Bounds Checking on GPU

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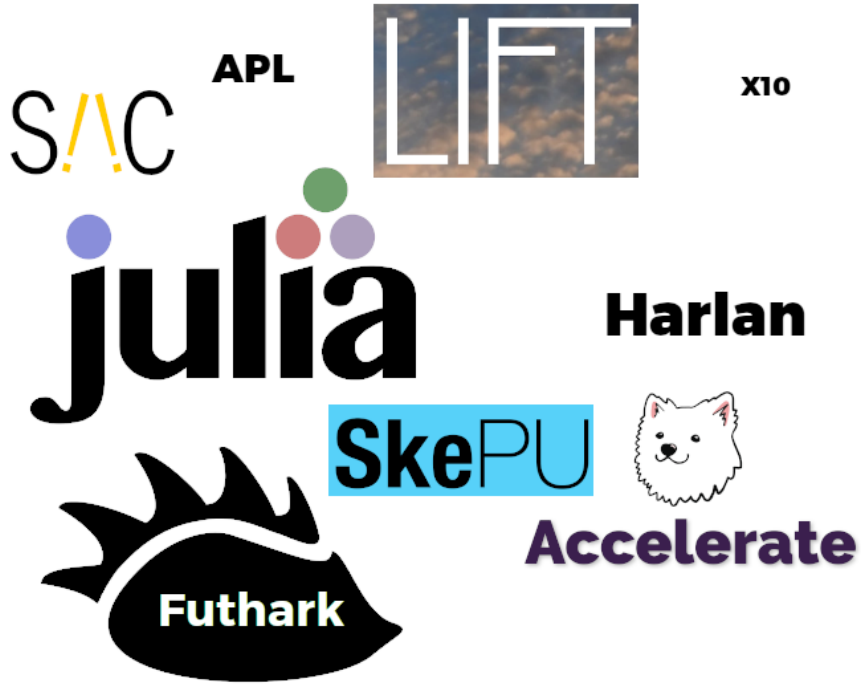
We have many nice high-level languages for GPUs!



- **Provide all you're used to from high level languages!**
- Abstracts low-level hardware details, memory management, race conditions...
- Safe and productive!

Well, almost safe...

A shared limitation

None of these languages provide bounds checking on GPUs (although some do when generating non-GPU code)

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- Bounds checking only helps **incorrect programs**
- **Slows down** correct programs
- Not obvious how to implement on GPU

Compilers are not very motivated to implement an optional feature that helps wrong programs and wrong good programs.

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Compilers are not very motivated to implement an optional feature that helps wrong programs and wrong good programs.

(Also: many high-level languages mainly use *bulk operations* such as `map` and `reduce`, which are index-correct by construction.)

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I will present an implementation technique for adding bounds checking to high-level parallel languages that target GPUs.

So what's the problem?

On a CPU, bounds checking is trivial.

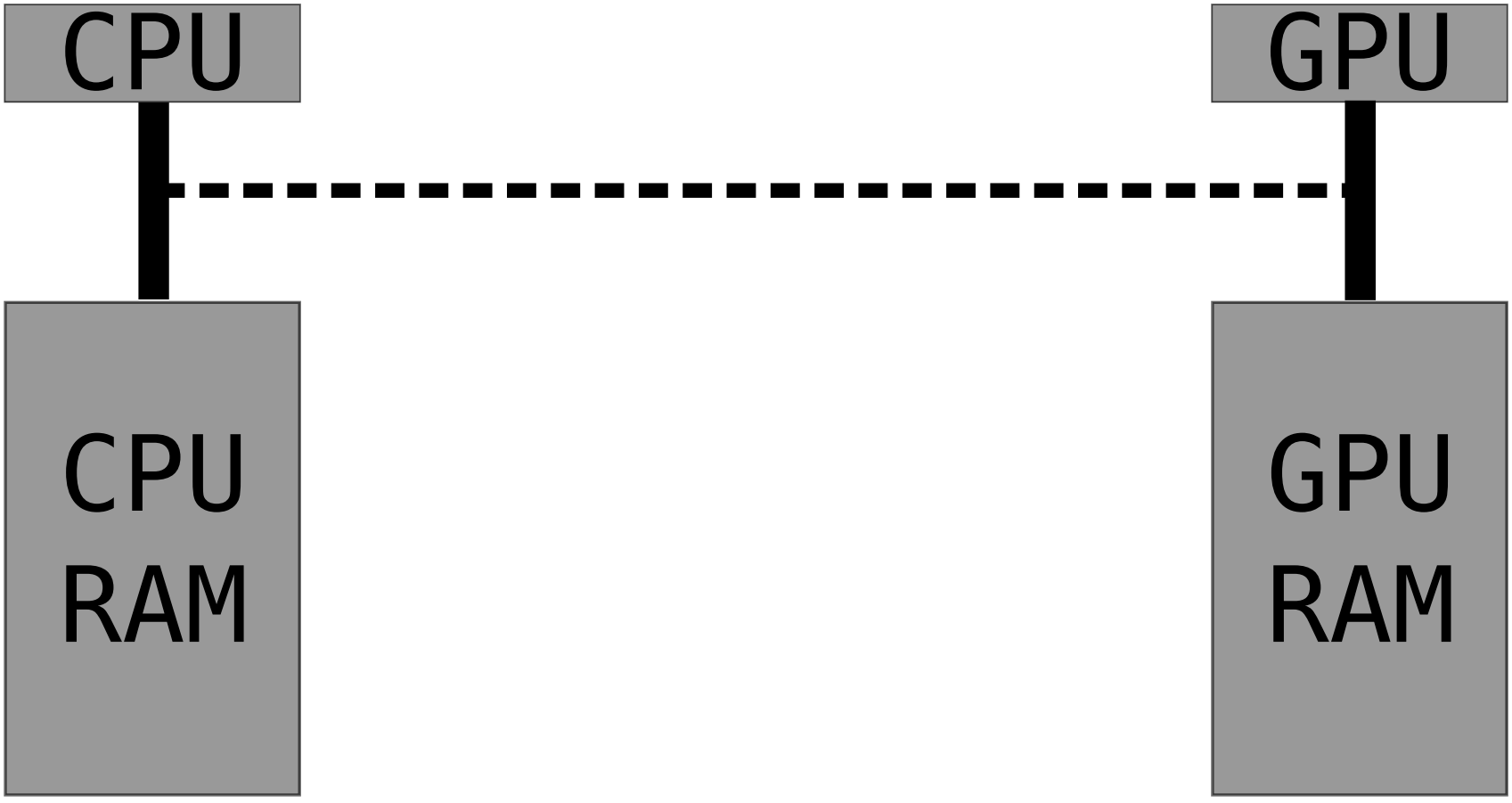
```
if (i < 0 || i > n) {
  // throw exception

  // OR print error message

  // OR terminate program

  // OR do anything else
}
```

Let's look at the conceptual GPU execution model to see why it's more difficult there.


