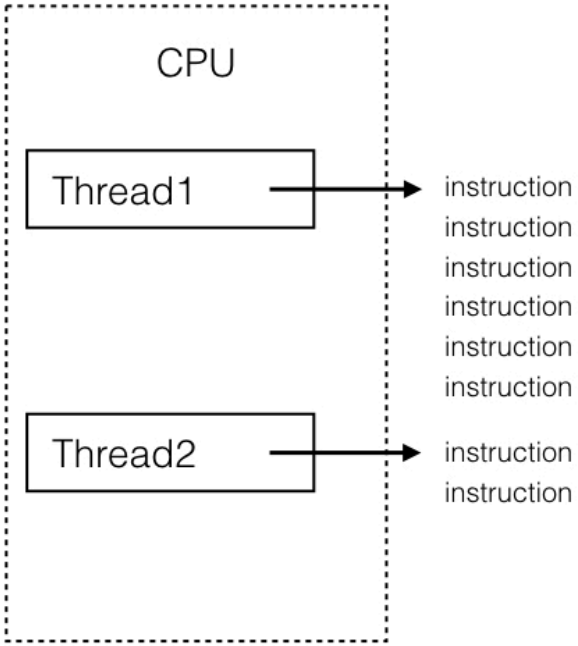
Verifying Multi-Threaded Programs

Susanne van den Elsen

Native Instruments

February 21, 2017

Threads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Thread2
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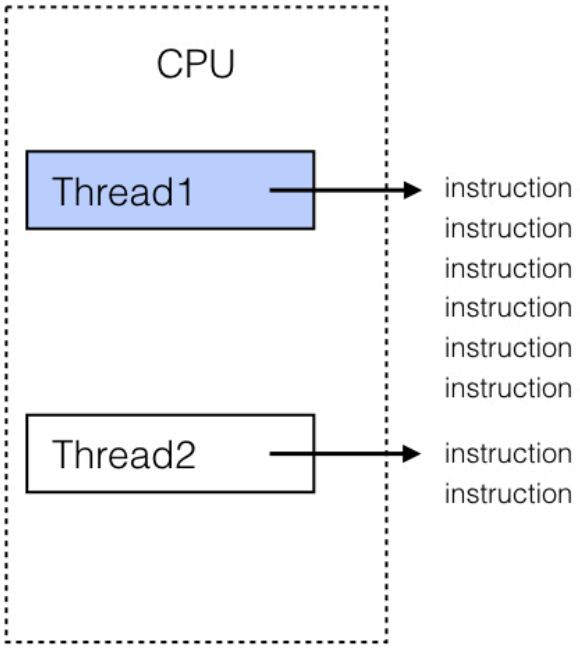
instruction

