Automatic verification of GPU kernels

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Based on work by the GPUVerify team: Adam Betts, Nathan Chong, Peter Collingbourne, Alastair Donaldson, Jeroen Ketema, Egor Kyshtymov, Shaz Qadeer, Paul Thomson

Imperial College London

CARP
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SEVENTH FRAMEWORK PROGRAMME

Supported by the FP7 project CARP: Correct and Efficient Accelerator Programming

Aims of this lecture

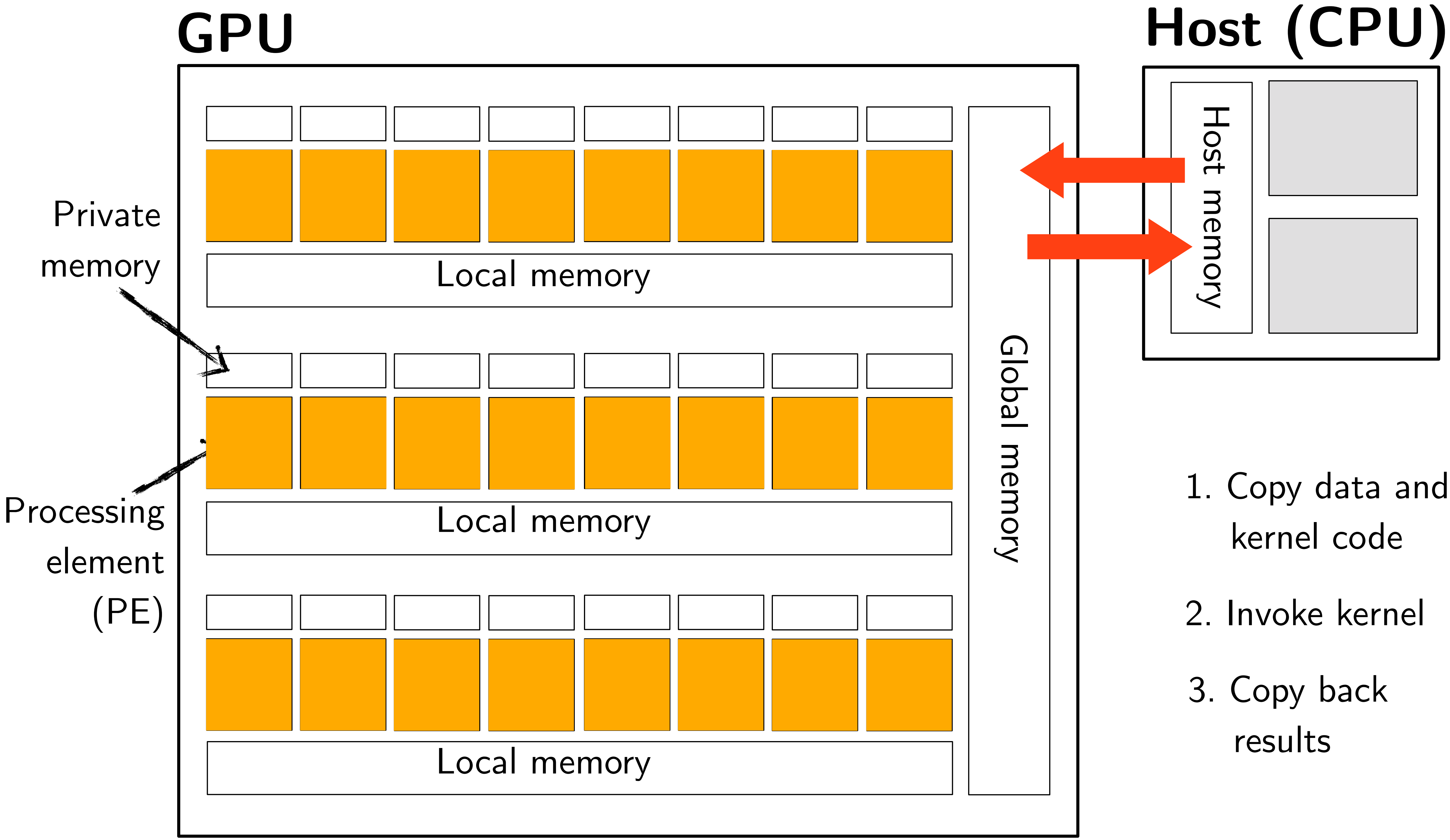
- Show a real-world application of Hoare Logic
- Introduce GPU programming: **data races** and **barrier divergence**
- Demonstrate **GPUVerify**, a tool for statically analysing GPU kernels to check for these kinds of defects
- Explain some of the novel verification techniques underlying GPUVerify

GPUs and GPU programming

GPUs

- Many parallel processing elements
- Originally designed to accelerate graphics processing, limited functionality, hard to program
- Recently, more general-purpose functionality. Accelerate such tasks as:
  - Medical imaging
  - Computational fluid dynamics
  - Financial simulation
  - DNA sequence alignment
  - Computer vision
  - ... and many more

