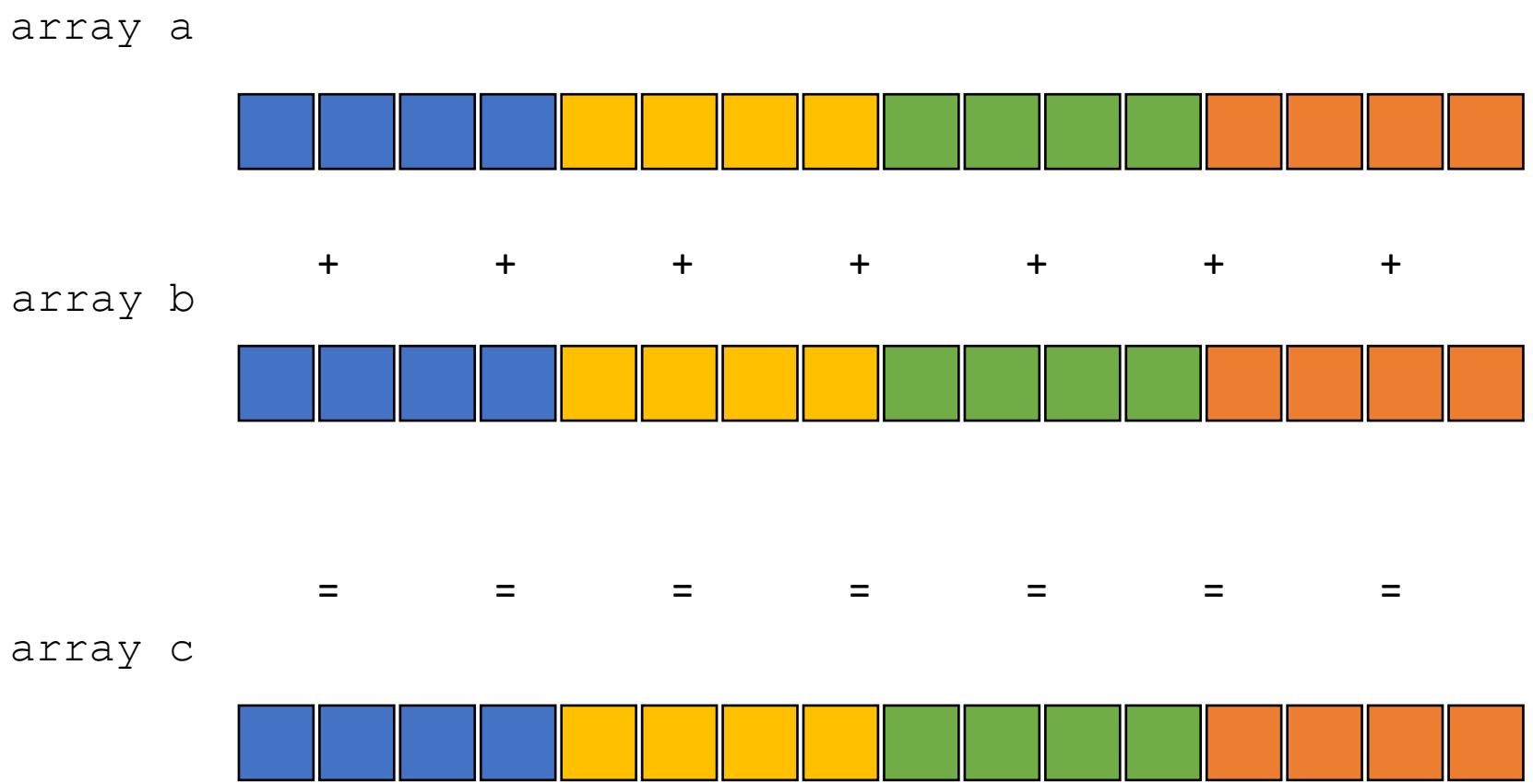
calling the function

```
vector_add<<<1,1024>>>(d_a, d_b, d_c, size);
```