Threads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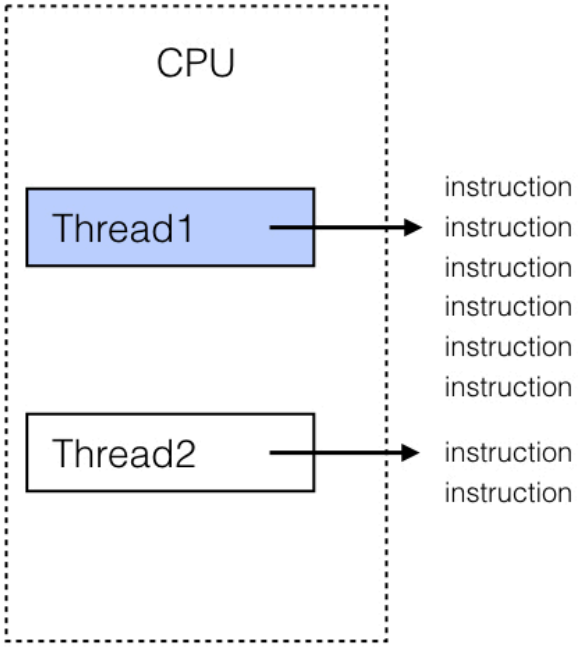
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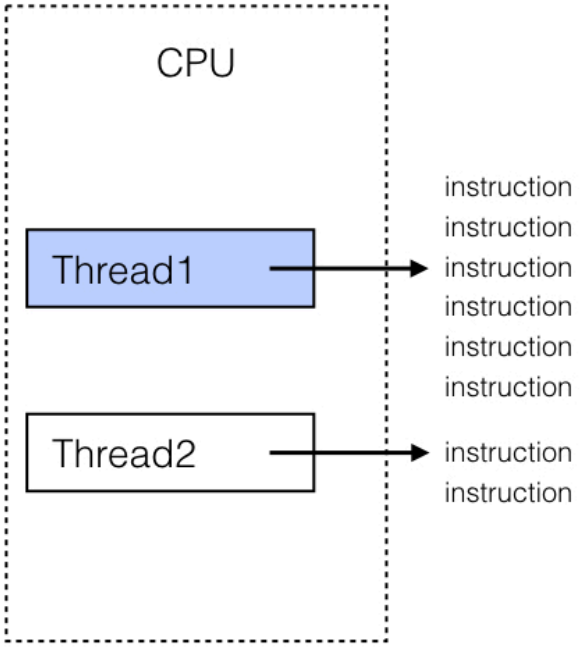
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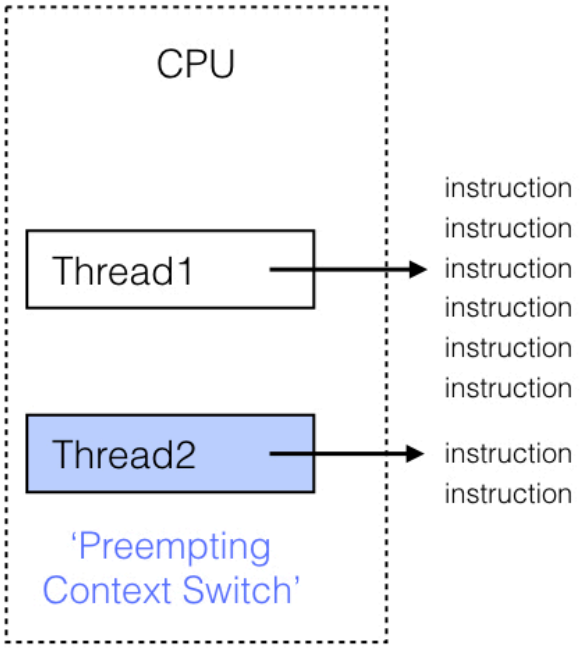
CPU
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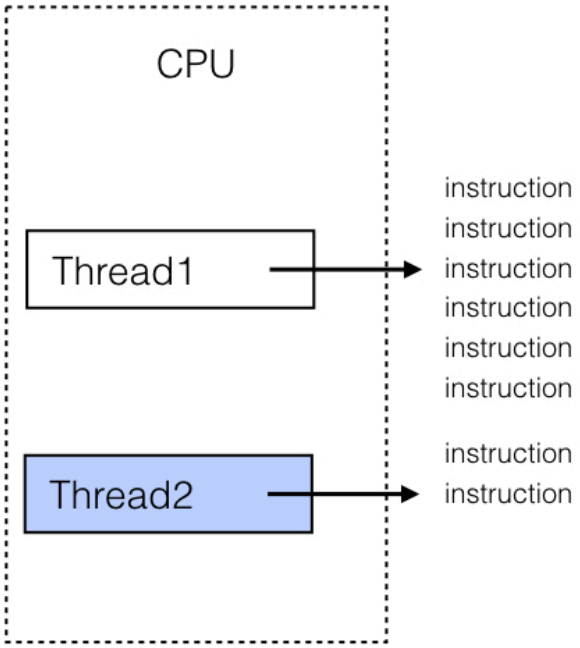
Threads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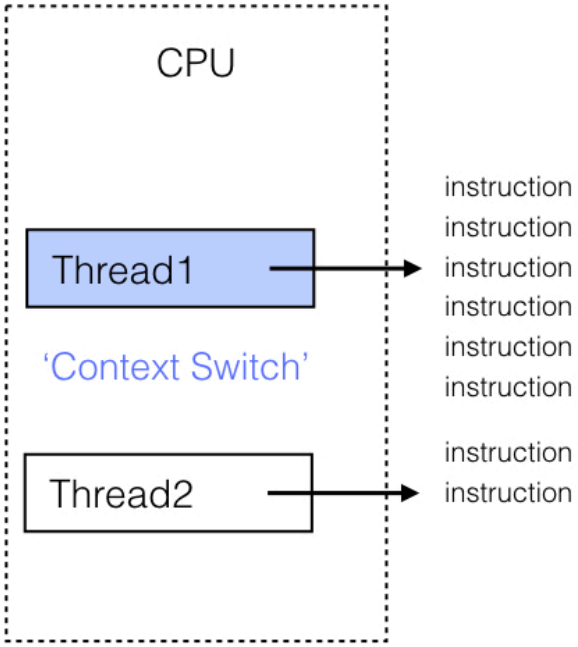
Threads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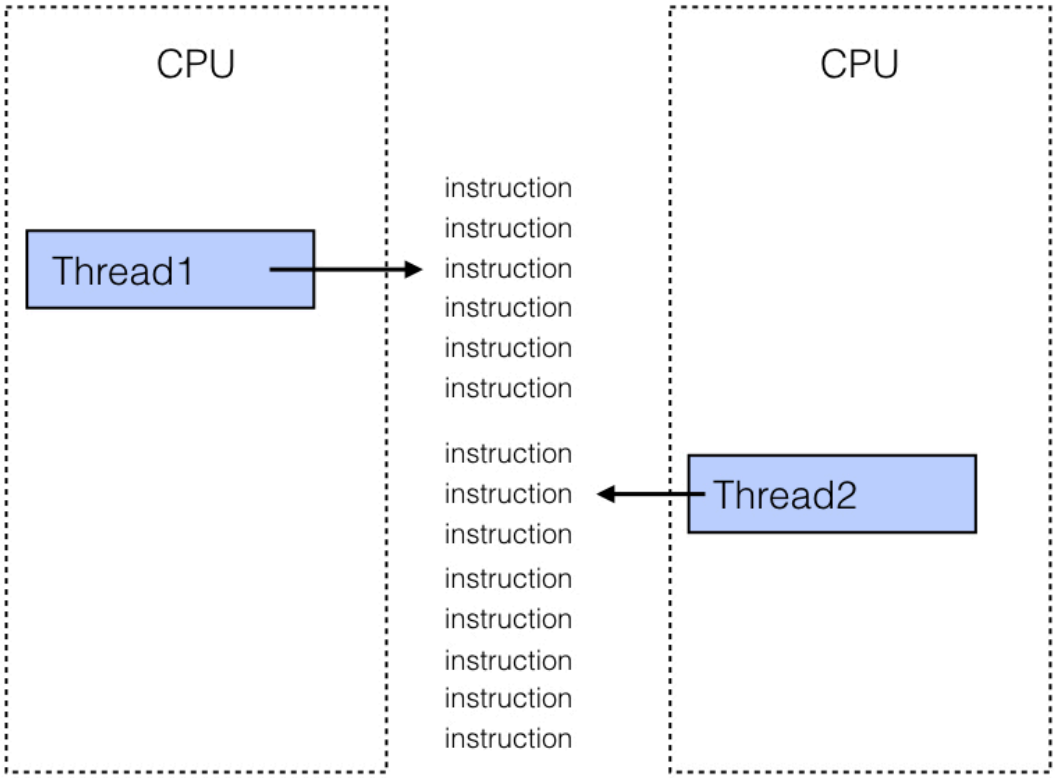
Threads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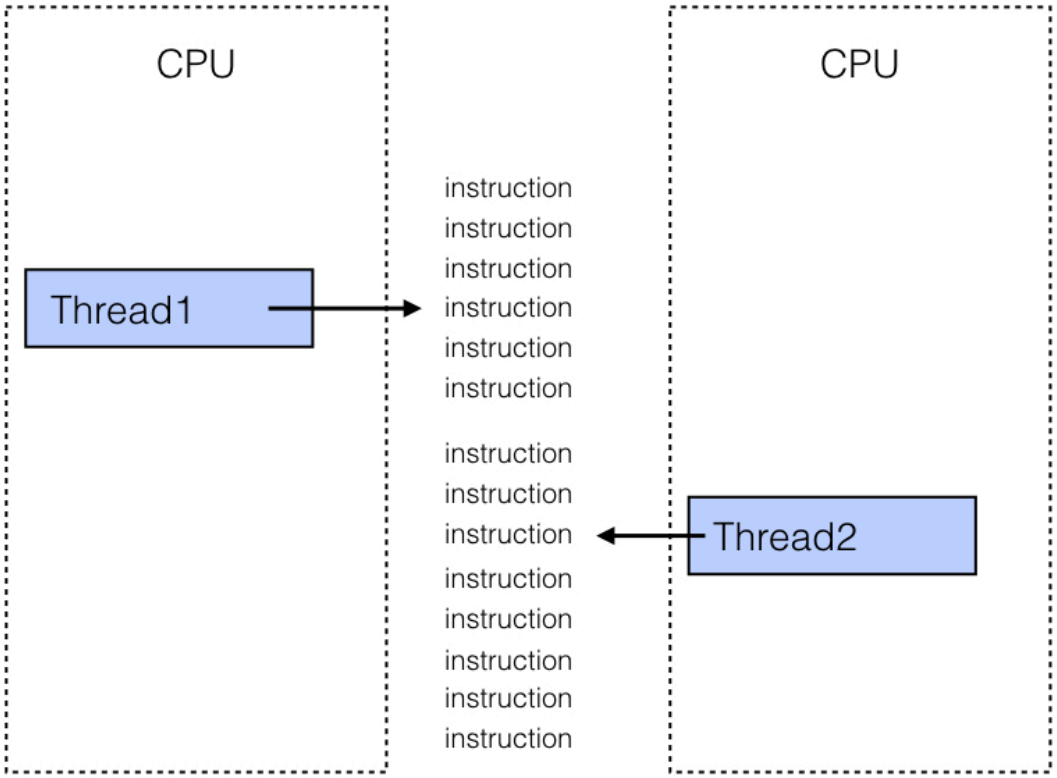
Threads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instruction
Thread1
Thread2

What's Hard About Concurrency?