CPU
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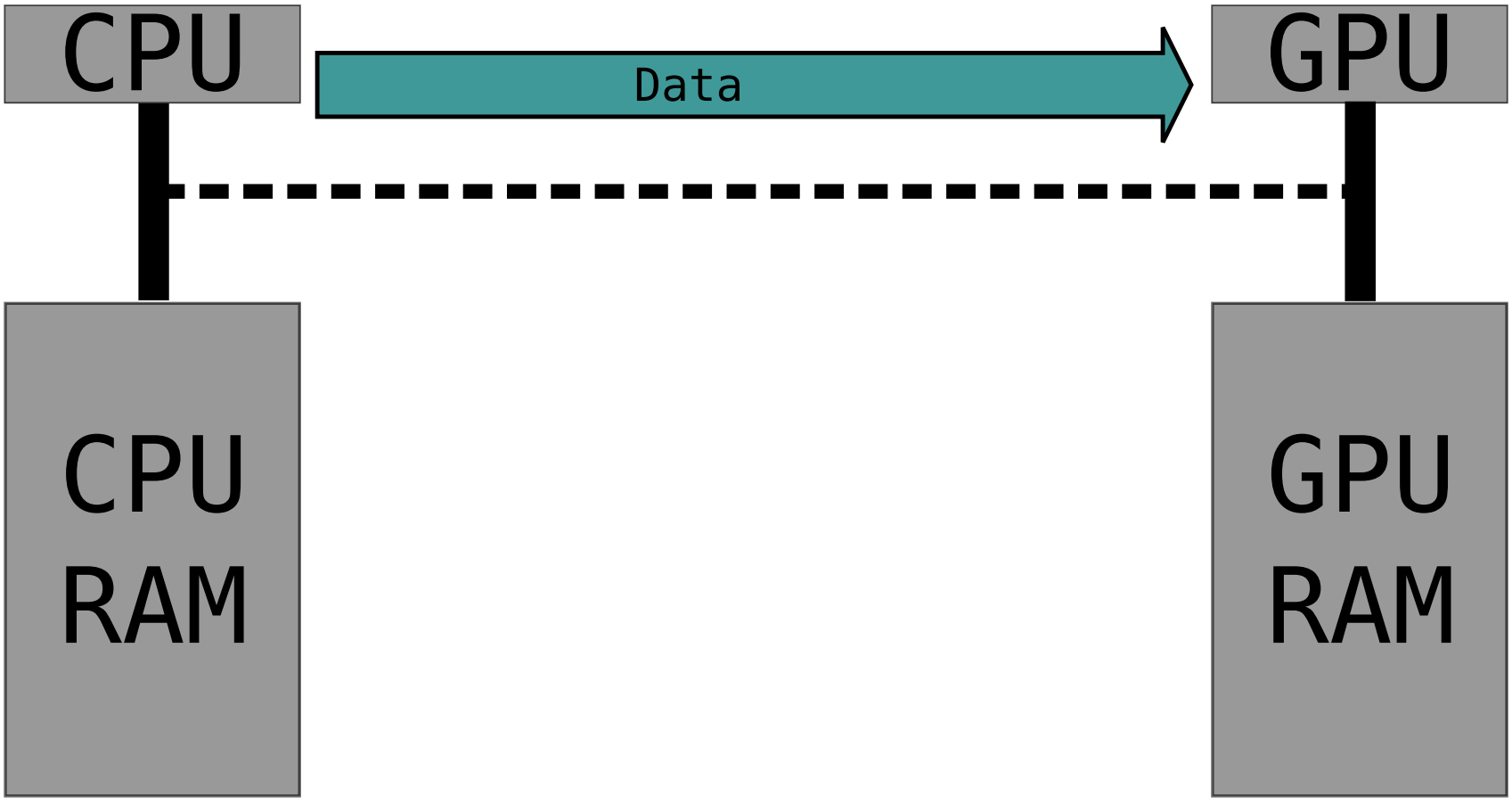
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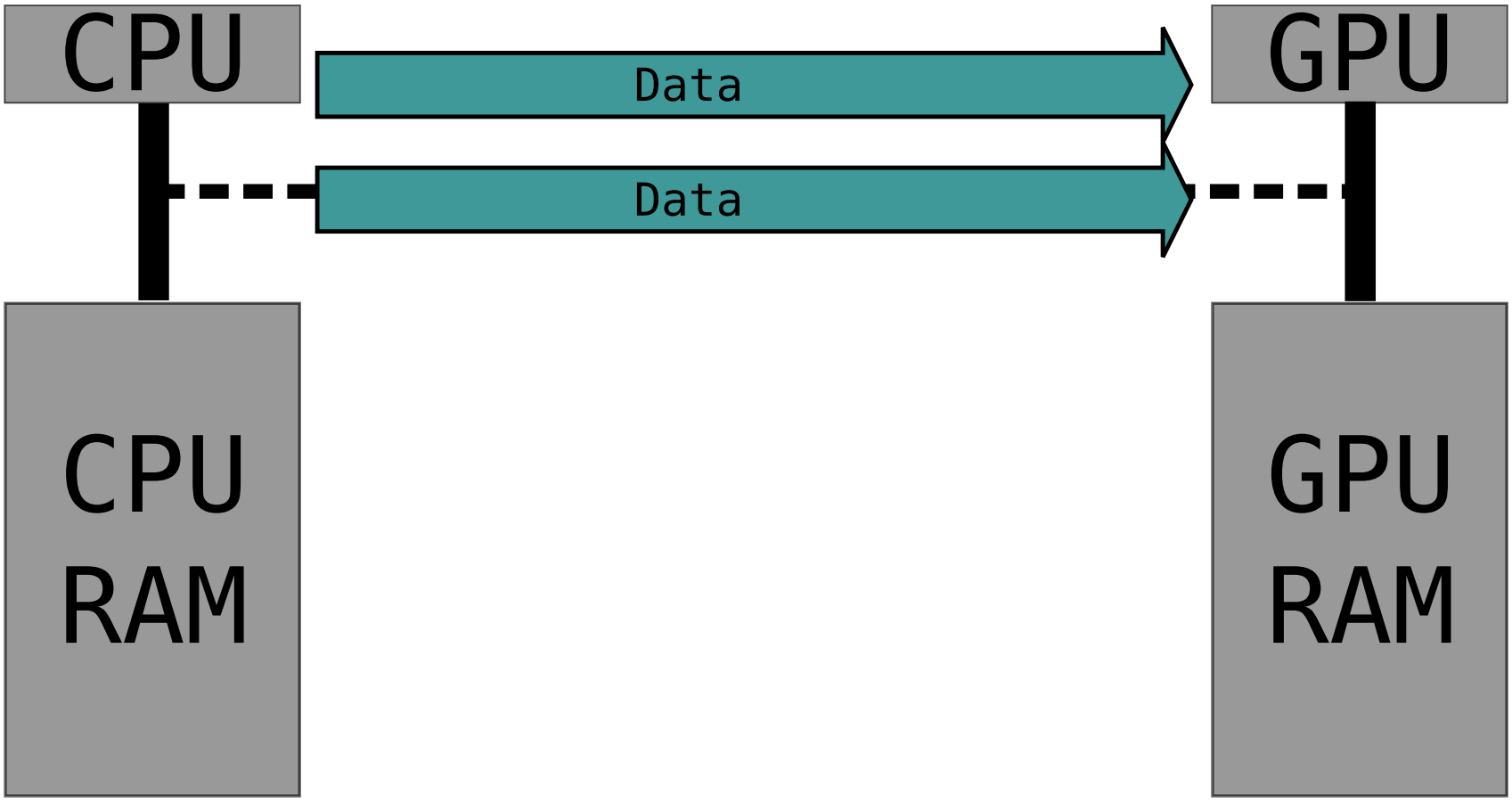
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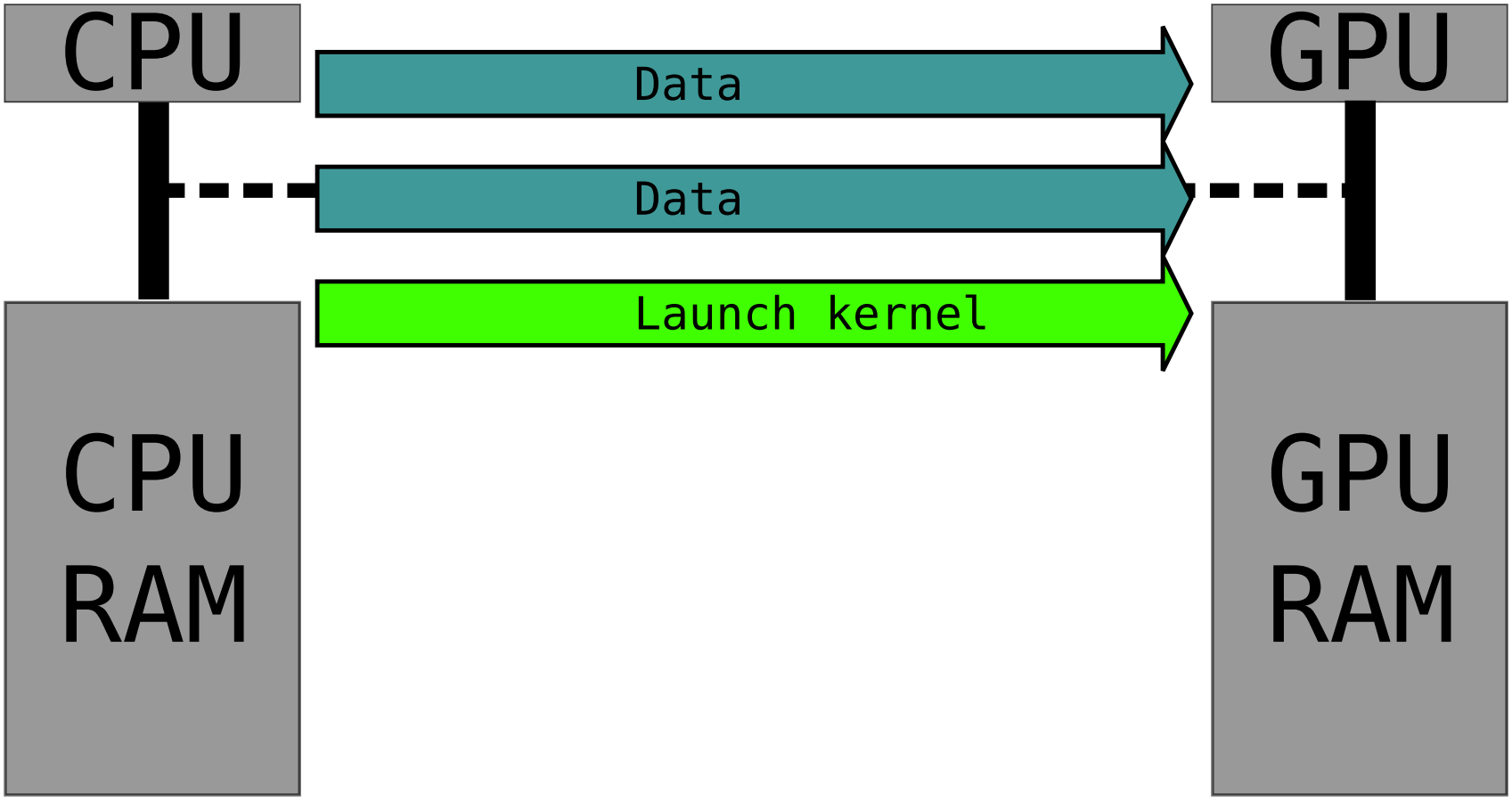
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Launch kernel