Chunked Pattern

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

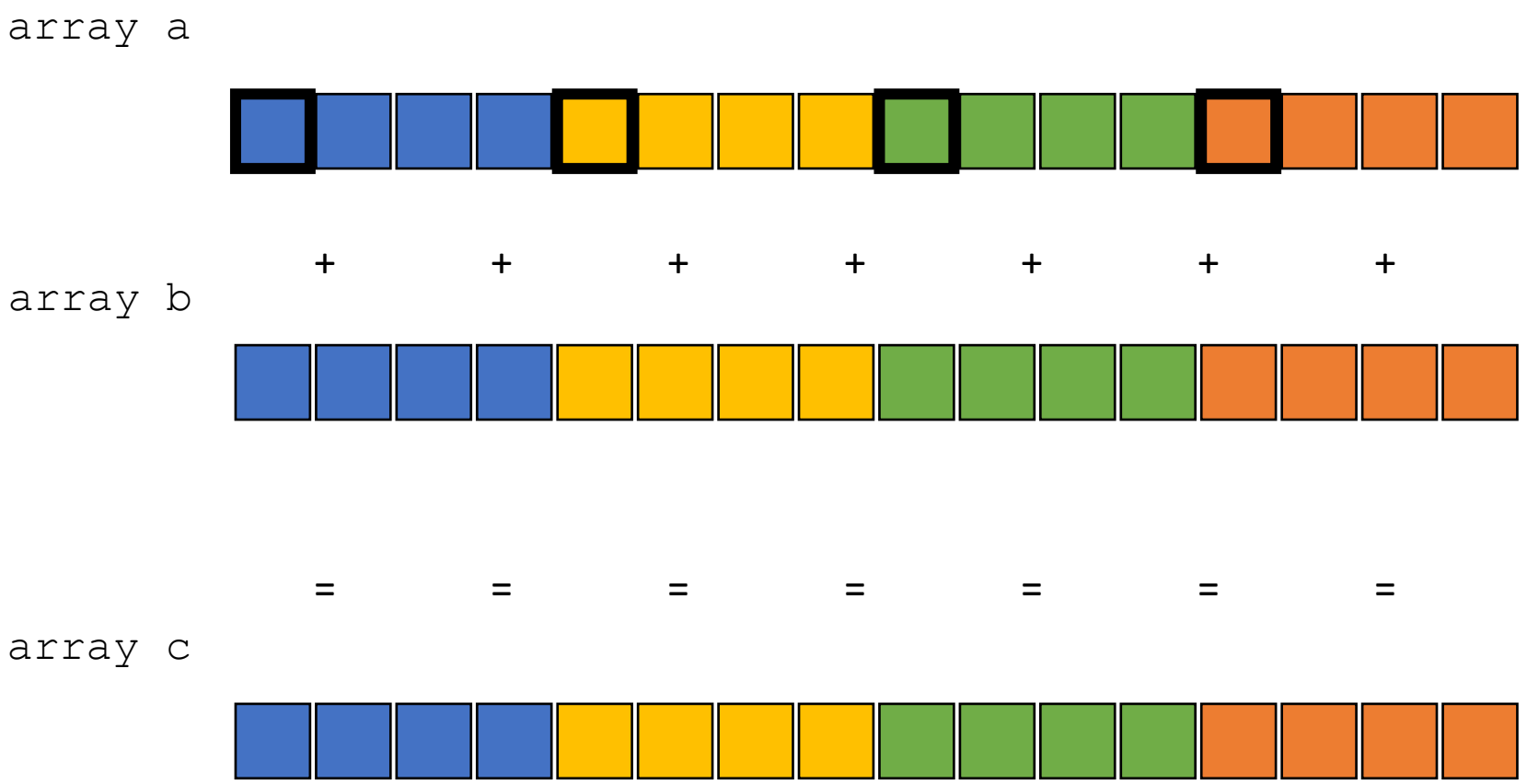


Chunked Pattern

the first element accessed by the 4 threads sharing a load store unit. What sort of access is this?