Shared Resources

```
int x, y, z = 0;

thread 0                    thread 1
--------                    --------

if (x == 1)                 x = 1;
{                           z = x + y;
   y = 1;                   std::cout << z << "\n";
}
```

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if (x == 1)                 x = 1;
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}
```

Datarace:

Two (or more) threads access the same memory location *concurrently* and at least one of them is a *write*

What's Hard About Concurrency?

Synchronisation

```
array<int,2> nr_meals_eaten = {0, 0};
mutex fork1, fork2;

philosopher 0                philosopher 1
-------------                -------------

lock(fork1);                 lock(fork2);
lock(fork2);                 lock(fork1);
++nr_meals_eaten[0];         ++nr_meals_eaten[1];
unlock(fork2);               unlock(fork1);
unlock(fork1);               unlock(fork2);
```

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```

Deadlock:

Two or more threads wait for each other indefinitely

What's Hard About Concurrency?

State Space Explosion

What's Hard About Concurrency?

State Space Explosion

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thread 0                    thread 1
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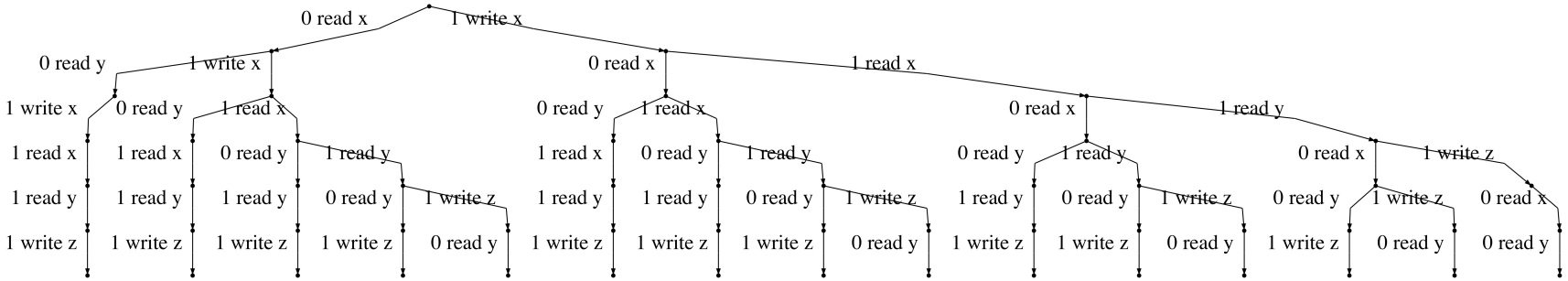
```

What's Hard About Concurrency?

State Space Explosion

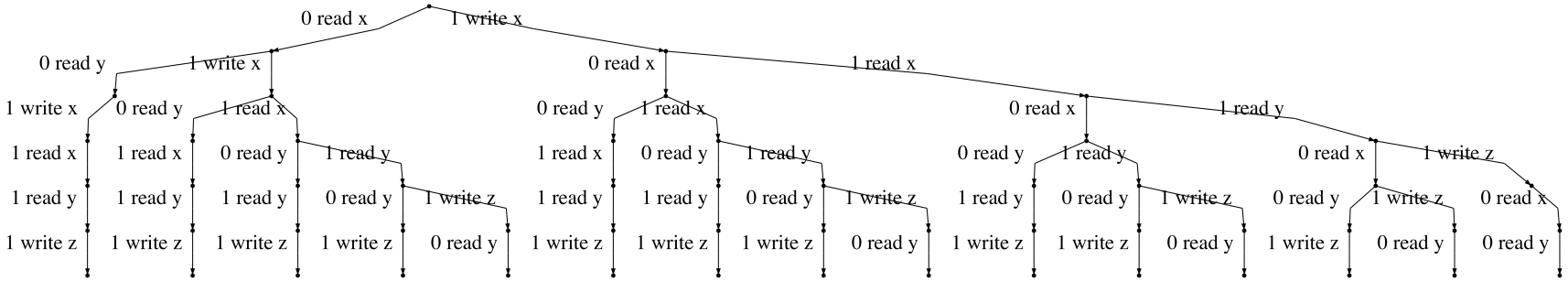
Number of possible thread interleavings is *exponential* in the number of threads and instructions!



What's Hard About Concurrency?

Nondeterminism

The interleaving of threads is out of the programmer's control



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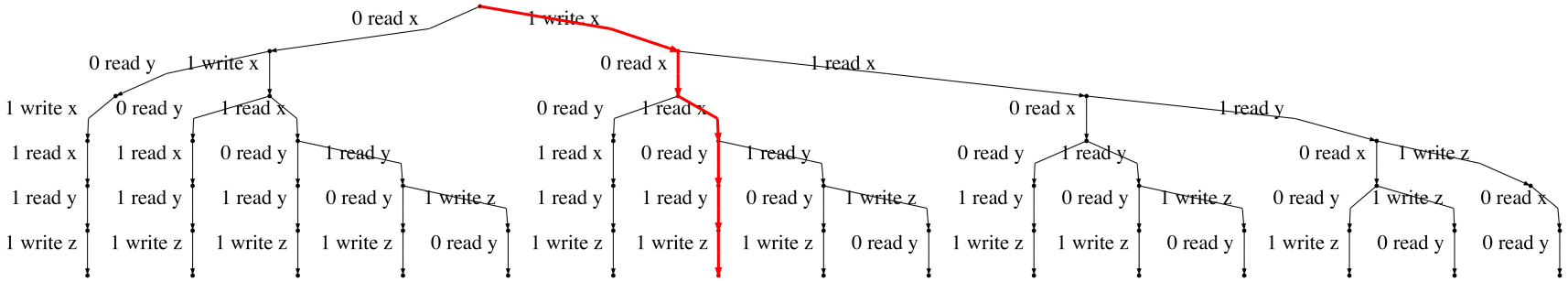

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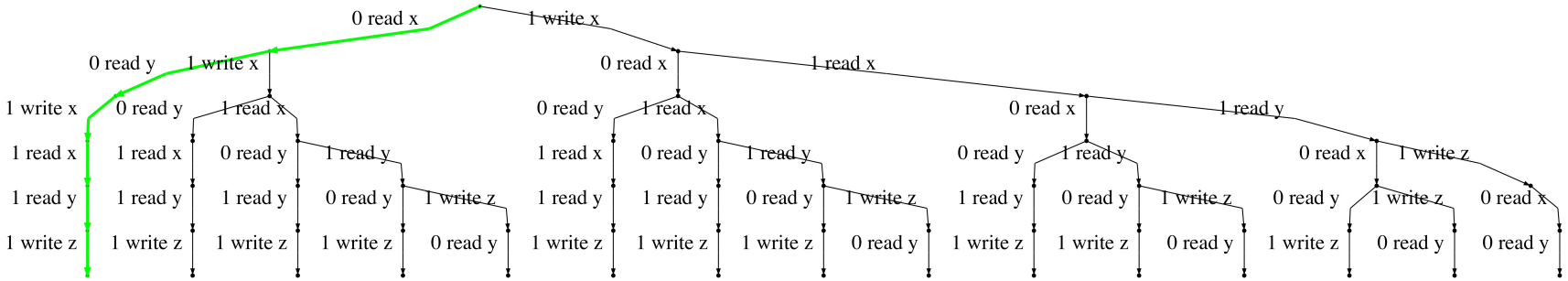