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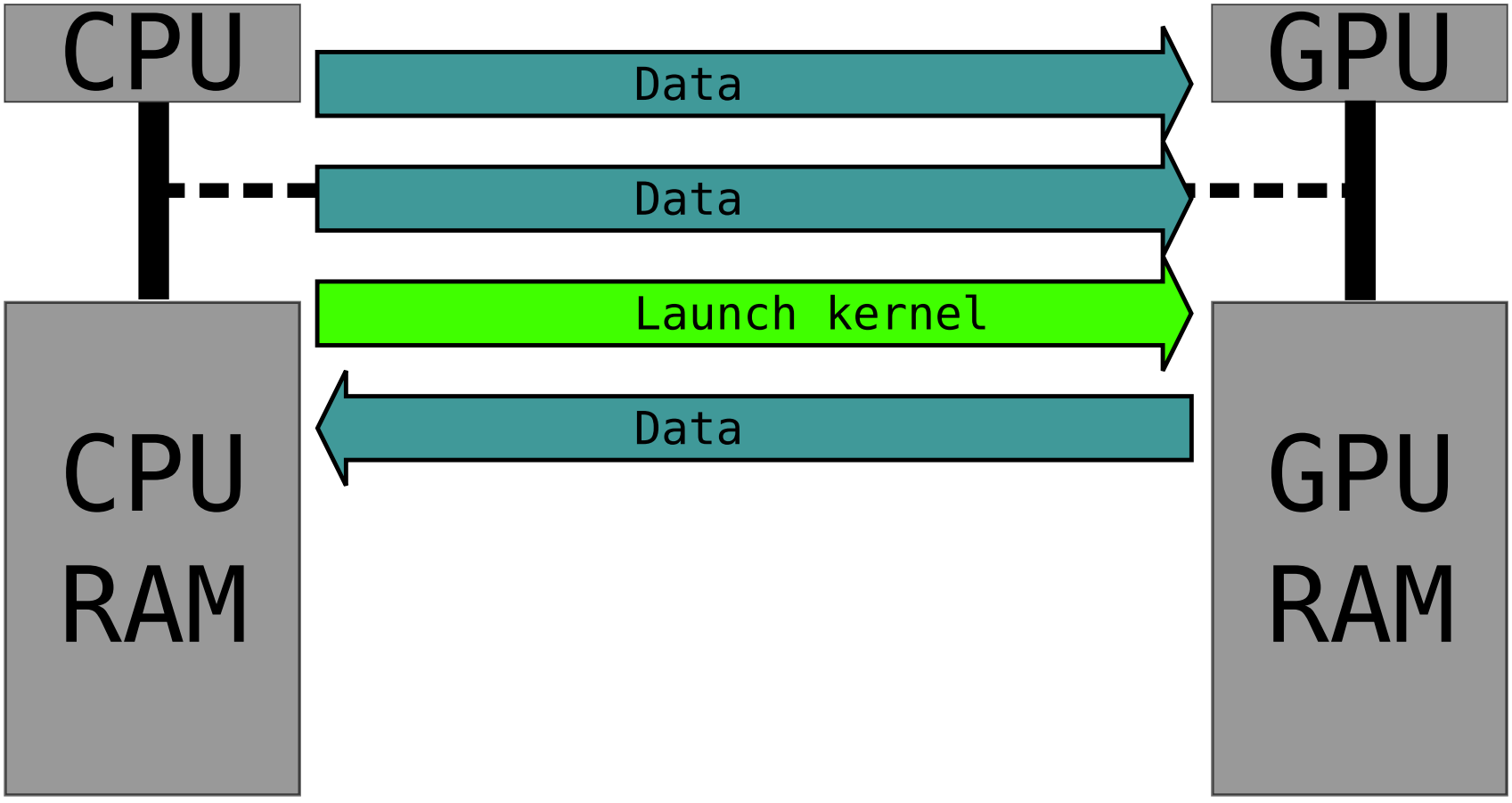
CPU
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Launch kernel
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RAM
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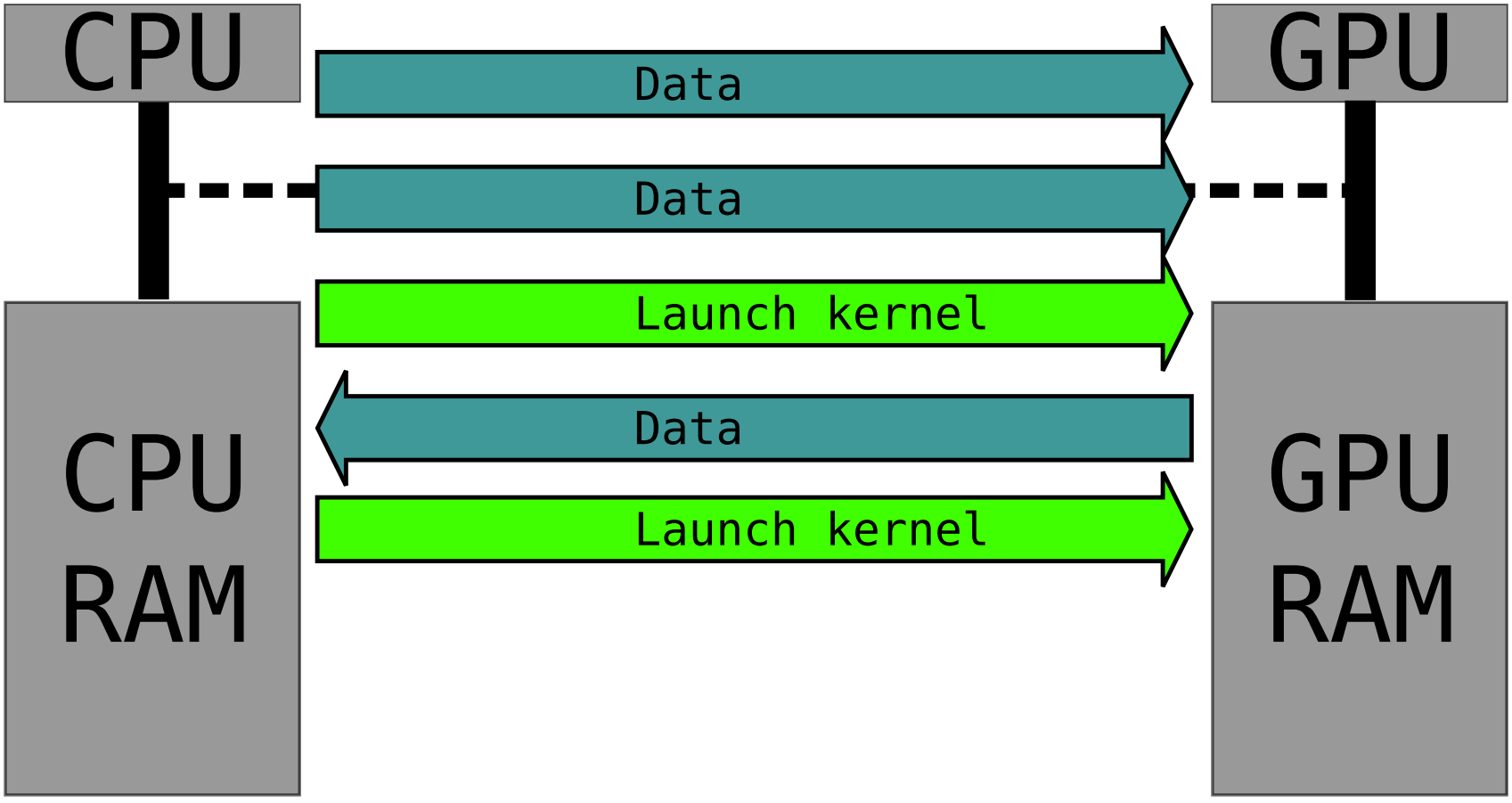
CPU
GPU
Data
Data
Launch kernel
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CPU
RAM
GPU
RAM