GPU Architecture

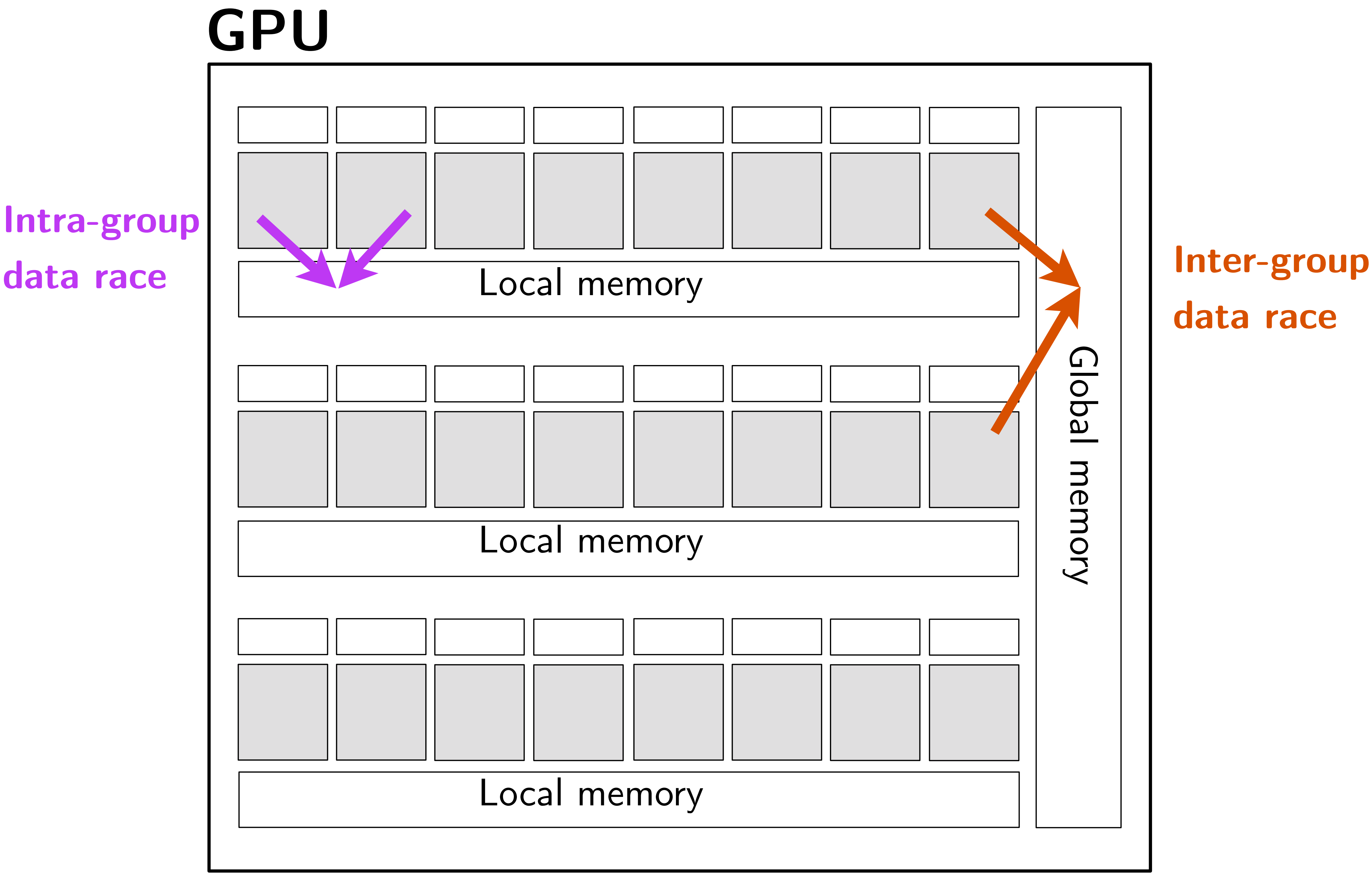


1. Copy data and kernel code
2. Invoke kernel
3. Copy back results

Data races

- A **data race** occurs when:
  - two **different** threads access the **same** memory location
  - at least one of the accesses is a **write**
  - the accesses are **not** separated by a **barrier**