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

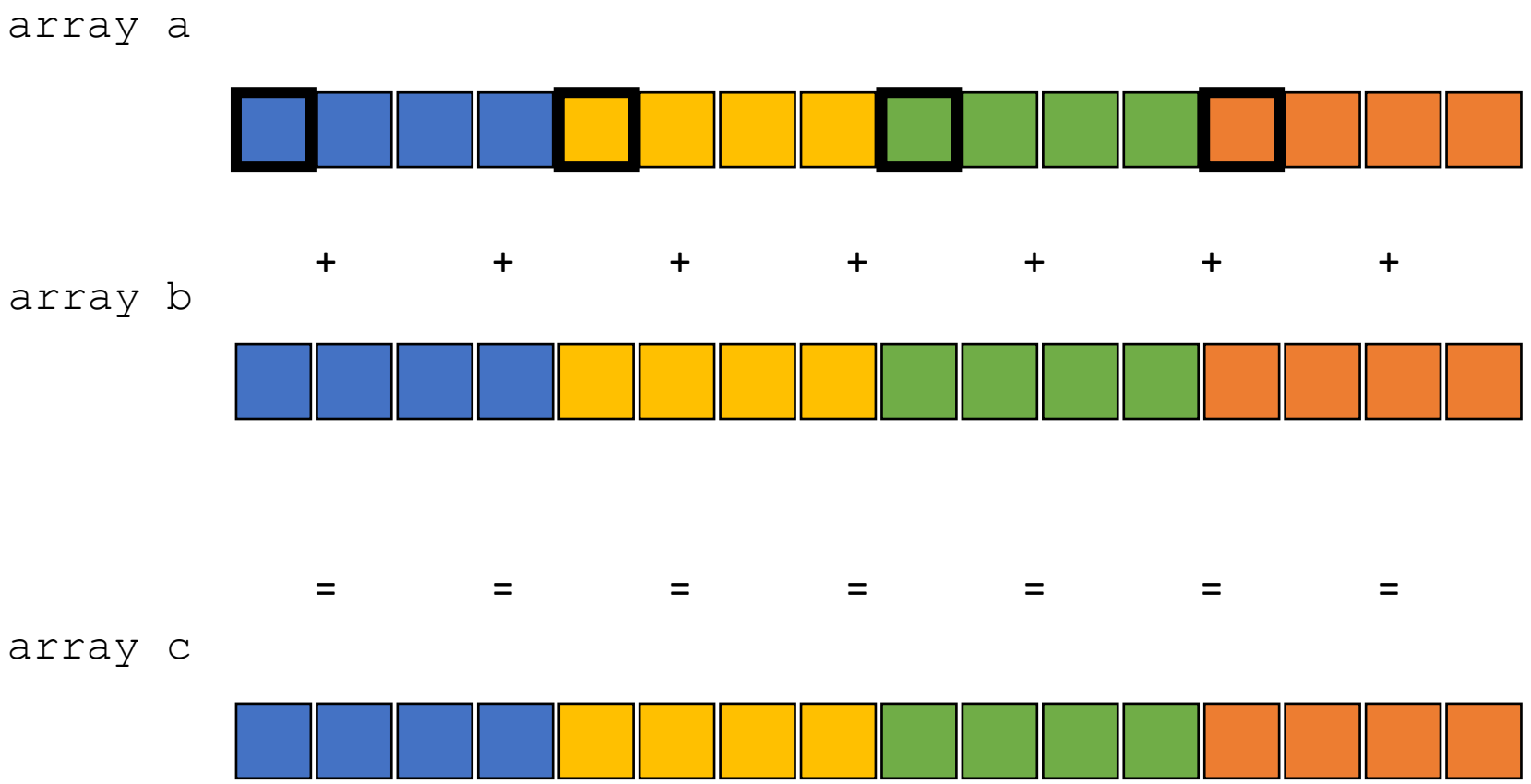


Chunked Pattern

the first element accessed by the 4 threads sharing a load store unit. What sort of access is this?