The basic problem

The GPU is a co-processor, and the CPU can neither directly control it, not be controlled by it.

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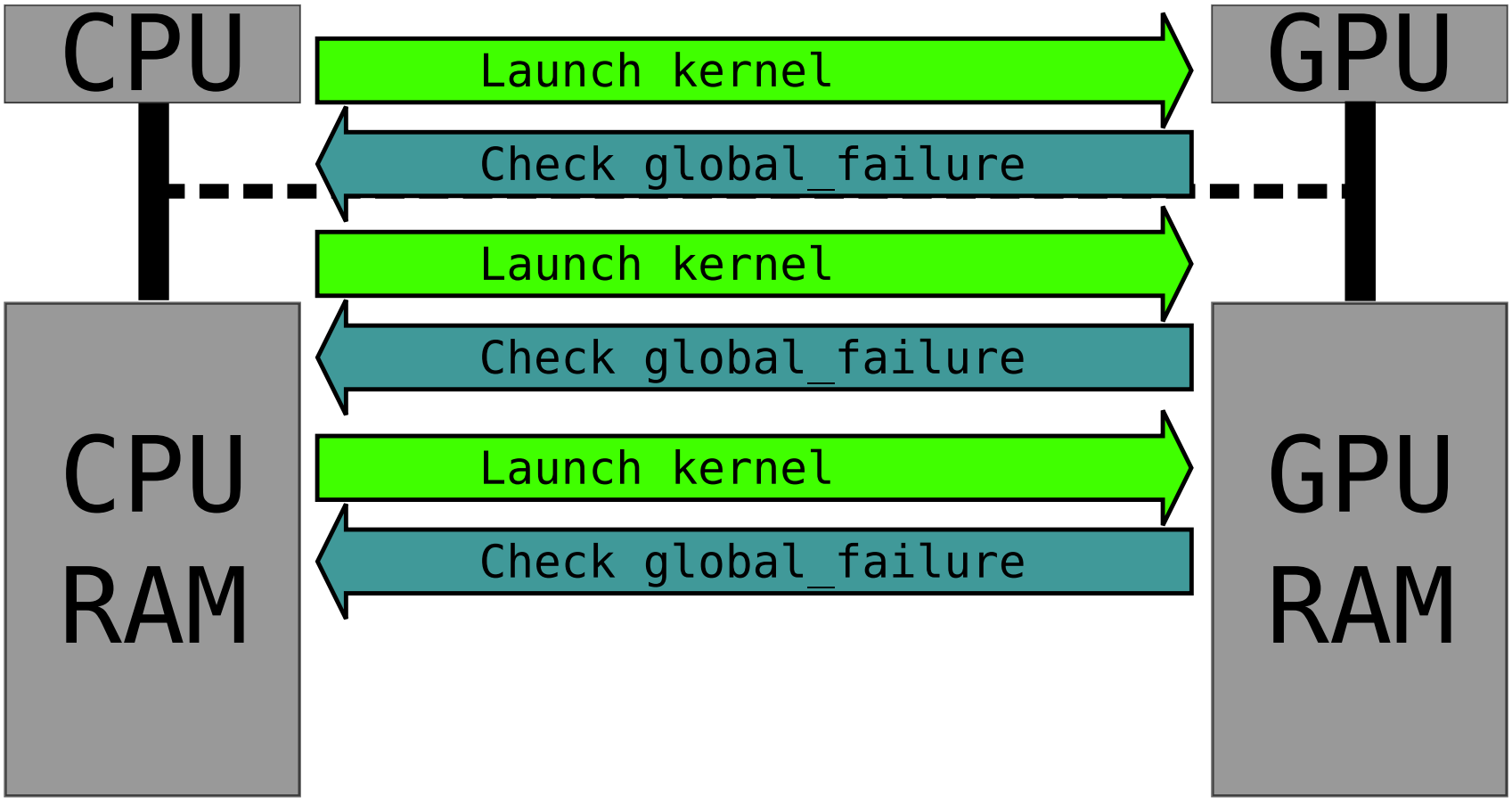
Solution idea

Whenever a bounds check on the GPU fails, write to a known location in GPU memory, and copy the value at that location back to the CPU after every GPU kernel.

```
if (i < 0 || i >= n) {
  *global_failure = 1;
  return;  // Terminate GPU thread
}
```



Surely reading a single byte after every kernel (which usually processes tens of thousands of elements) must be fast?