Concurrency Error Detectors

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ThreadSanitzer

```
clang++ program_under_test.cpp -fsanitize=thread -o program_under_test
./program_under_test
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Compiler Instrumentation (LLVM IR)

Instrument every potentially *visible* instruction (e.g. `load`, `store`)

Concurrency Error Detectors

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./program_under_test
```

Compiler Instrumentation (LLVM IR)

Instrument every potentially *visible* instruction (e.g. `load`, `store`)

```
define void @function() {
__tsan_func_entry(caller)
%2 = alloca i32
__tsan_store(%2)
store i32 %0, i32* %2
__tsan_load(%2)
%4 = load i32, i32* %2
ret i32 %4
__tsan_func_exit()
}
```

Concurrency Error Detectors

ThreadSanitzer

Runtime library

The `__tsan_` functions are callbacks to a Runtime Library (part of clang-rt)

Maintains a state maschine using shadow state for analysis

Concurrency Error Detectors

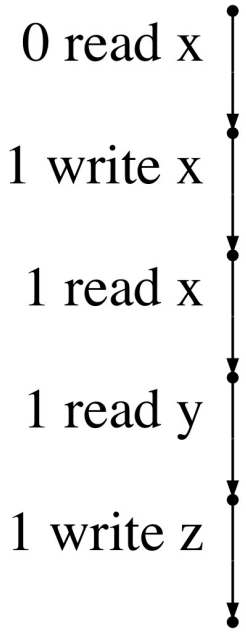
Helgrind

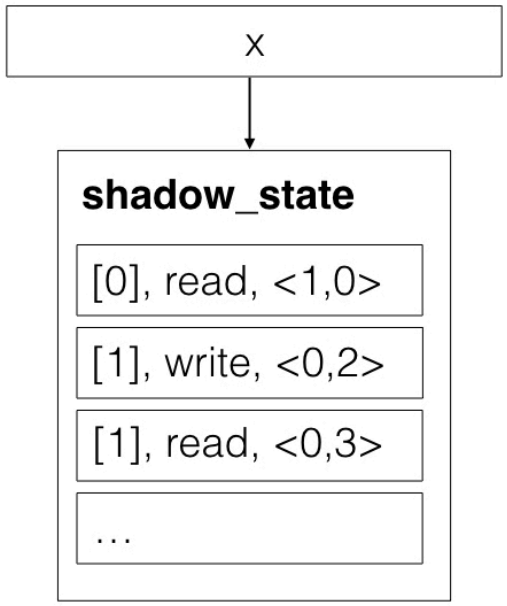
Binary Instrumentation

```
valgrind --tool=helgrind -v program
```

- Program is run on synthetic CPU provided by Valgrind Core
- Threads are fully serialzed (only single CPU used)

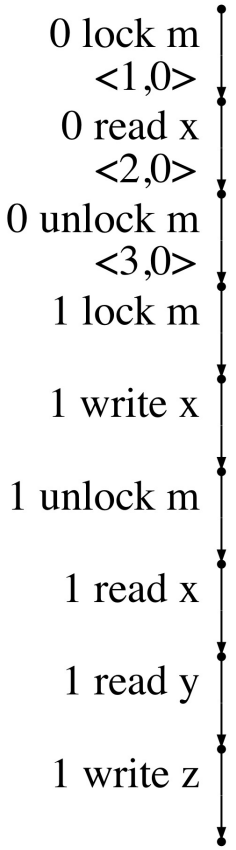
ThreadSanitizer & Helgrind: Data Races





ThreadSanitizer & Helgrind: Data Races

Using the *happens-before* relation:



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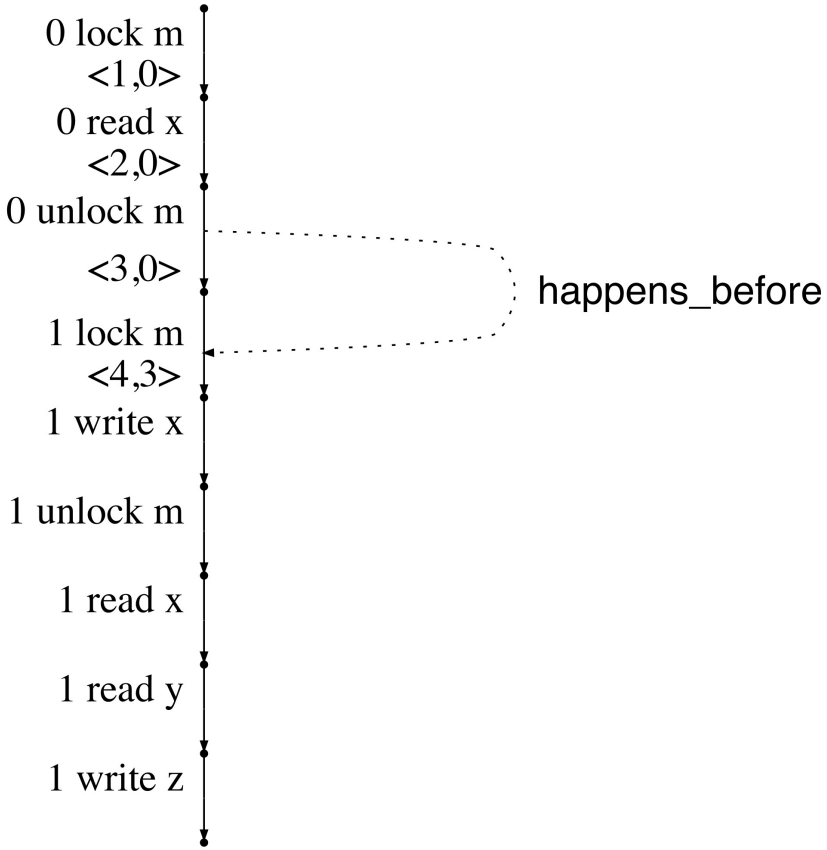