Data races

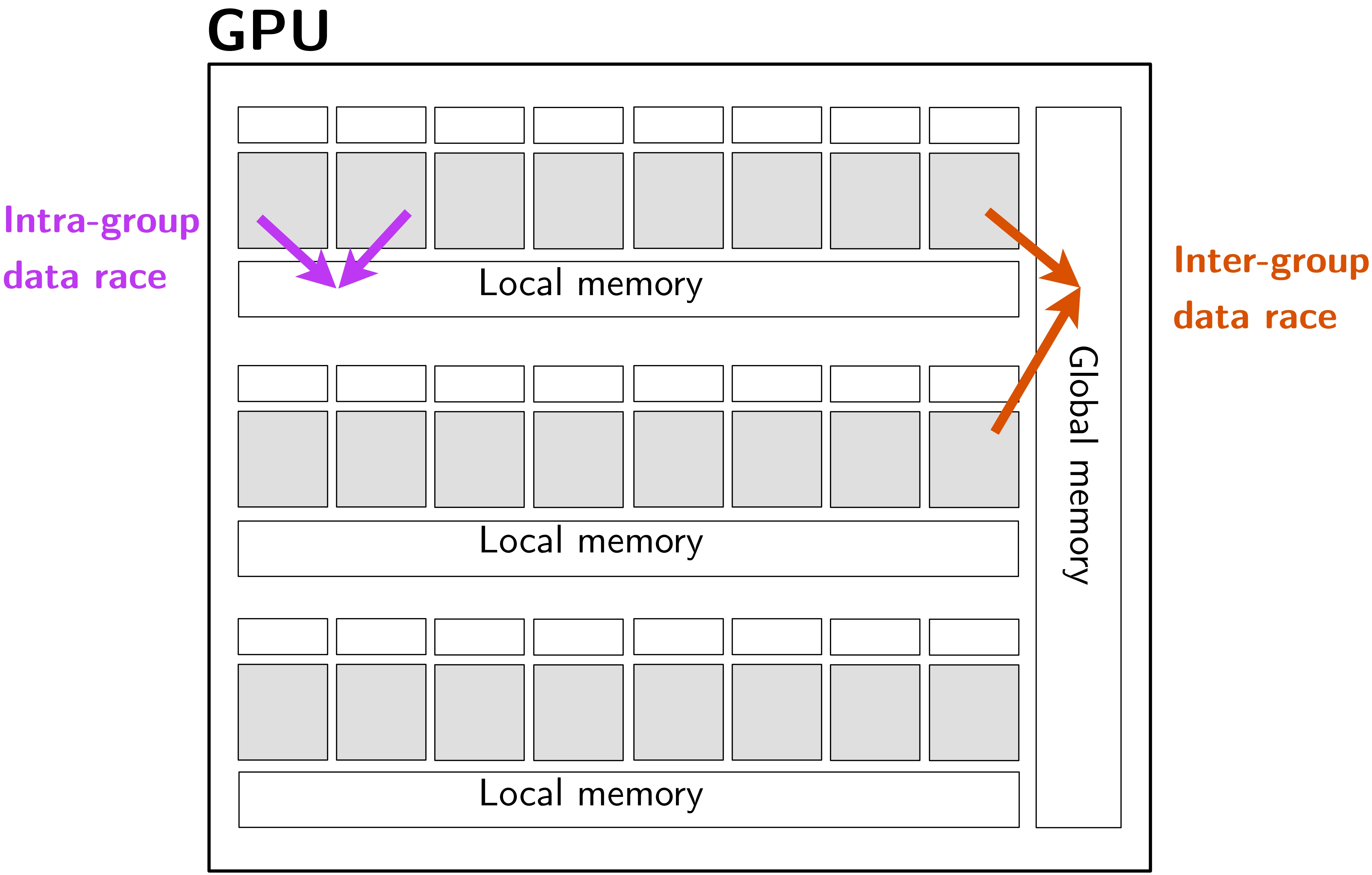


GPU
Intra-group
data race
Local memory
Local memory
Local memory
Global memory
Inter-group
data race

Data races

- A **data race** occurs when:
  - two **different** threads access the **same** memory location
  - at least one of the accesses is a **write**
  - the accesses are **not** separated by a **barrier**
- Data races can cause **undefined behaviour**
- Almost always **accidental** and **unwanted**

Data races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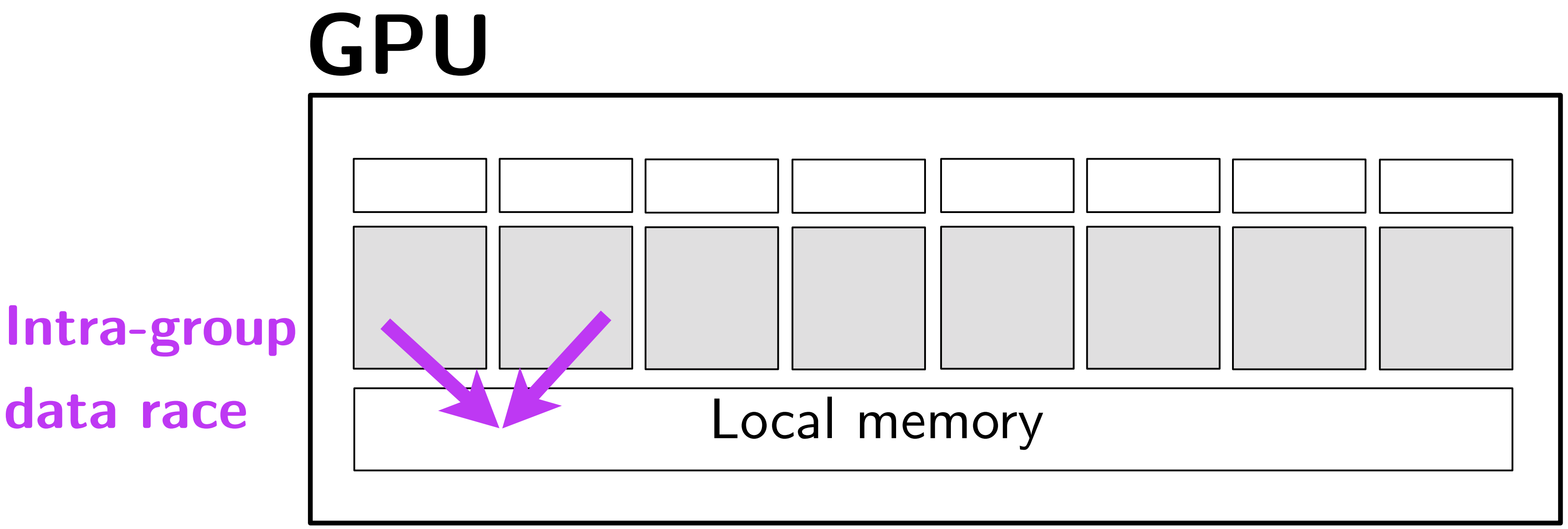
Data races



A GPU kernel

This function is the kernel's entry point

The array A is stored in the group's local memory

```
#define tid (get_local_id(0))

__kernel void
add_neighbour(__local int* A, int offset) {
  A[tid] = A[tid] + A[tid + offset];
}
```

Identifies the current thread

A GPU kernel

```
__kernel void
add_neighbour(__local int* A, int offset) {
  A[tid] = A[tid] + A[tid + offset];
}
```