Some experimental evaluation

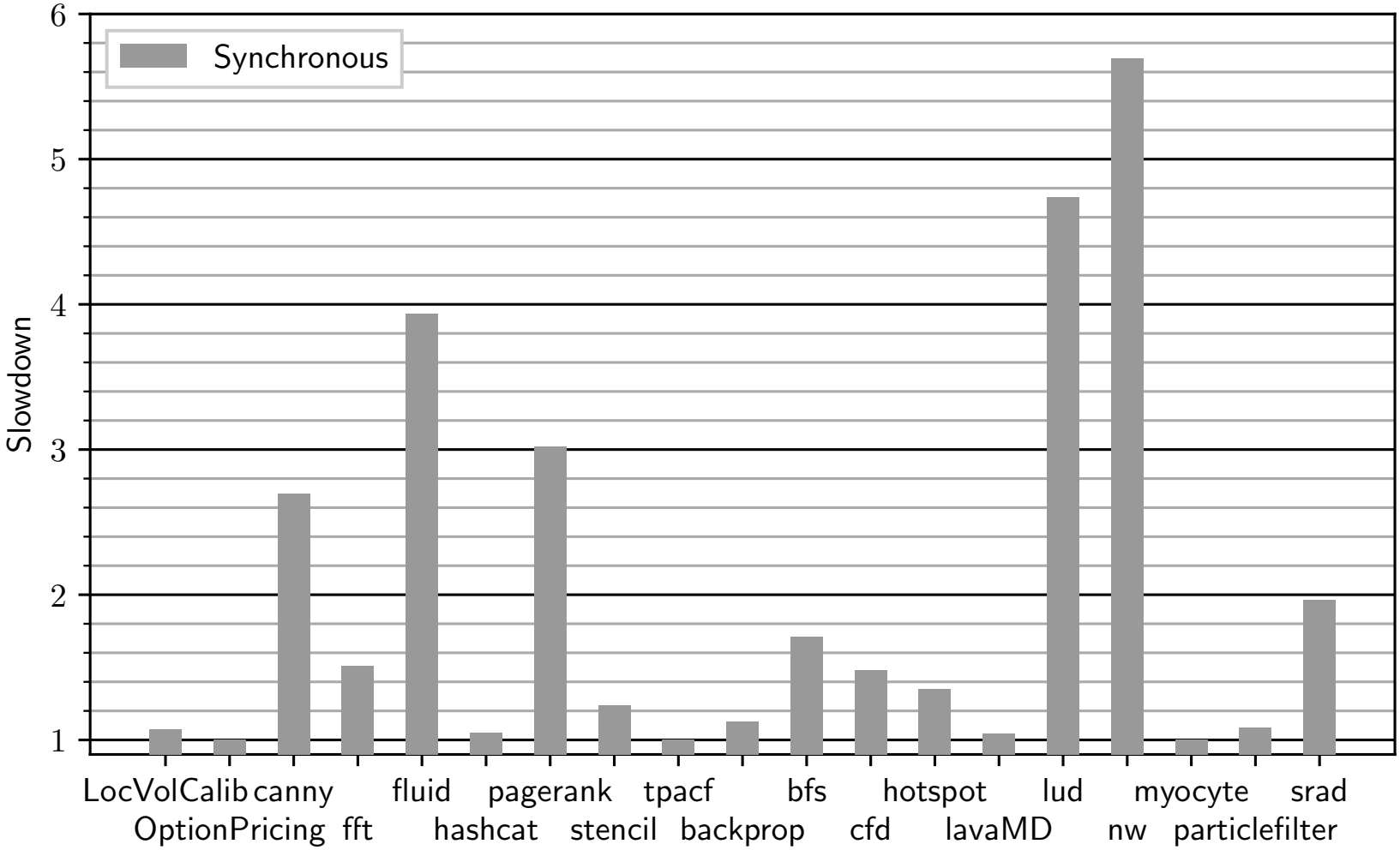
Experimental setup

- NVIDIA RTX 2080 Ti GPU (and an AMD GPU in the paper)
- Bounds checking implemented in the compiler for *Futhark*
- Bounds checking overhead measured on the Futhark benchmark suite

But note that the technique is not Futhark-specific in any way—only the concrete implementation

- The Futhark benchmark suite contains 41 programs, of which 19 require bounds-checking in GPU code
- We will show overhead of bounds checking on these

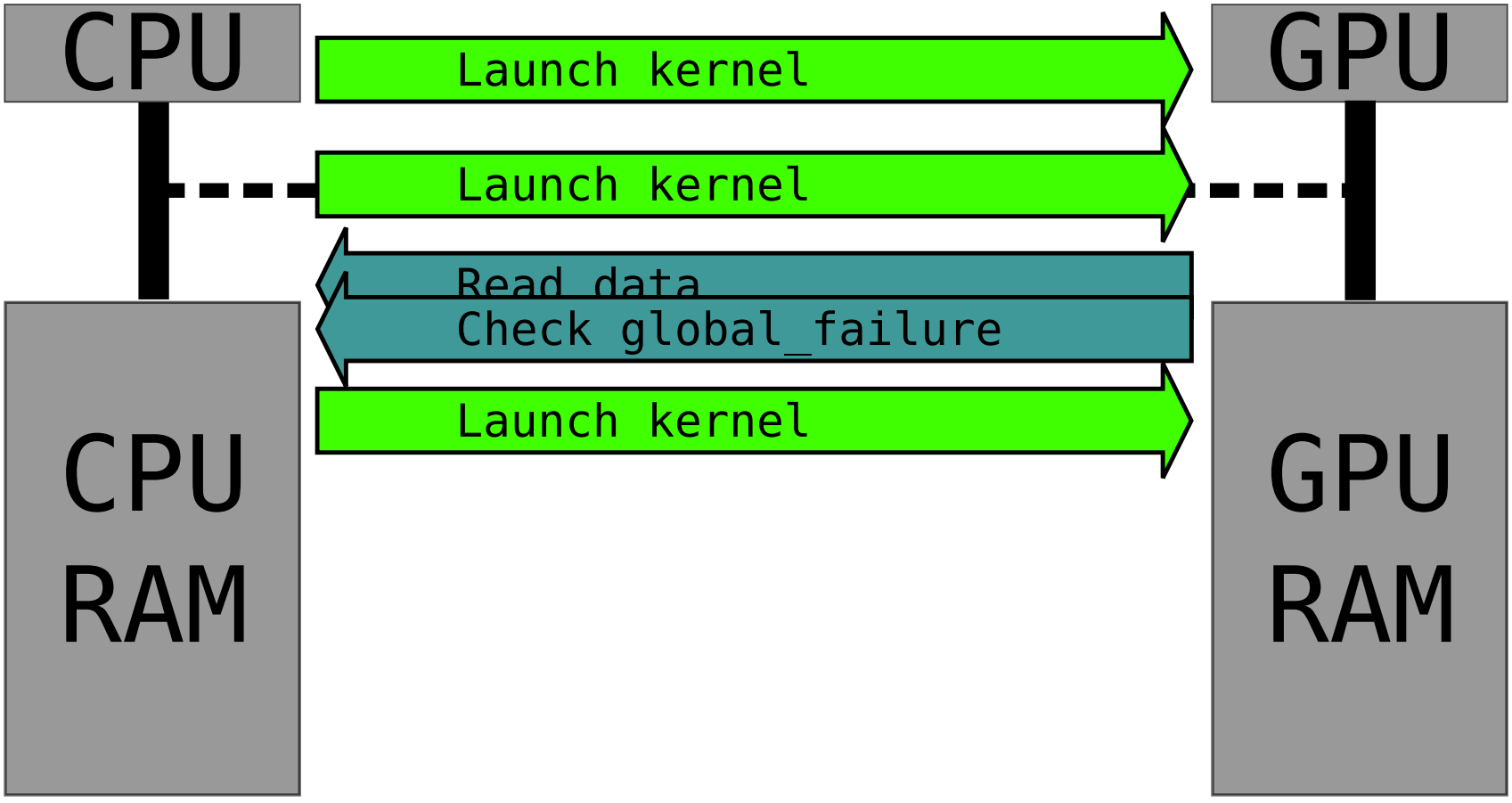
Overhead of fully synchronous bounds checking