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

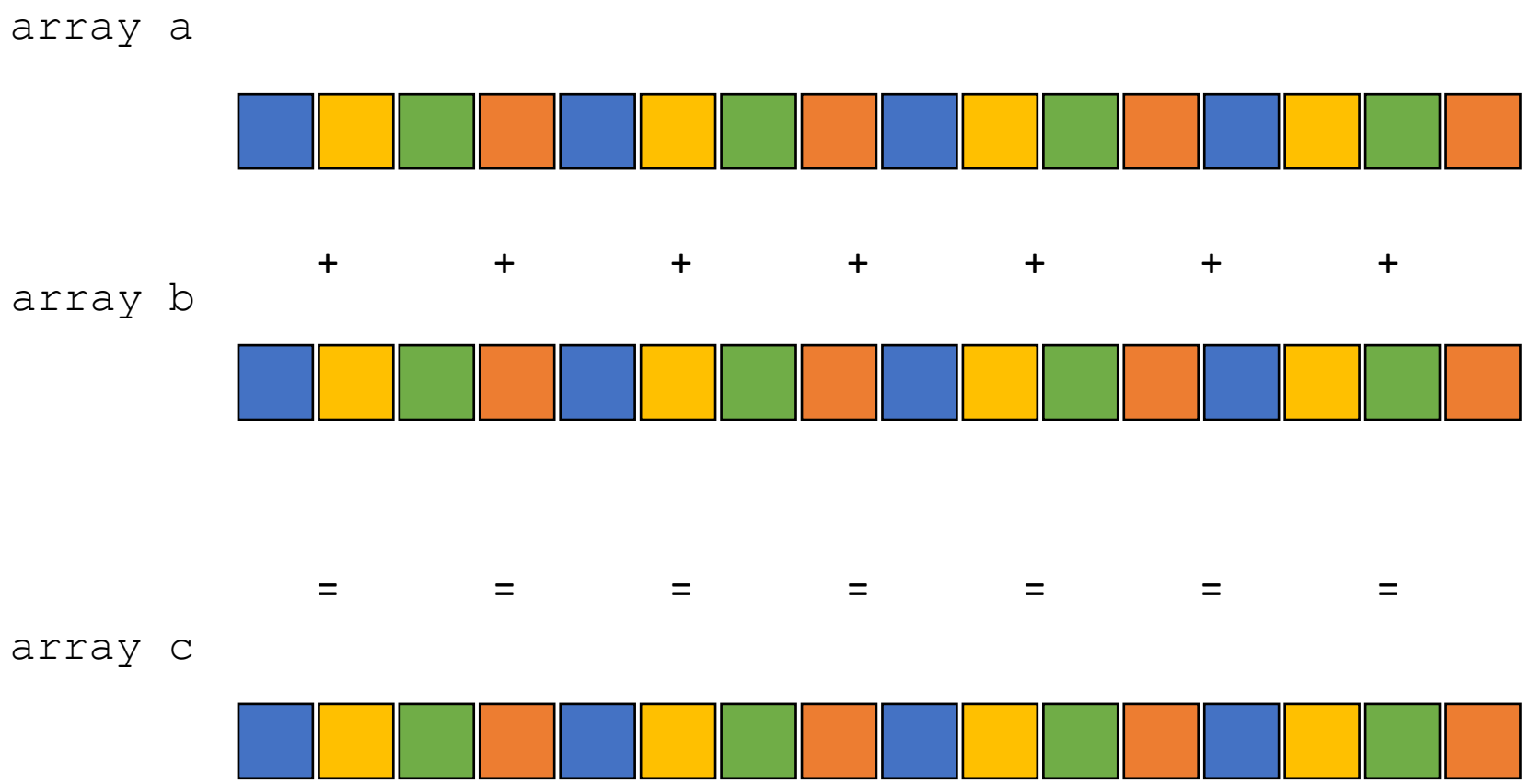


How can we fix this

Stride Pattern

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange

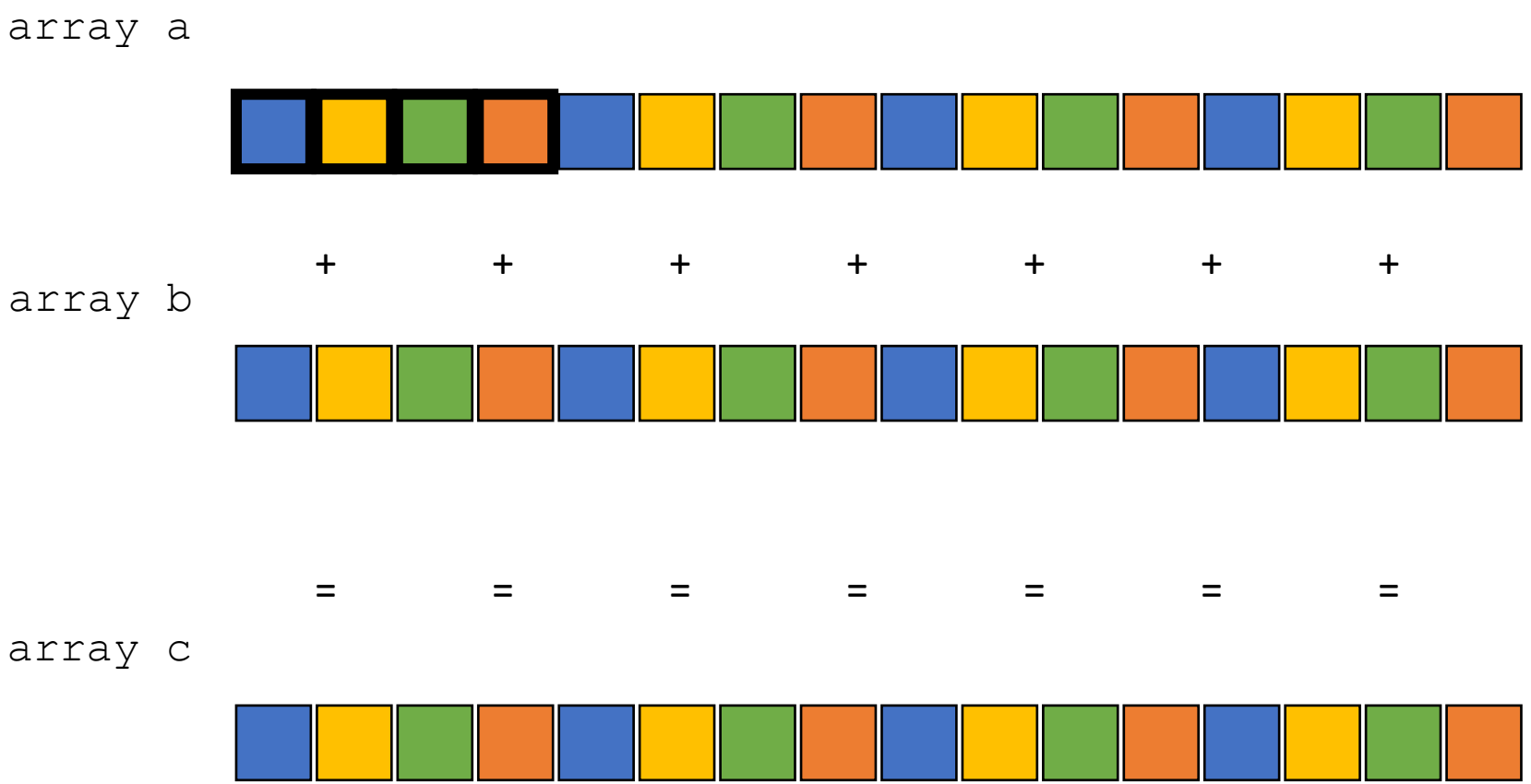


Stride Pattern

What sort of pattern is this?