- Suppose offset $= 1$, and that there are four threads

Thread:	0	1	2	3
Reads:	A[0] A[1]	A[1] A[2]	A[2] A[3]	A[3] A[4]
Writes:	A[0]	A[1]	A[2]	A[3]

data race

Effects of a data race

- Suppose `offset` = 1, and that there are four threads

A[0]	A[1]	A[2]	A[3]	A[4]
1	1	1	1	1

Thread 0

A[0]	A[1]	A[2]	A[3]	A[4]
2	1	1	1	1

Thread 1

A[0]	A[1]	A[2]	A[3]	A[4]
2	2	1	1	1

Thread 2

A[0]	A[1]	A[2]	A[3]	A[4]
2	2	2	1	1

Thread 3

A[0]	A[1]	A[2]	A[3]	A[4]
2	2	2	2	1

A[0]	A[1]	A[2]	A[3]	A[4]
1	1	1	1	1

Thread 3

A[0]	A[1]	A[2]	A[3]	A[4]
1	1	1	2	1

Thread 2

A[0]	A[1]	A[2]	A[3]	A[4]
1	1	3	2	1

Thread 1

A[0]	A[1]	A[2]	A[3]	A[4]
1	4	3	2	1

Thread 0

A[0]	A[1]	A[2]	A[3]	A[4]
5	4	3	2	1

Barrier synchronisation

- No thread can proceed beyond a `barrier()` until all threads have reached it
- Reads and writes from before the barrier are guaranteed to have completed after the barrier

```
__kernel void
add_neighbour(__local int* A, int offset) {
  int tmp = A[tid] + A[tid + offset];
  barrier();
  A[tid] = tmp;
}
```

Barrier divergence

- Threads must reach the same barrier

```
__kernel void foo() {
  if (tid == 0)
    barrier();
  else
    barrier();
}
```

NOT ALLOWED

Barrier divergence

- Threads must reach the same barrier
- If the barrier is in a loop, threads must have performed the same number of iterations upon reaching it

```
__kernel void foo() {
  int i_max = (tid==0 ? 4 : 1);
  int j_max = (tid==0 ? 1 : 4);
  for (int i = 0; i < i_max; i++)
    for (int j = 0; j < j_max; j++)
      barrier();
}
```