- Geomean overhead of 1.66 ×
- Max overhead exceeding 5 ×
- **Not viable**

The problem

- GPUs (viewed from the CPU) are **asynchronous machines** where we provide a *queue* of work
- Constantly halting the GPU to inspect a boolean is wasteful
- We should only check `global_failure` when we need to get data from the GPU anyway for other purposes


CPU
GPU
Launch kernel
Launch kernel
Read data
Check global_failure
Launch kernel
CPU
RAM
GPU
RAM

What if kernel $i + 1$ is *only* safe to run if kernel i ran succesfully?

How do we efficiently ensure that failures in one kernel prevent later kernels in the queue from running?

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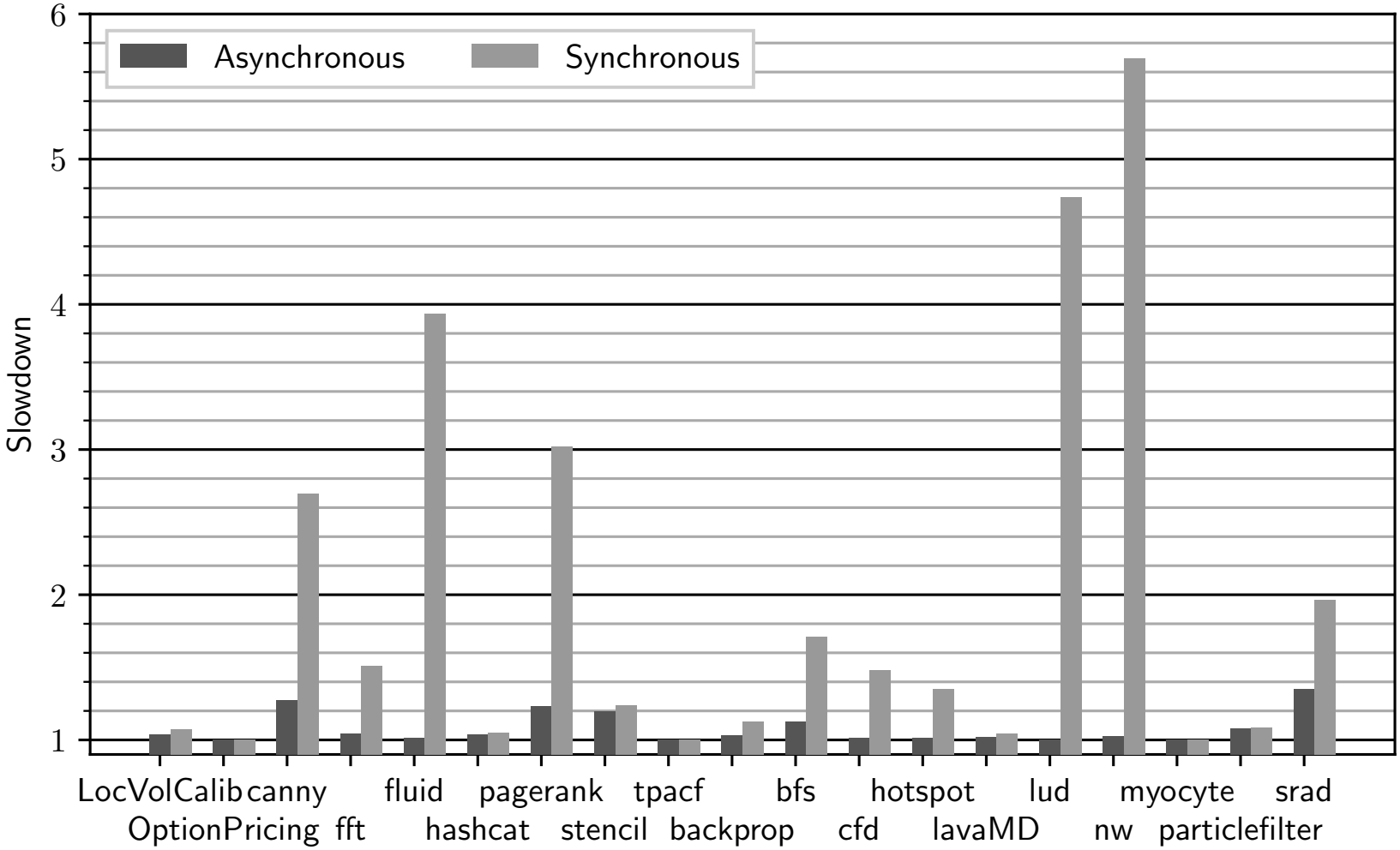
How do we efficiently ensure that failures in one kernel prevent later kernels in the queue from running?

Answer: put a check into each GPU kernel itself!

```
// Prelude added to every GPU kernel
if (*global_failure) {
  return;
}
```

- To the GPU, the work queue is processed as normal
- But after the first failure, all kernels just exit immediately

Overhead of asynchronous bounds checking



- Geomean overhead of 1.07 × (vs 1.66 ×)
- Max overhead about 1.4 × (over 5 × before)
- **Viable**

What about error messages?

Error messages with 1 bit of information is not good enough.

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Solution: at compile time, produce a table in CPU RAM mapping each distinct *failure point* to a `printf()` style format string.

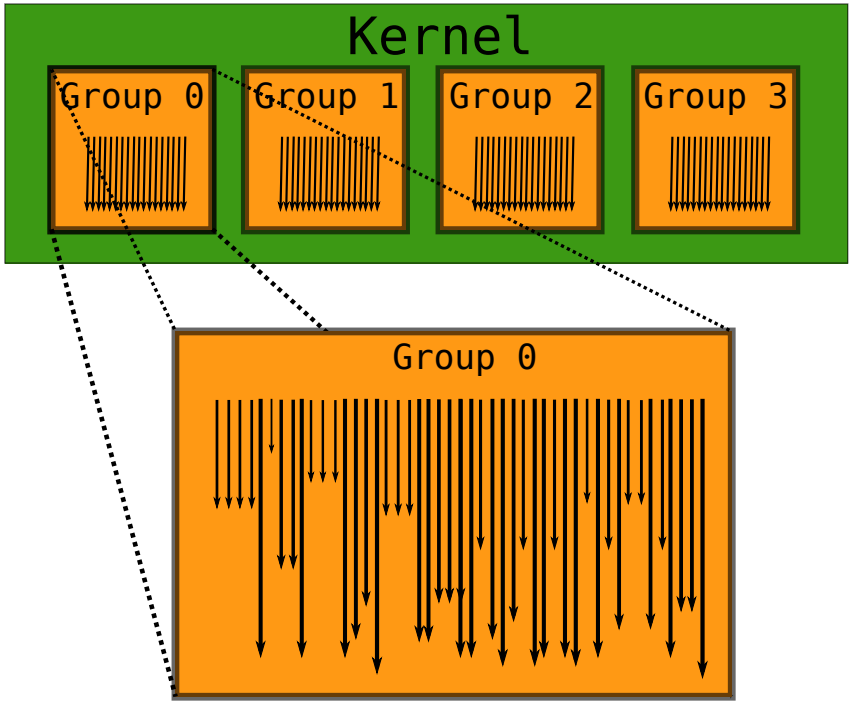
```
const char *errors[] =
  { "line 10: index %d invalid for array of size %d",
    "line 17: division by zero",
    "line 42: index %d invalid for array of size (%d,%d)" }
```

On failure, write arguments to GPU array.

```
if (i < 0 || i >= n) {
  if (atomic_cmpxchg(global_failure, -1, 0) < 0) {
    global_failure_args[0] = i;
    global_failure_args[1] = n;
  }
  return; // stop thread
}
```

Now `global_failure` is an index into an array of error messages.