Computation can easily be divided into threads

Thread 0 - Blue
Thread 1 - Yellow
Thread 2 - Green
Thread 3 - Orange



Go back to our program

```
__global__ void vector_add(int * d_a, int * d_b, int * d_c, int size) {
    int chunk_size = size/blockDim.x;
    int start = chunk_size * threadIdx.x;
    int end = start + end;
    for (int i = start; i < end; i++) {
      d_a[i] = d_b[i] + d_c[i];
   }
}
```

calling the function

Lets change this to a stride pattern

```
vector_add<<<1,1024>>>(d_a, d_b, d_c, size);
```

Go back to our program

```
__global__ void vector_add(int * d_a, int * d_b, int * d_c, int size) {
  for (int i = threadIdx.x; i < size; i+=blockDim.x) {
     d_a[i] = d_b[i] + d_c[i];
  }
}
```

calling the function

```
vector_add<<<1,1024>>>(d_a, d_b, d_c, size);
```

Coalesced memory accesses

This is about 4x faster.

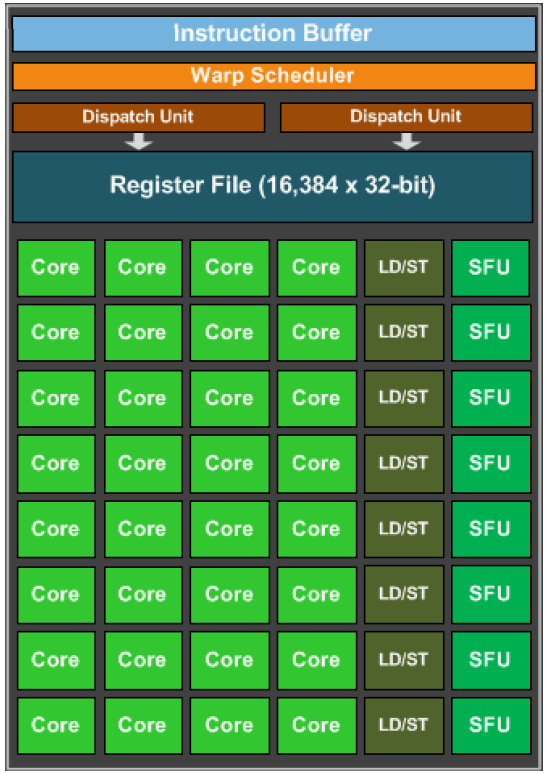
Coalesced memory accesses

This is about 4x faster.

What else can we do?