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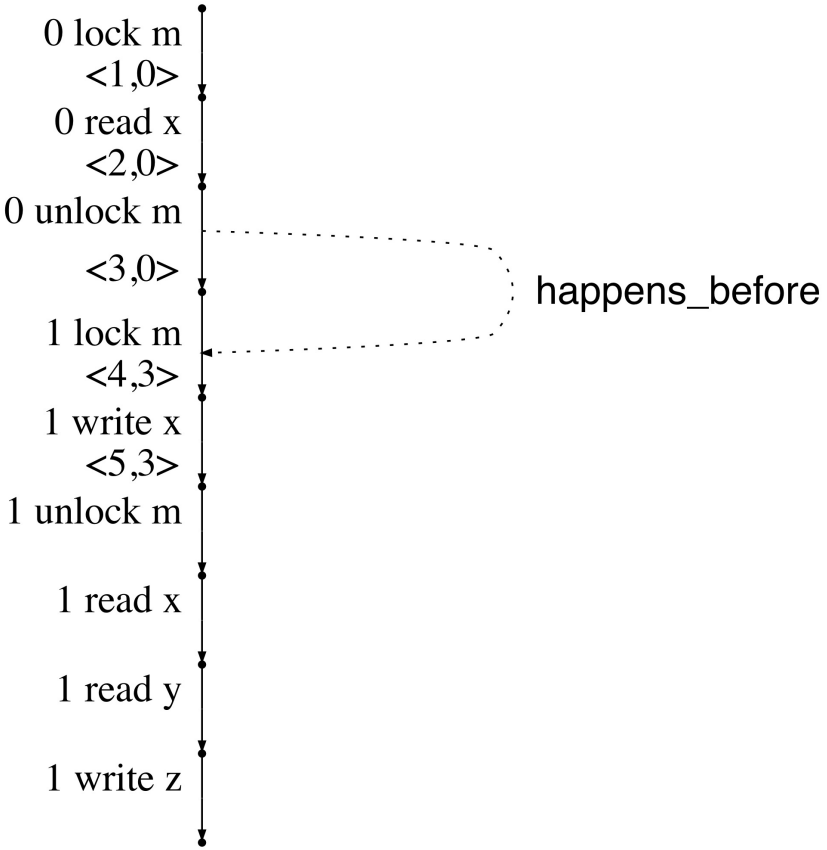
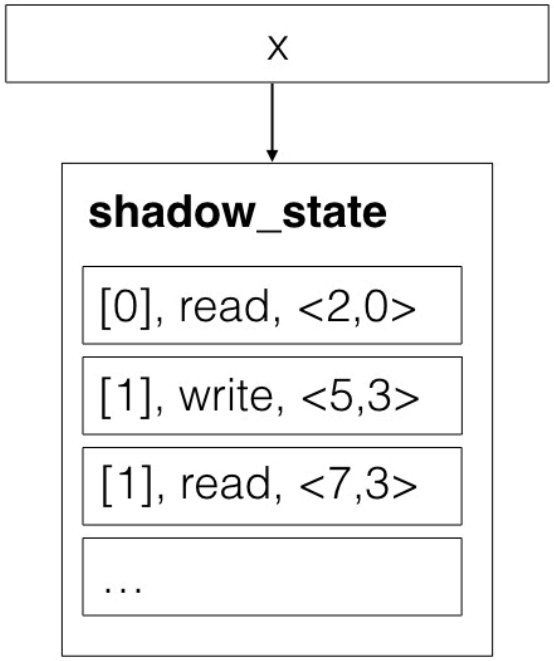
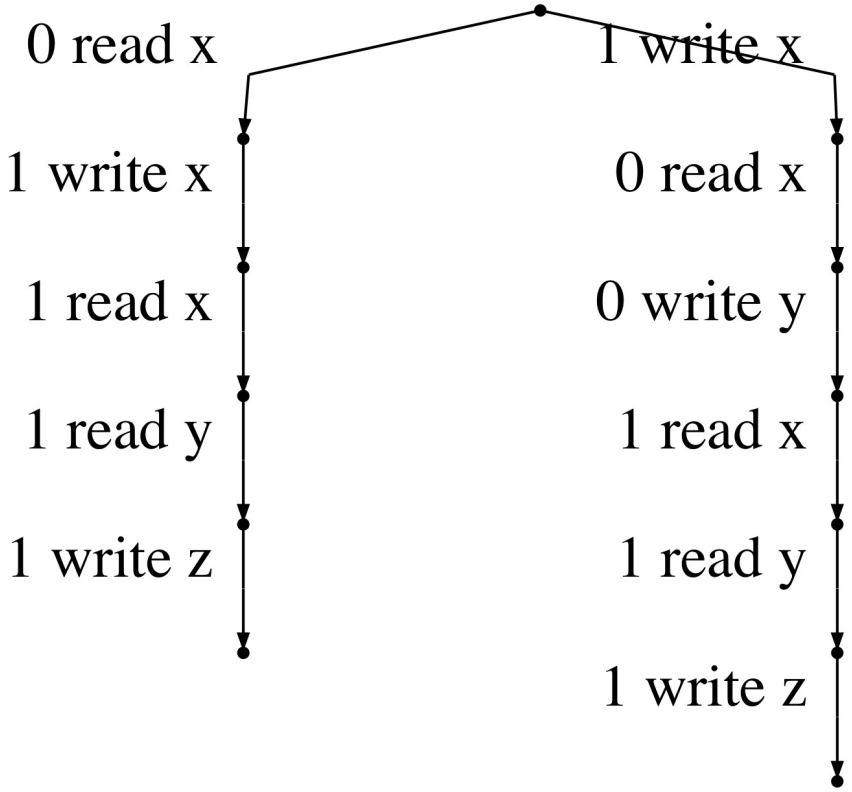


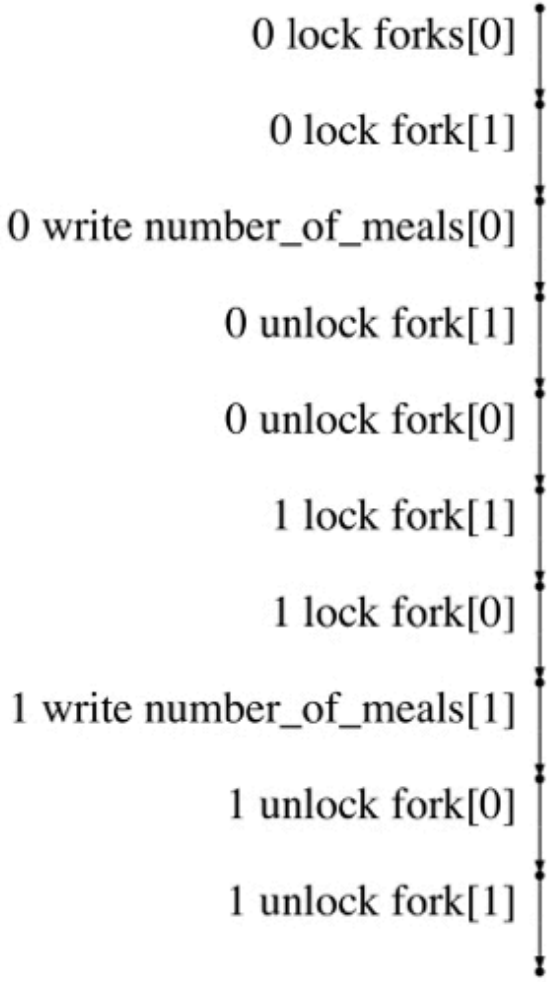


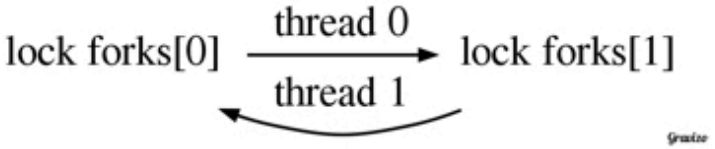
ThreadSanitizer & Helgrind: Data Races

Limited information in *single* execution:



ThreadSanitizer: Deadlock





Systematic Exploration

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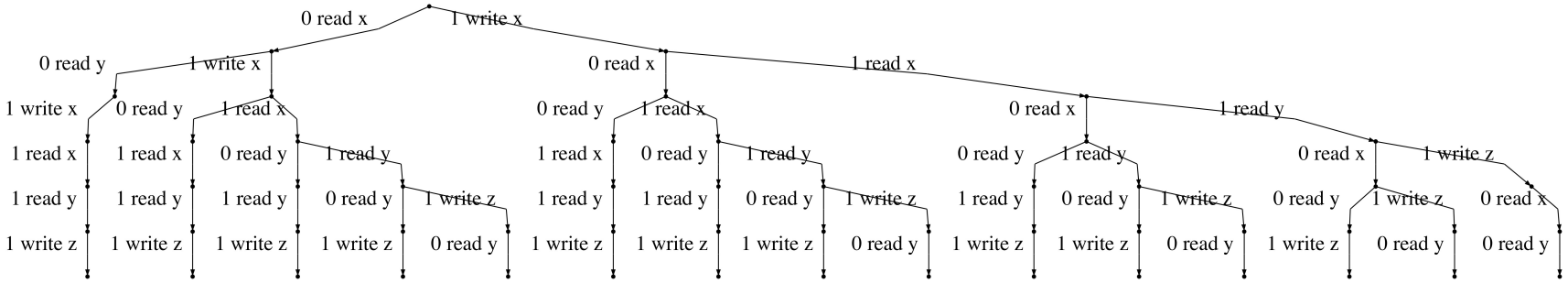


Taking Control Over the Thread Interleavings

LLVM IR Instumentation Pass

Replace

```
pthread_create(pid, attr, start_routine, args)
pthread_join(pid)
```

by

```
wrapper_spawn_thread(pid, attr, start_routine, args)
wrapper_pthread_join()
```

Scheduler

```
void wrapper_spawn_thread(pid, attr, start_routine, args)
{
   semaphores.insert({ pid, semaphore() })
   pthread_create(pid, attr, start_routine, args)
}
```

Taking Control Over the Thread Interleavings

LLVM IR Instumentation Pass

Insert call to potentially *visible* instructions

```
wrap_post_task(instruction(store, %2, is_atomic))
store i32 %0, i32* %2
```

Scheduler

```
void wrapper_post_task(instruction)
{
   task_pool.insert({ this_thread::id(), instruction });
   semaphores[this_thread::id()].wait();
   // wait for turn

   task_pool.remove(this_thread::id());
   // perform instructions
}
```

Taking Control Over the Thread Interleavings

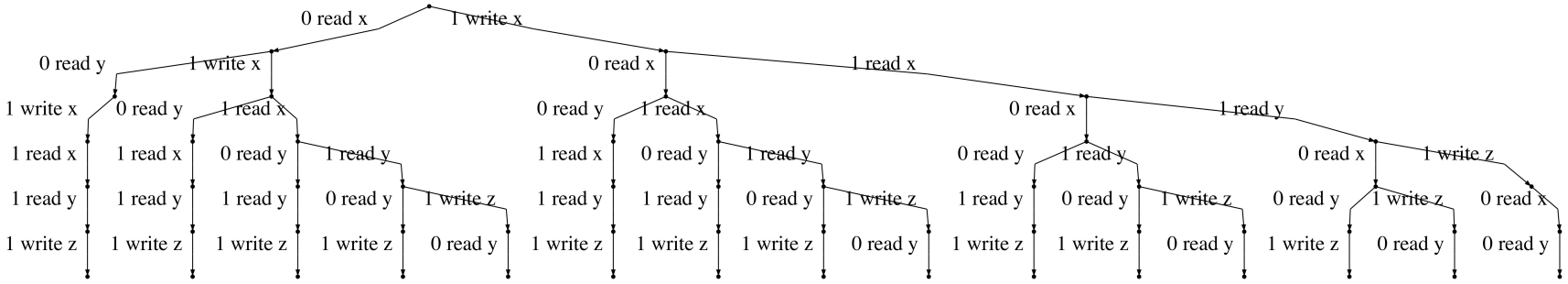
Scheduler

```
void scheduler_thread(schedule)
{
   for (thread_id : schedule)
   {
      wait_until(task_pool.contains_key(thread_id));
      current_thread_id = thread_id;
      semaphore[thread_id].post();
      // notify the waiting thread
   }
}
```

Systematic Exploration

Simple depth-first exploration

State space explosion: becomes infeasible for larger programs



State Space Reduction

- Explore only a subset of interleavings
- Provide coverage guarantees: quantify the class / number of interleavings seen

Bounded Search

```
bounded_search(program, bound_function, bound)
{
   for (interleaving : program.interleavings())
   {
      if (bound_function(interleaving) <= bound)
      {
         explore(interleaving);
      }
   }
}
```