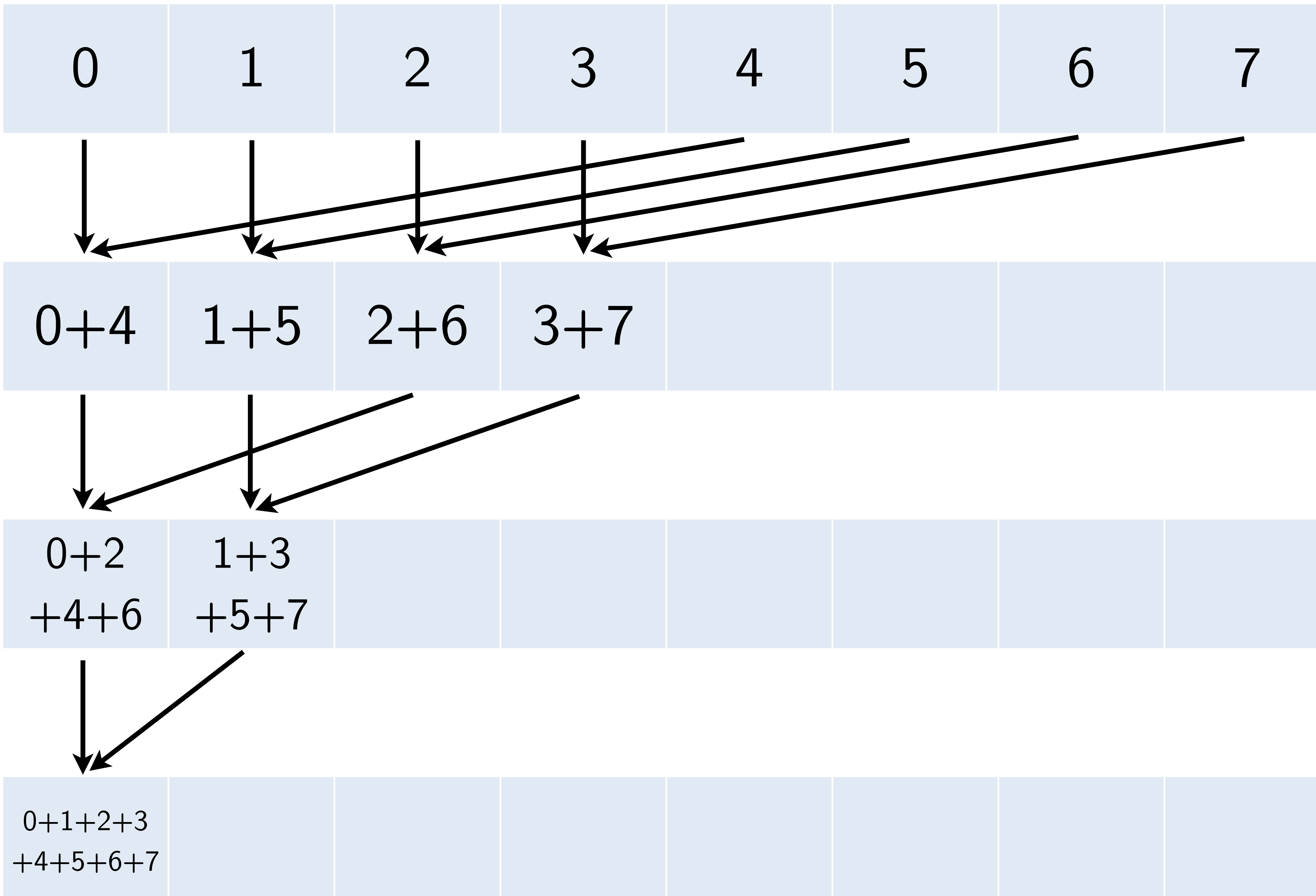
NOT ALLOWED

The GPUVerify tool

The GPUVerify tool

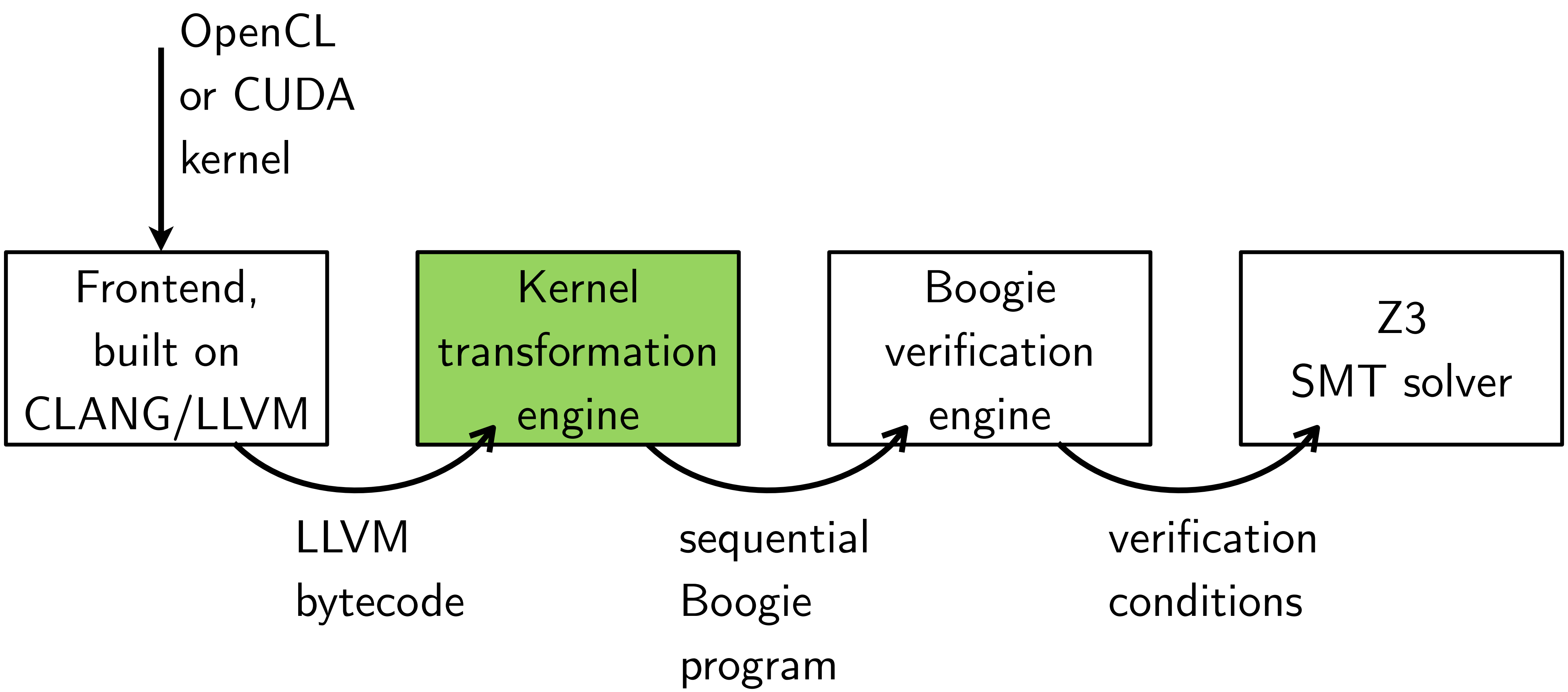
- A verifier for GPU kernels
- Analyses the source code of OpenCL and CUDA kernels to check for:
  - Intra-group and inter-group data races
  - Barrier divergence
  - Violations of user-specified assertions
- Download from multicore.doc.ic.ac.uk/tools/GPUVerify
- Or try it online at rise4fun.com/GPUVerify-OpenCL

Parallel reduction



How the GPUVerify tool works

Architecture of GPUVerify



Verification technique

- Plan:

Transform massively-parallel kernel **K**
into a sequential program **P**
such that if **P** is correct
then **K** has no data races
and no barrier divergence.

Making the problem tractable

- Data race analysis focuses on each barrier-separated region separately

```
barrier();
S_0;
S_1;
...
S_{k-1};
barrier();
```