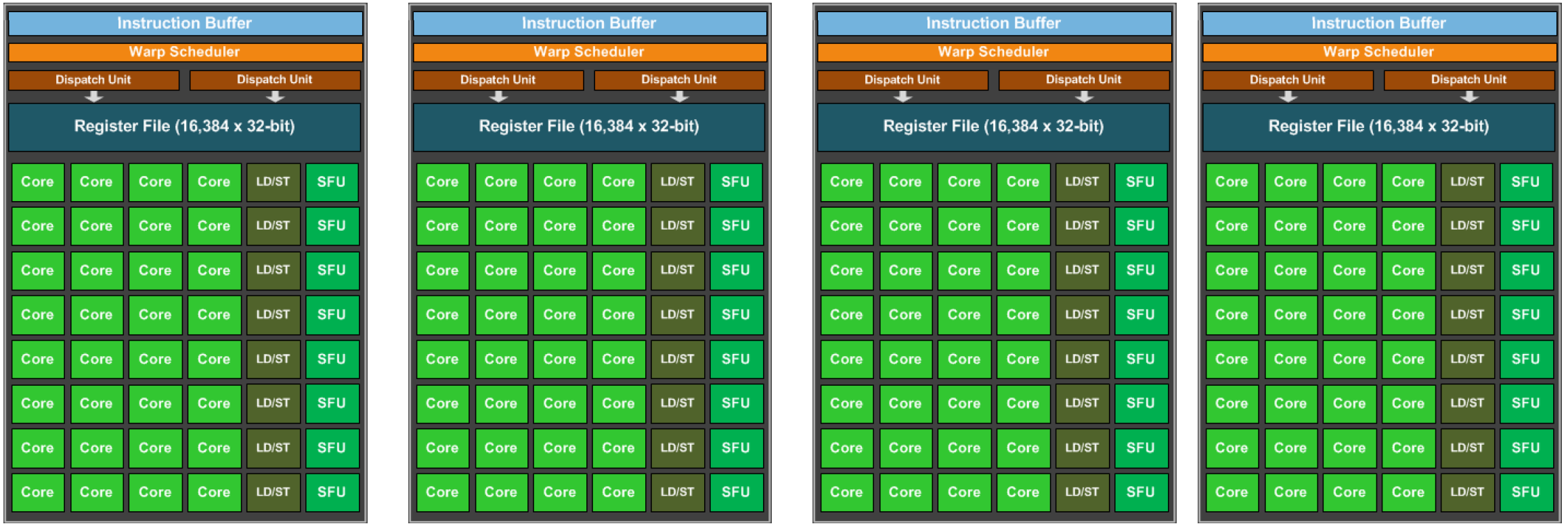
Multiple streaming multiprocessors

We've been talking only about 1 streaming multiprocessor, most GPUs have multiple SMs big ML GPUs have 32.



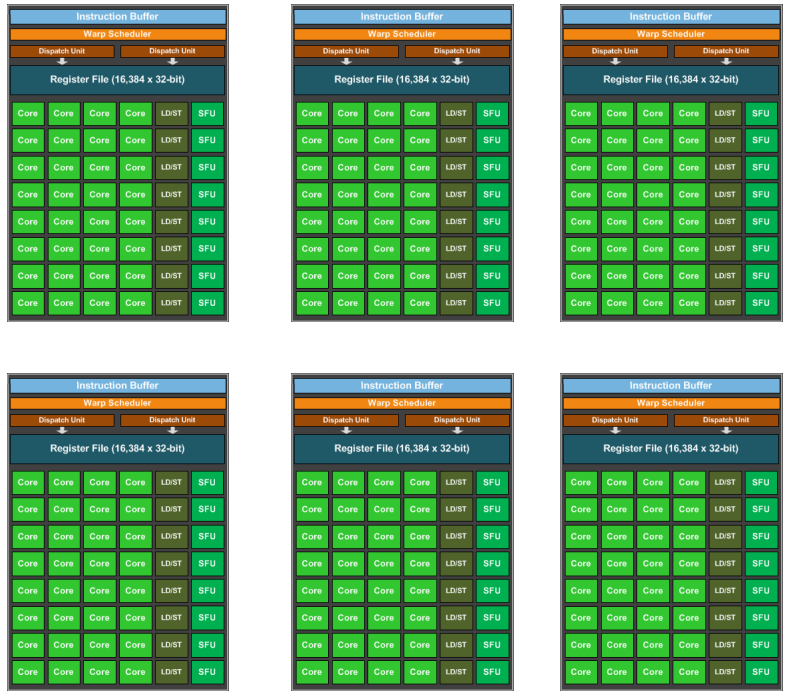
Multiple streaming multiprocessors

We've been talking only about 1 streaming multiprocessor, most GPUs have multiple SMs big ML GPUs have 32. This little GPU has 4



Multiple streaming multiprocessors

CUDA provides virtual streaming multiprocessors called **blocks**
They hide memory latency
Very efficient at launching and joining **blocks.**
No limit on blocks: launch as many as you need to map 1 thread to 1 data element



Go back to our program

```
__global__ void vector_add(int * d_a, int * d_b, int * d_c, int size) {
  for (int i = threadIdx.x; i < size; i+=blockDim.x) {
     d_a[i] = d_b[i] + d_c[i];
  }
}
```

calling the function

Launch with many thread blocks

```
vector_add<<<1,1024>>>(d_a, d_b, d_c, size);
```

Go back to our program

```
__global__ void vector_add(int * d_a, int * d_b, int * d_c, int size) {
  int i = blockIdx.x * blockDim.x + threadIdx.x;
  d_a[i] = d_b[i] + d_c[i];
}
```

blockIdx.x is the block id.
blockDim.x is the number of threads per block.
threadIdx.x is the thread id within block.

Need to recalculate some thread ids.

calling the function

```
vector_add<<<1024,1024>>>(d_a, d_b, d_c, size);
```

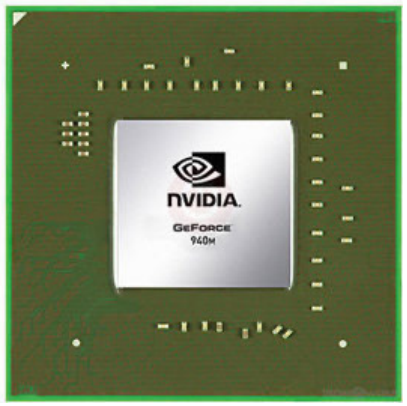
Launch with many thread blocks

Now we have 1 thread for each element

```
#define SIZE (1024*1024)
```

Final Round

Tiny GPU in an embedded system



Nvidia Jetson Nano (whole chip, CPU + GPU)
2 Billion transistors
10 TDP
Est. $99

Fight!