Problem: threads are not actually isolated



- Threads within a group can communicate through memory
- Synchronisation through **barriers**, which block the thread until all threads in the group have reached the barrier

Barrier rule: if *one* thread in a group reaches `barrier()`, then *all* threads must eventually reach it.

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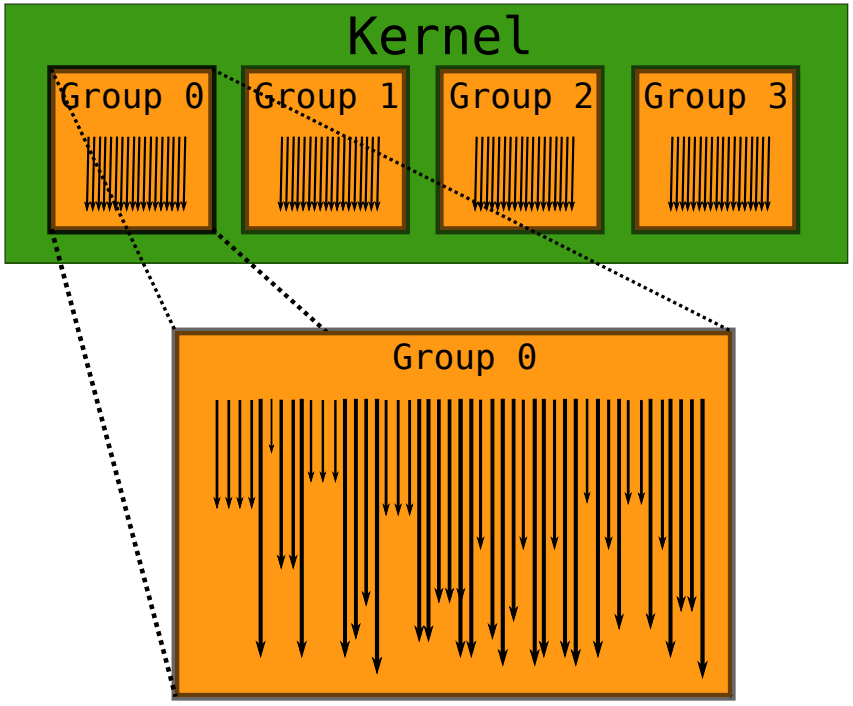

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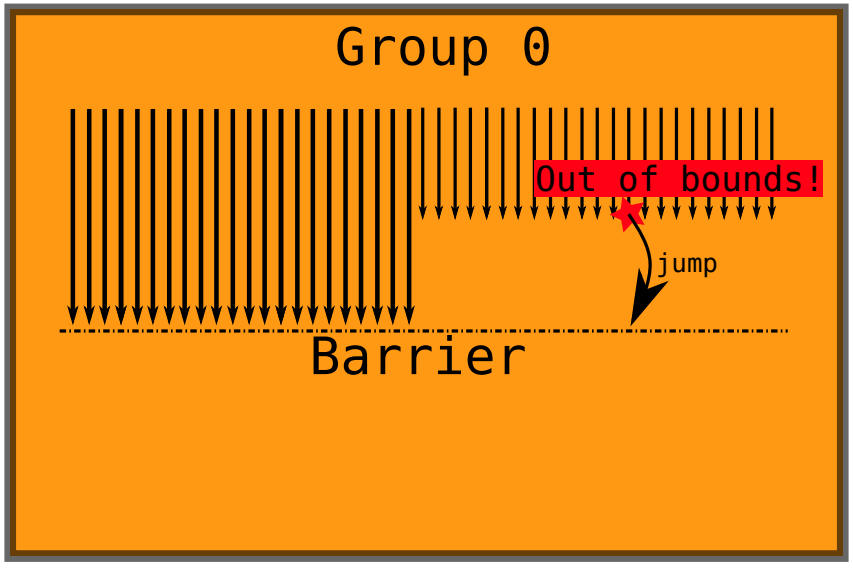
Barrier rule: if *one* thread in a group reaches `barrier()`, then *all* threads must eventually reach it.

Consequence: a GPU thread cannot unilaterally just terminate itself—and prevailing GPU APIs provide *no* sound way for abnormally terminating a running kernel!

```
1  kernel sum(int *global_failure,
2             int n, int *js,
3             int m, int *vs,
4             ...) {
5    local int sums[GROUP_SIZE];
6    int i, gtid, ltid, k, acc; ...
7    for (i = gtid; i < n; i += k) {
8      int j = js[i];
9      if (j < 0 || j >= m) {
10       *global_failure = 1;
11       return; // What if another thread has reached the barrier?
12     }
13     acc += vs[j];
14   }
15
16   sums[ltid] = acc;
17
18
19   barrier();
20
21
22
23
24
25   // Perform parallel
26   // reduction of sums...
27 }
```

Avoiding barrier divergence

Instead of `return`ing from the kernel, a failing thread should jump to the next `barrier()`.



After the barrier, we then check whether any threads have failed.

We call this a *synchronisation point*.