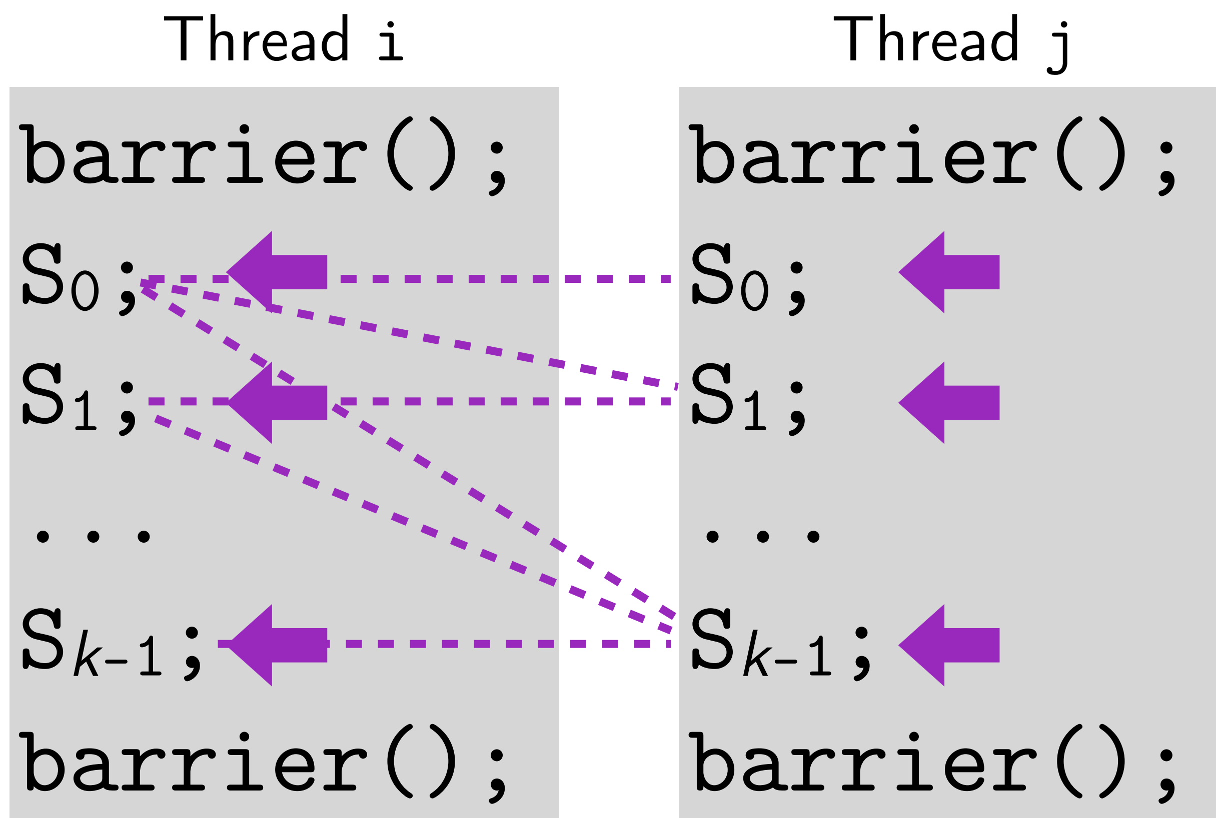
Making the problem tractable

- There are about N^k possible interleavings ...
  but **any one of them** will do!

Thread 0	Thread 1		Thread N-1
barrier();	barrier();		barrier();
S_0;	S_0;		S_0;
S_1;	S_1;	...	S_1;
...	...		...
S_{k-1};	S_{k-1};		S_{k-1};
barrier();	barrier();		barrier();

Reduction to two threads

- We can do better still!
- Pick **arbitrary** threads `i` and `j` (ensuring $i \neq j$)



Reduction to two threads

- We can do better still!
- Pick **arbitrary** threads `i` and `j` (ensuring `i` ≠ `j`)
- Problem: it's like threads `i` and `j` are the **only threads**
- Account for the effects of other threads by **randomising the shared state** at each barrier

Verification technique

- Plan:

> Transform massively-parallel kernel **K**
> into a sequential program **P**
> such that if **P** is correct
> then **K** has no data races
> and no barrier divergence.

- Three key observations:
  - any schedule will do
  - two threads will do
  - abstracting the shared state

Details of the two-thread reduction

The two-thread reduction

- Assume kernel has this form:

```
__kernel void foo(<parameters>) {
  <declare local variables>
  S_0; S_1; ...; S_{k-1};
}
```

- where each statement S_k has one of these forms:

`x = e` `x = A[e]` `A[e] = e'` `barrier()`

local variable (x) — expression over local variables (e) — `__local` array parameter (A)

Our example kernel

Kernel **K**:

```
__kernel void foo(
  __local int* A,
  __local int* B,
  int idx)
{
  int x, y;
  x = A[tid + idx];
  y = A[tid];
  A[tid] = x + y;
}
```

Picking two arbitrary threads

- Introduce two global variables:

```
var tid$1 : int;
var tid$2 : int;
```

and assume that they are in-range and different:

```
requires 0 <= tid$1 && tid$1 < N;
requires 0 <= tid$2 && tid$2 < N;
requires tid$1 != tid$2;
```

Logging reads and writes

- Replace each `__local` array parameter A with four global variables:

```
var READ_HAS_OCCURRED_A : bool;
var WRITE_HAS_OCCURRED_A : bool;
var READ_OFFSET_A : int;
var WRITE_OFFSET_A : int;
```

- and four procedures:

```
procedure LOG_READ_A(offset : int);
procedure LOG_WRITE_A(offset : int);
procedure CHECK_READ_A(offset : int);
procedure CHECK_WRITE_A(offset : int);
```

The transformation so far...

Kernel **K**:

```
__kernel void foo(
  __local int* A,
  __local int* B,
  int idx)
{
  ...
}
```

Sequential program **P**:

```
var tid$1, tid$2 : int;
var READ_HAS_OCCURRED_A : bool;
var READ_HAS_OCCURRED_B : bool;
var WRITE_HAS_OCCURRED_A : bool;
var WRITE_HAS_OCCURRED_B : bool;
var READ_OFFSET_A, READ_OFFSET_B : int;
var WRITE_OFFSET_A, WRITE_OFFSET_B : int;
procedure foo(idx : int)
  requires 0 <= tid$1 && tid$1 < N;
  requires 0 <= tid$2 && tid$2 < N;
  requires tid$1 != tid$2;
{
  ...
}
```

Duplicating local variables

- Both threads need a copy of each local variable
- E.g. `int x;` becomes `var x$1, x$2 : int;`
- Same goes for non-array parameters
- Note that the values of the parameters are the same across all threads:

```
requires param$1 == param$2;
```

Translating statements

S	translate(S)
`x = e;`	`x$1 := e$1;` `x$2 := e$2;`

`x = A[e];`	`call LOG_READ_A(e$1);`
	`call CHECK_READ_A(e$2);`
	`havoc x$1, x$2;`

`A[e] = e';`	`call LOG_WRITE_A(e$1);` `call CHECK_WRITE_A(e$2);`
`barrier();`	`call barrier();`
S_1; S_2;	translate(S_1); translate(S_2);

The transformation so far...