The CPU in my professor workstation

Intel i7-9700K
2.16 Billion transistors
95 TDP
Est. $316

https://www.techpowerup.com/gpu-specs/geforce-940m.c2648
https://www.alibaba.com/product-detail/Intel-Core-i7-9700K-8-Cores_62512430487.html
https://www.prolast.com/prolast-elevated-boxing-rings-22-x-22/

Final round

With 10x energy efficiency, GPU is as fast as CPU.
With the same energy efficiency, GPU is about 33x as CPU.

Consequences of Warps

```
__global__ void vector_add(float * d_a, float * d_b, float * d_c, int size) {
  int global_id = (blockIdx.x * blockDim.x) + threadIdx.x;
  if (global_id % 4 == 0)
      d_a[global_id] = d_b[global_id] + d_c[global_id];
  else if (global_id % 4 == 1)
      d_a[global_id] = d_b[global_id] * d_c[global_id];
  else if (global_id % 4 == 2)
      d_a[global_id] = d_b[global_id] / d_c[global_id];
  else if (global_id % 4 == 3)
      d_a[global_id] = d_b[global_id] - d_c[global_id];
}
```

Consequences of Warps

```
__global__ void vector_add_chunked(float * d_a, float * d_b, float * d_c, int size) {
  int global_id = (blockIdx.x * blockDim.x) + threadIdx.x;
  if (global_id < (size/4)*1)
      d_a[global_id] = d_b[global_id] + d_c[global_id];
  else if (global_id < (size/4)*2)
      d_a[global_id] = d_b[global_id] * d_c[global_id];
  else if (global_id < (size/4)*3)
      d_a[global_id] = d_b[global_id] / d_c[global_id];
  else if (global_id < (size/4)*4)
      d_a[global_id] = d_b[global_id] - d_c[global_id];
}
```

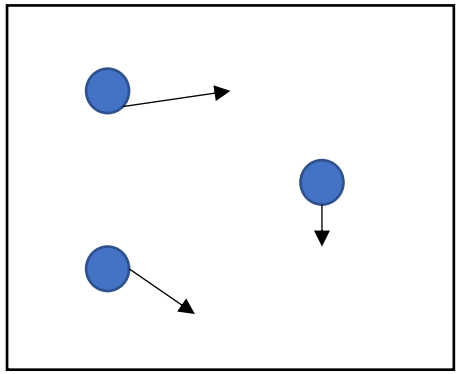
What is the right way to program GPUs?

- Still an open question!

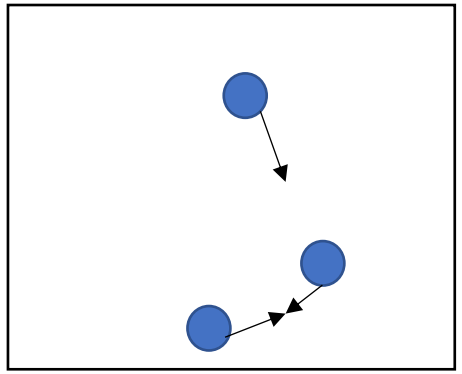
Homework 4 - first look

- Your assignment:
  - N-body simulation

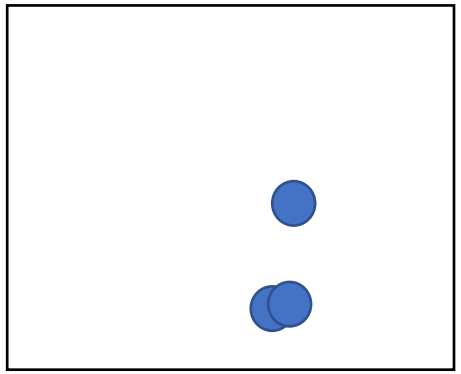
- Each particle interacts with every other particle