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      }
   }
}
```
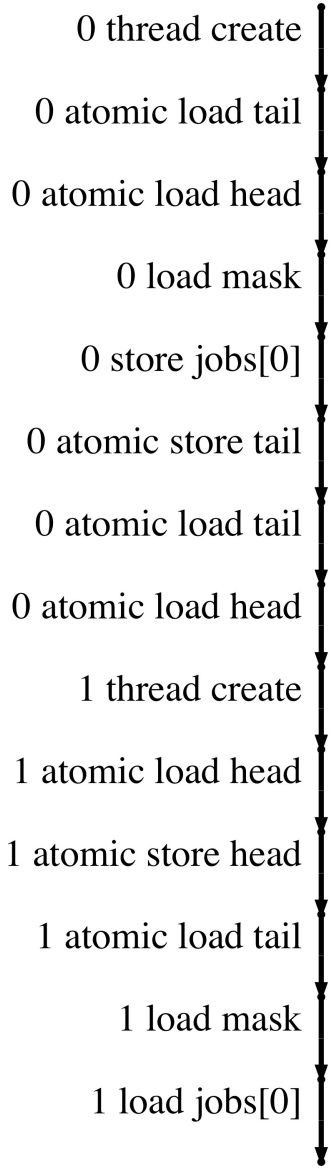

Bound Functions

- Number of context-switches
- Number of preemptions

Bounded Search with Preemption Bound = 0



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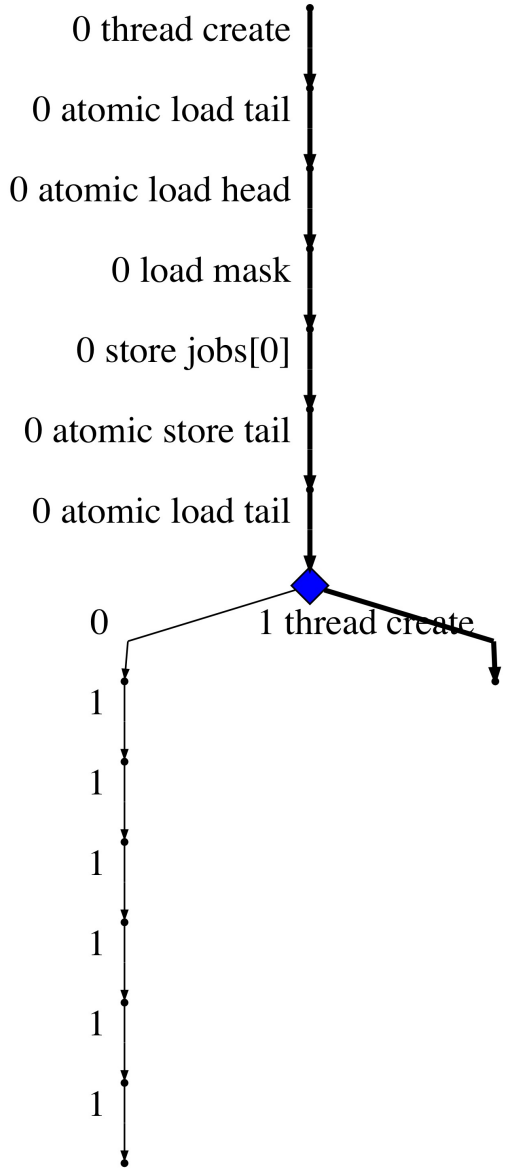

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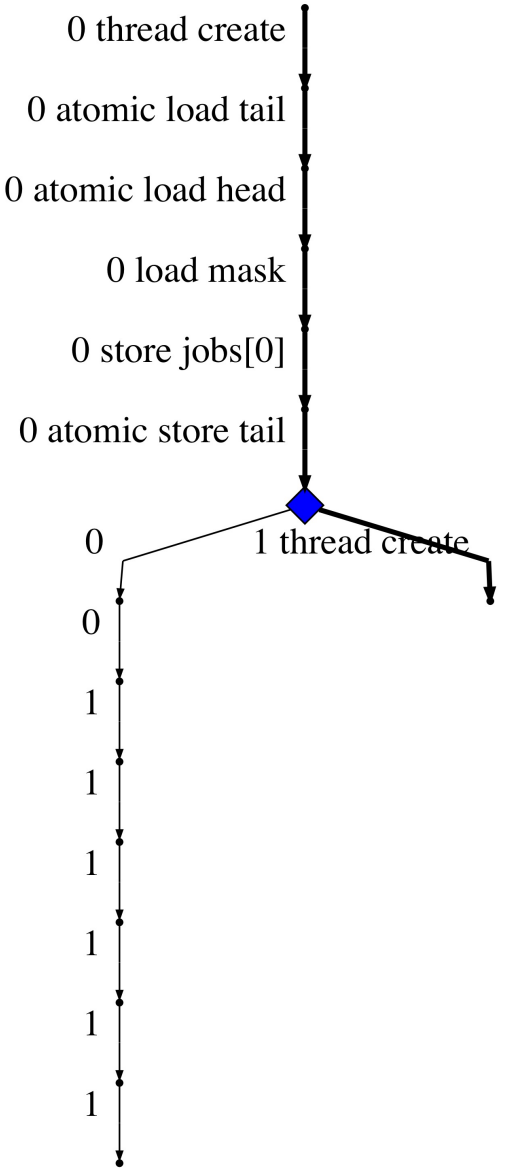

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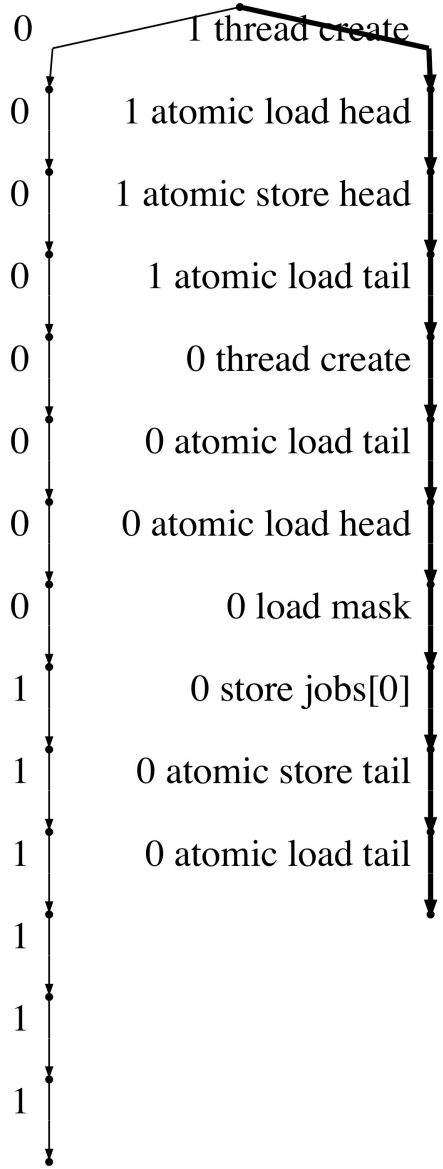
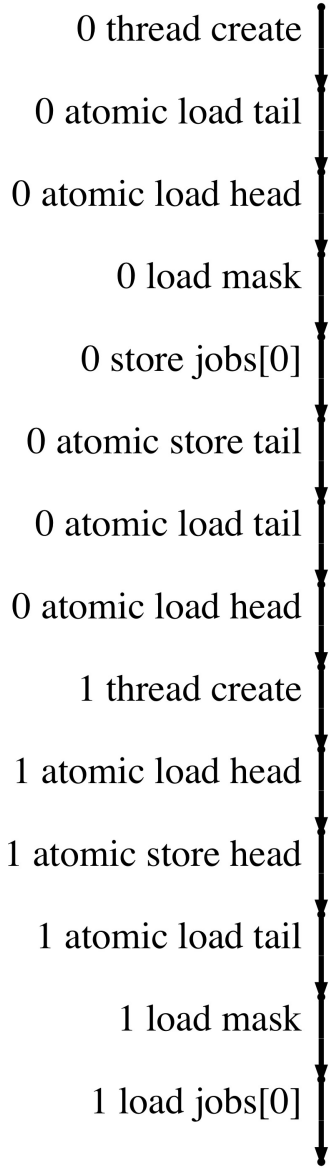


Bounded Search with Preemption Bound = 1