Kernel **K**:

```
__kernel void foo(
  __local int* A,
  __local int* B,
  int idx)
{
  int x, y;
  x = A[tid + idx];
  y = A[tid];
  A[tid] = x + y;
}
```

Sequential program **P**:

```
var tid$1, tid$2 : int;
var READ_HAS_OCCURRED_A : bool;
var READ_HAS_OCCURRED_B : bool;
var WRITE_HAS_OCCURRED_A : bool;
var WRITE_HAS_OCCURRED_B : bool;
var READ_OFFSET_A, READ_OFFSET_B : int;
var WRITE_OFFSET_A, WRITE_OFFSET_B : int;
procedure foo(idx$1 : int, idx$2 : int)
  requires 0 <= tid$1 && tid$1 < N;
  requires 0 <= tid$2 && tid$2 < N;
  requires tid$1 != tid$2;
  requires idx$1 == idx$2;
{
  var x$1, x$2, y$1, y$2 : int;
  call LOG_READ_A(tid$1 + idx$1);
  call CHECK_READ_A(tid$2 + idx$2);
  havoc x$1, x$2;
  call LOG_READ_A(tid$1);
  call CHECK_READ_A(tid$2);
  havoc y$1, y$2;
  call LOG_WRITE_A(tid$1);
  call CHECK_WRITE_A(tid$2);
}
```

The logging functions

```
procedure LOG_READ_A(offset : int) {
  if (*) {
    READ_HAS_OCCURRED_A := true;
    READ_OFFSET_A := offset;
  }
}
```

```
procedure LOG_WRITE_A(offset : int) {
  if (*) {
    WRITE_HAS_OCCURRED_A := true;
    WRITE_OFFSET_A := offset;
  }
}
```

The checking functions

```
procedure CHECK_READ_A(offset : int) {
  assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != offset);
}
```

```
procedure CHECK_WRITE_A(offset : int) {
  assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != offset);
  assert (READ_HAS_OCCURRED_A ==> READ_OFFSET_A != offset);
}
```

The transformation so far...

Kernel **K**:

```
__kernel void foo(
  __local int* A,
  __local int* B,
  int idx)
{
  int x, y;
  x = A[tid + idx];
  y = A[tid];
  A[tid] = x + y;
}
```

Sequential program **P**:

```
var tid$1, tid$2 : int;
var READ_HAS_OCCURRED_A : bool;
var READ_HAS_OCCURRED_B : bool;
var WRITE_HAS_OCCURRED_A : bool;
var WRITE_HAS_OCCURRED_B : bool;
var READ_OFFSET_A, READ_OFFSET_B : int;
var WRITE_OFFSET_A, WRITE_OFFSET_B : int;
procedure foo(idx$1 : int, idx$2 : int)
  requires 0 <= tid$1 && tid$1 < N;
  requires 0 <= tid$2 && tid$2 < N;
  requires tid$1 != tid$2;
  requires idx$1 == idx$2;
  requires !READ_HAS_OCCURRED_A;
  requires !WRITE_HAS_OCCURRED_A;
{
  var x$1, x$2, y$1, y$2 : int;
  call LOG_READ_A(tid$1 + idx$1);
  call CHECK_READ_A(tid$2 + idx$2);
  havoc x$1, x$2;
  call LOG_READ_A(tid$1);
  call CHECK_READ_A(tid$2);
  havoc y$1, y$2;
  call LOG_WRITE_A(tid$1);
  call CHECK_WRITE_A(tid$2);
}
```

Non-deterministic logging

```
var x$1, x$2, y$1, y$2 : int;
call LOG_READ_A(tid$1 + idx$1);
call CHECK_READ_A(tid$2 + idx$2);
havoc x$1, x$2;
call LOG_READ_A(tid$1);
call CHECK_READ_A(tid$2);
havoc y$1, y$2;
call LOG_WRITE_A(tid$1);
call CHECK_WRITE_A(tid$2);
```

Non-deterministic logging

```
call LOG_READ_A(tid$1 + idx$1);
call CHECK_READ_A(tid$2 + idx$2);
call LOG_READ_A(tid$1);
call CHECK_READ_A(tid$2);
call LOG_WRITE_A(tid$1);
call CHECK_WRITE_A(tid$2);
```

Non-deterministic logging

```
//call LOG_READ_A(tid$1 + idx$1);
if (*) { READ_HAS_OCCURRED_A := true; READ_OFFSET_A := tid$1 + idx$1; }
//call CHECK_READ_A(tid$2 + idx$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2 + idx$2);
//call LOG_READ_A(tid$1);
if (*) { READ_HAS_OCCURRED_A := true; READ_OFFSET_A := tid$1; }
//call CHECK_READ_A(tid$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2)
//call LOG_WRITE_A(tid$1);
if (*) { WRITE_HAS_OCCURRED_A := true; WRITE_OFFSET_A := tid$1; }
//call CHECK_WRITE_A(tid$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2);
assert (READ_HAS_OCCURRED_A ==> READ_OFFSET_A != tid$2);
```

Non-deterministic logging

```
//call LOG_READ_A(tid$1 + idx$1);
if (*) { [redacted] }
//call CHECK_READ_A(tid$2 + idx$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2 + idx$2);
//call LOG_READ_A(tid$1);
if (*) { READ_HAS_OCCURRED_A := true; READ_OFFSET_A := tid$1; }
//call CHECK_READ_A(tid$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2)
//call LOG_WRITE_A(tid$1);
if (*) { WRITE_HAS_OCCURRED_A := true; WRITE_OFFSET_A := tid$1; }
//call CHECK_WRITE_A(tid$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2);
assert (READ_HAS_OCCURRED_A ==> READ_OFFSET_A != tid$2);
```