time = 0



time = 1

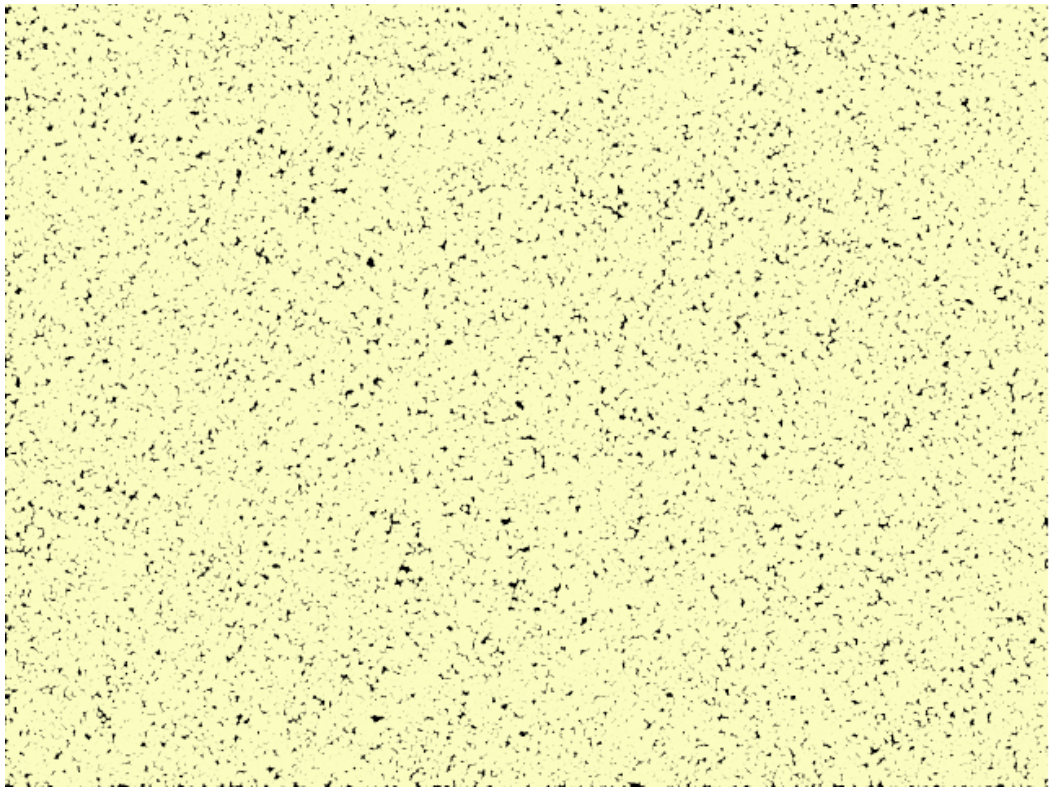


time = 2

Examples

- Gravity

- Boids:
  - https://en.wikipedia.org/wiki/Boids



Your homework

- N-body require a little bit of physics background so we will do something simpler.
  - If you want to explore with physics please feel free

- Local attraction clustering:
  - For each particle: find your closest neighbor
  - You can take one step in the x direction and one step in the y direction towards your closest neighbor.

Your homework

- Part 1 of your homework will do this on a single javascript thread

- Demo

Your homework

- Looks good, but with more particles, things start to go slower...

Your homework

- Looks good, but with more particles, things start to go slower...
- Part 2 of the homework is to implement with multiple CPU threads using javascript webworkers
  - Should get a linear speedup
- Part 3 is to implement with webGPU
  - Should get a BIG speedup!
- You need to explore how many particles you can simulate while keeping a 60 FPS framerate.

Homework 4 - first look

- Prerequisits
  - Google Chrome
  - Should be stable on Linux, Windows and Mac.

- No docker container for this assignment.

Homework 4 - first look

- Javascript shared array buffer:
  - How javascript threads can actually share memory
  - Similar to memory in C++

```
var buffer = new SharedArrayBuffer(Float32Array.BYTES_PER_ELEMENT * NUM);
var array = new Float32Array(buffer);
```

Shared Array Buffer

- Like Malloc, allocates a ”pointer” to a contagious array of bytes
- Can pass the “pointer” to different threads
- Need to instantiate a typed array to access the values

Web Workers

- How to do multi-threading in javascript

- Async
  - Concurrent (executes on the same thread)
  - Good for I/O and user interactions

- Web Workers will execute on multiple cores
  - Better for compute intensive applications
  - Better performance

How to use?

- Create a new worker with a file
  - Doesn’t do anything yet
- File contains a function: “on message”
- Main file calls “post message” along with arguments to start the thread
- Worker sends a message back to the main file, it can catch the data

WebGPU

- The language is wgsl (WebGPU Shading Language)
  - It is new, there are not many examples (and the specification changes!)
  - Official specification is here: https://www.w3.org/TR/WGSL/

WebGPU

- wgsl is NOT javascript
- Javascript is interpreted: not possible on GPUs
- wgsl is compiled
  - into Vulkan on Linux
  - into Metal on Apple
  - into HLSL on Windows
- No printing (so GPU code can be difficult to debug)

WebGPU

- variables (optional types):

var <name> = <value>;

```
var cluster_dist = 3.0;
```

```
var <name> : <type> = <value>;
var cluster_dist : f32 = 3.0;
```

WebGPU

- types:
  - i32
  - u32
  - f32
  - vec2<f32>
  - array<*type*>
- structures
- Built-ins (global id)

```
struct Particle {
    pos : vec2<f32>;
};
```

```
struct Particles {
    particles : array<Particle>;
};
```

```
var index_pos : vec2<f32> = particlesA.particles[index].pos;
```

```
var index : u32 = GlobalInvocationID.x;
```

you have one thread for each particle!

WebGPU

- Built in functions:
  - arrayLength
  - sqrt
  - pow
  - distance

WebGPU

For loops:

```
for (var i : u32 = 0u; i < arrayLength(&particlesA.particles); i = i + 1u) {
...
}
```

WebGPU

- Types can be frustrating

- But compiler errors will help you, and you can do casts.