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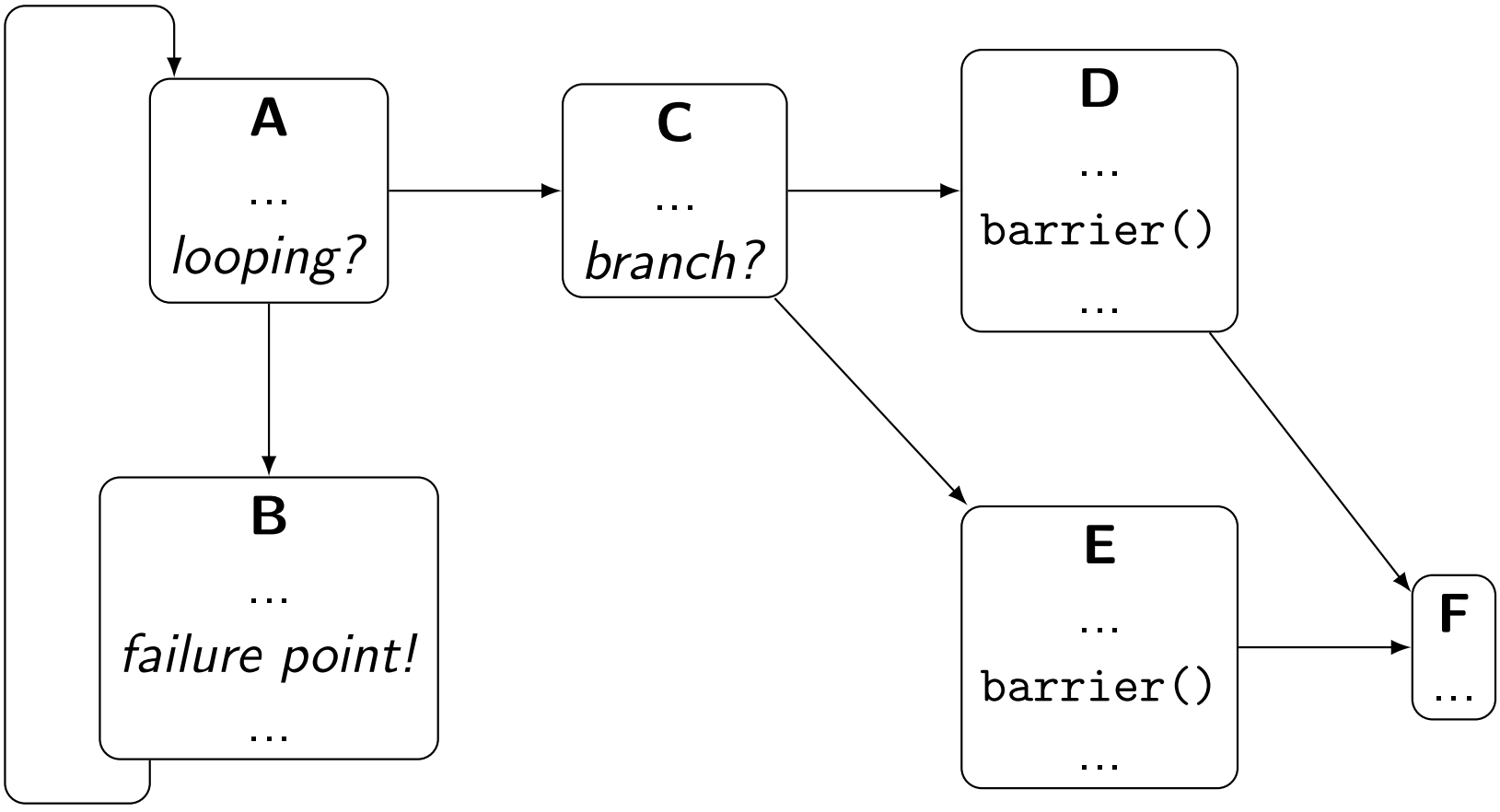
6    int i, gtid, ltid, k, acc; ...
7    for (i=gtid; i<n; i+=k) {
8      int j = js[i];
9      if (j < 0 || j >= m) {
10       *global_failure = 1;
11       goto sync;
12     }
13     acc += vs[j];
14   }
15
16   sums[ltid] = acc;
17
18   sync:
19   barrier();
20   if (*global_failure != -1) {
21     return;
22   }
23   barrier();
24
25   // Perform parallel
26   // reduction of sums...
27 }
```

Viewed as a control-flow graph



- Compiler must insert a synchronisation point in node **C**
- Straightforward when compiling a high-level language where programmer does not control thread communication

Correct error checking prelude

This prelude is wrong:

```
// Prelude added to every GPU kernel
if (*global_failure >= 0) {
  return;
}
```

Thread i may race ahead and fail (setting `global_failure`) before thread j has a chance to run.

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Thread *i* may race ahead and fail (setting `global_failure`) before thread *j* has a chance to run.

Fixed:

```
if (*global_failure >= 0) {
  return;
}
barrier();
```

Stops *all threads* or *no threads*.

More optimisations (details in paper)

- Do not protect *error-tolerant* kernels (e.g. copies, transpositions)

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if (*global_failure >= 0) { return; }
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- Cache failure information in GPU *local memory*

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local int local_failure;
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  Failure points write to both `global_failure` and `local_failure`, but synchronisation points read only from `local_failure`

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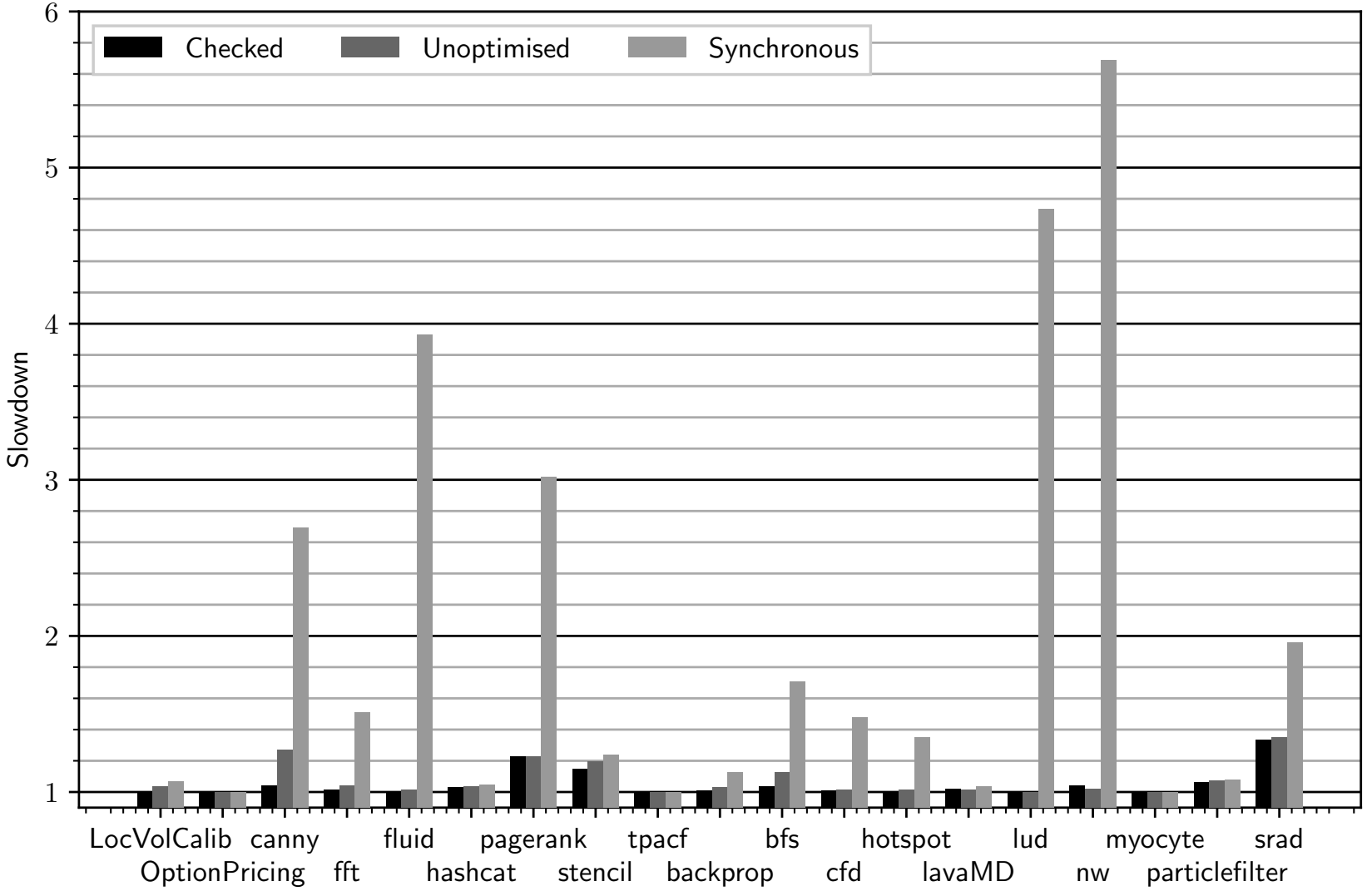
These optimisations have relatively small impact



- Geomean overhead of 1.04 × (1.07 × without optimisations)
- Max overhead about 1.4 ×
- **Fast enough to be default behaviour**

Conclusions

- Bounds checking on GPU can be implemented non-invasively in the code generator for a high-level language
- Overhead low enough to do by default
- Asynchronous checking is crucial for low overhead
- Care must be taken to work around API limitations
- Other optimisations are nice to have, but not crucial

`https://futhark-lang.org`