Non-deterministic logging

```
//call LOG_READ_A(tid$1 + idx$1);
if (*) { READ_HAS_OCCURRED_A := true; READ_OFFSET_A := tid$1 + idx$1; }
//call CHECK_READ_A(tid$2 + idx$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2 + idx$2);
//call LOG_READ_A(tid$1);
if (*) { [redacted] }
//call CHECK_READ_A(tid$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2)
//call LOG_WRITE_A(tid$1);
if (*) { WRITE_HAS_OCCURRED_A := true; WRITE_OFFSET_A := tid$1; }
//call CHECK_WRITE_A(tid$2);
assert (WRITE_HAS_OCCURRED_A ==> WRITE_OFFSET_A != tid$2);
assert (READ_HAS_OCCURRED_A ==> READ_OFFSET_A != tid$2);
```

The `barrier()` function

```
procedure barrier() {
  assume (!READ_HAS_OCCURRED_A);
  assume (!WRITE_HAS_OCCURRED_A);
  // Do this for every array
}
```

Summary so far

- For each array parameter `A`:
  - Add variables to log `A`'s reads and writes
  - Generate procedures to log and check reads and writes, using non-determinism to consider all possibilities
  - Remove `A`, and model reads from `A` using non-determinism
- For each statement in kernel **K**:
  - generate corresponding statement(s) in sequential program **P**
  - interleave two arbitrary threads using round-robin schedule
- Next up: conditionals and loops

Handling conditionals

- Use predicated execution to flatten **conditional code** into **straight line code**

```
if (x < 100) {
  x = x+1;
} else {
  y = y+1;
}
```

```
P := (x < 100);
Q := !(x < 100);
x := (P ? x+1 : x);
y := (Q ? y+1 : y);
```

Handling conditionals

- Use predicated execution to flatten **conditional code** into **straight line code**
- Each statement is tagged with a predicate that determines which threads are enabled
- This complicates the translation...

Translating statements (revised)

<table>
<tr><th>S</th><th>translate(S,P)</th></tr>
<tr><td>x = e;</td><td>x$1 := P$1 ? e$1 : x$1;
x$2 := P$2 ? e$2 : x$2;</td></tr>
<tr><td>x = A[e];</td><td>call LOG_READ_A(P$1, e$1);
call CHECK_READ_A(P$2, e$2);
x$1 := P$1 ? * : x$1;
x$2 := P$2 ? * : x$2;</td></tr>
<tr><td>A[e] = e’;</td><td>call LOG_WRITE_A(P$1, e$1);
call CHECK_WRITE_A(P$2, e$2);</td></tr>
<tr><td>barrier();</td><td>call barrier(P$1, P$2);</td></tr>
<tr><td>S_1; S_2;</td><td>translate(S_1,P); translate(S_2,P);</td></tr>
</table>

<table>
<tr><th>S</th><th>translate(S,P)</th></tr>
<tr><td>if(e) {
S_1;
} else {
S_2;
}</td><td>Q$1 := P$1 && e$1;
Q$2 := P$2 && e$2;
R$1 := P$1 && !e$1;
R$2 := P$2 && !e$2;
translate(S_1,Q);
translate(S_2,R);</td></tr>
<tr><td>while(e) {
S;
}</td><td>Q$1 := P$1 && e$1;
Q$2 := P$2 && e$2;
while (Q$1 || Q$2) {
translate(S,Q);
Q$1 := P$1 && e$1;
Q$2 := P$2 && e$2;
}</td></tr>
</table>

The logging functions (revised)

```
procedure LOG_READ_A(enabled : bool, offset : int) {
  if (enabled && *) {
    READ_HAS_OCCURRED_A := true;
    READ_OFFSET_A := offset;
  }
}
```

```
procedure LOG_WRITE_A(enabled : bool, offset : int) {
  if (enabled && *) {
    WRITE_HAS_OCCURRED_A := true;
    WRITE_OFFSET_A := offset;
  }
}
```

The checking functions (revised)

```
procedure CHECK_READ_A(enabled : bool, offset : int) {
  assert (enabled && WRITE_HAS_OCCURRED_A
    ==> WRITE_OFFSET_A != offset);
}
```

```
procedure CHECK_WRITE_A(enabled : bool, offset : int) {
  assert (enabled && WRITE_HAS_OCCURRED_A
    ==> WRITE_OFFSET_A != offset);
  assert (enabled && WRITE_HAS_OCCURRED_A
    ==> WRITE_OFFSET_A != offset);
}
```

The `barrier()` function (revised)

```
procedure barrier(enabled$1 : bool, enabled$2 : bool) {
  assert (enabled$1 == enabled$2);
  if (!enabled$1) return;

  assume (!READ_HAS_OCCURRED_A);
  assume (!WRITE_HAS_OCCURRED_A);
  // Do this for every array
}
```

Find out more

- Download GPUVerify:
  - multicore.doc.ic.ac.uk/tools/GPUVerify
- Or try it online:
  - rise4fun.com/GPUVerify-OpenCL
- The Multicore Group at Imperial
  - multicore.doc.ic.ac.uk

Further reading

- A. Betts, N. Chong, A. Donaldson, S. Qadeer, P. Thomson. *GPUVerify, a verifier for GPU kernels*, **OOPSLA 2012**
- P. Collingbourne, A. Donaldson, J. Ketema, S. Qadeer. *Interleaving and lock-step semantics for analysis and verification of GPU kernels*, **ESOP 2013**
- G. Li, G. Gopalakrishnan. *Scalable SMT-based verification of GPU kernel functions*, **FSE 2010**
- G. Li, P. Li, G. Sawaya, G. Gopalakrishnan, I. Ghosh, S. Rajan. *GKLEE: Concolic verification and test generation for GPUs*, **PPoPP 2012**
- A. Leung, M. Gupta, Y.Agarwal, R. Gupta, R. Jhala, S. Lerner. *Verifying GPU kernels by test amplification*, **PLDI 2012**.