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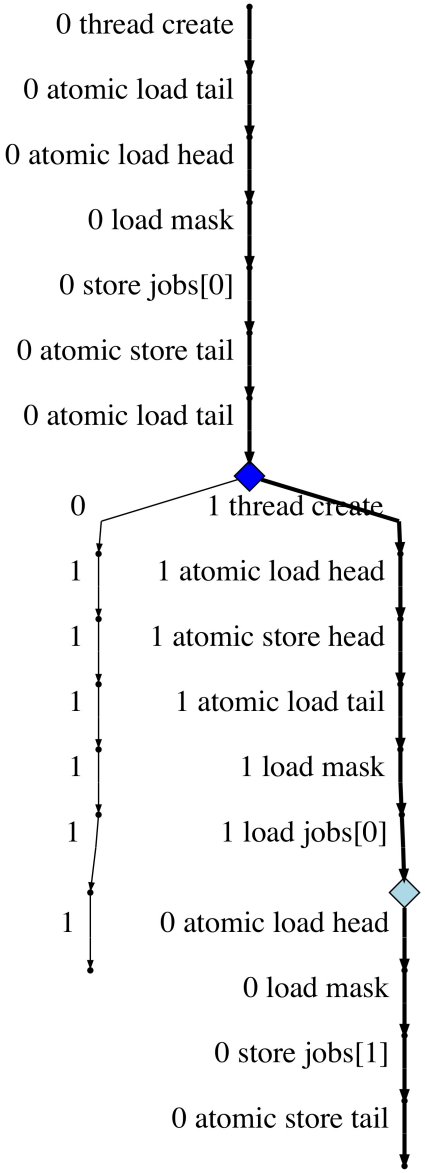

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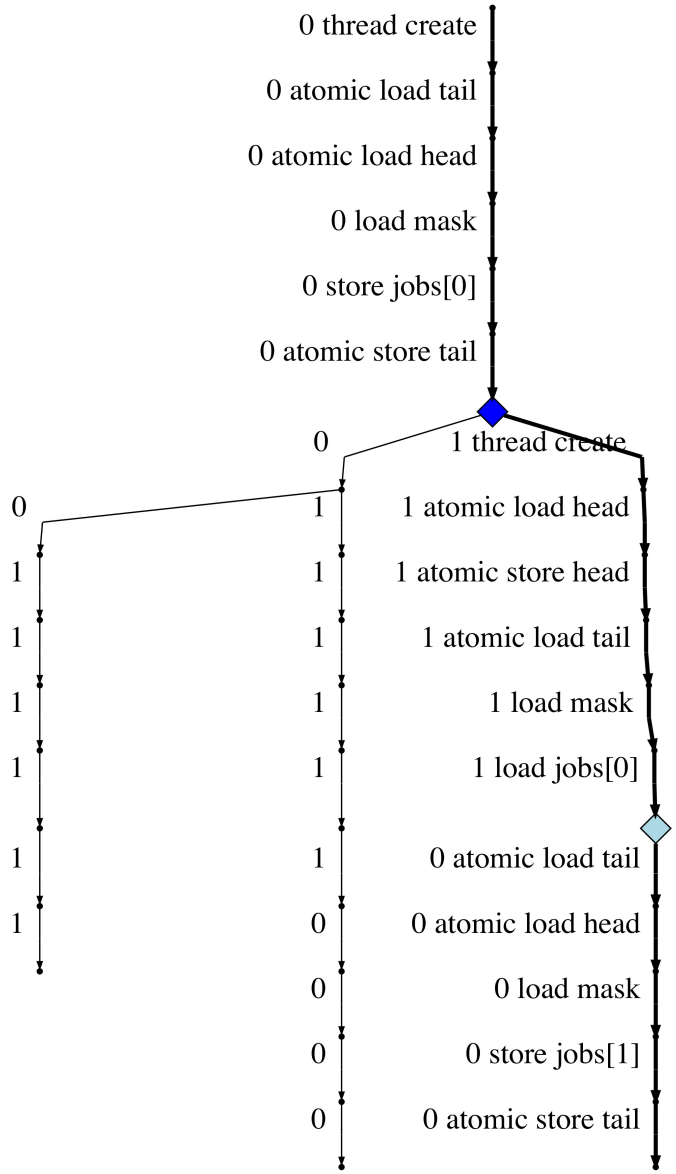

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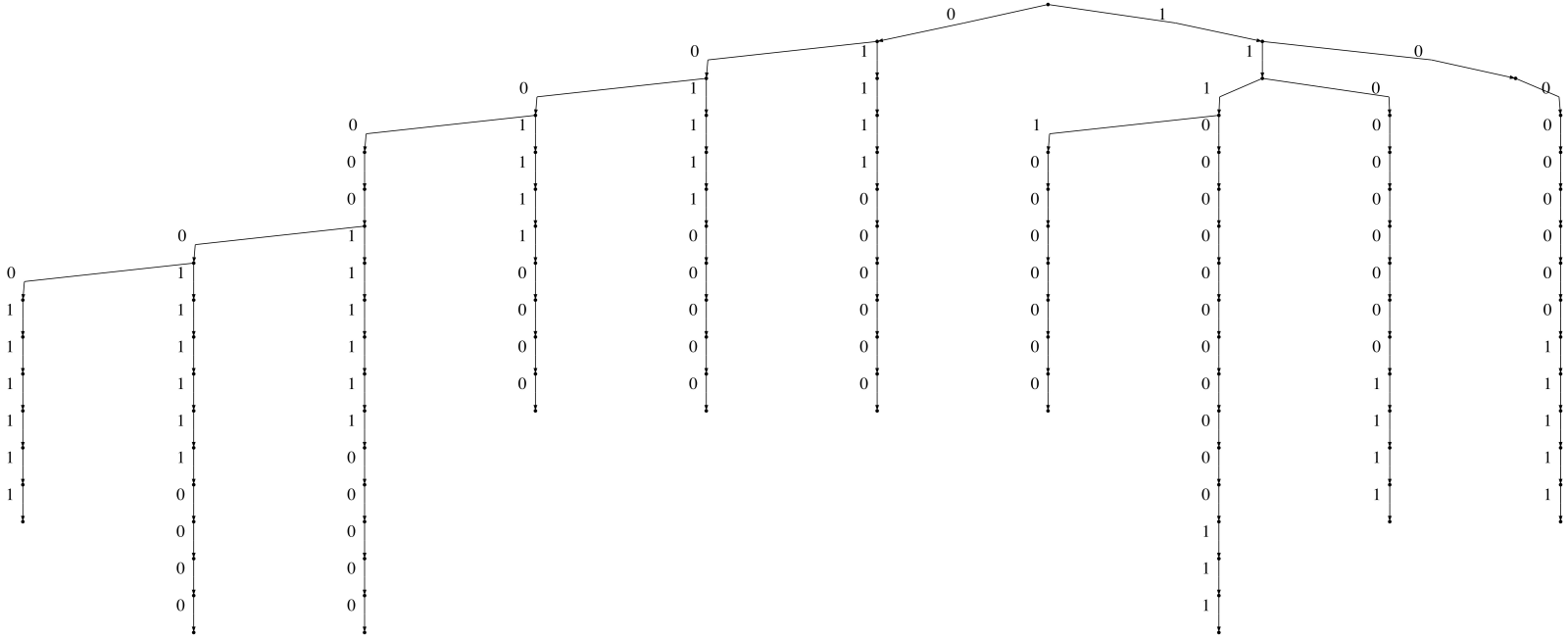

Bounded Search

Advantages:

- Very fast for low bounds
- Quantifiable coverage
- Incremental

Disadvantages:

- Incomplete
- For high bounds not better than depth first search

Partial Order Reduction

Different interleavings may yield *equivalent* executions: Ideally explore only a single one of those

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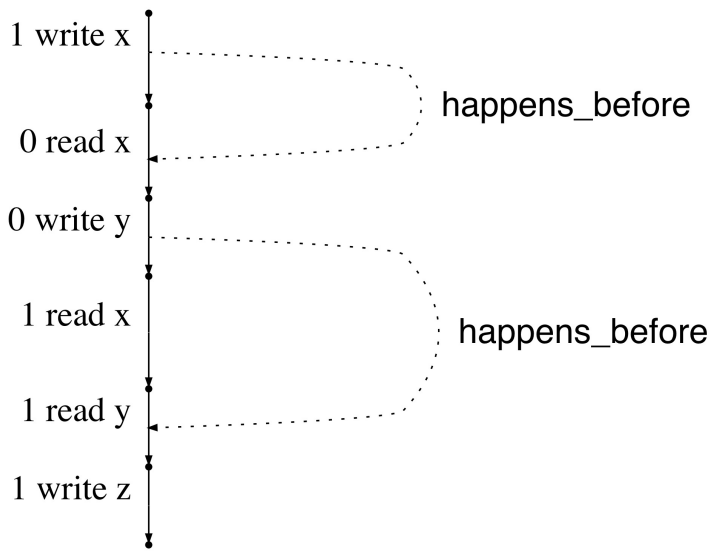
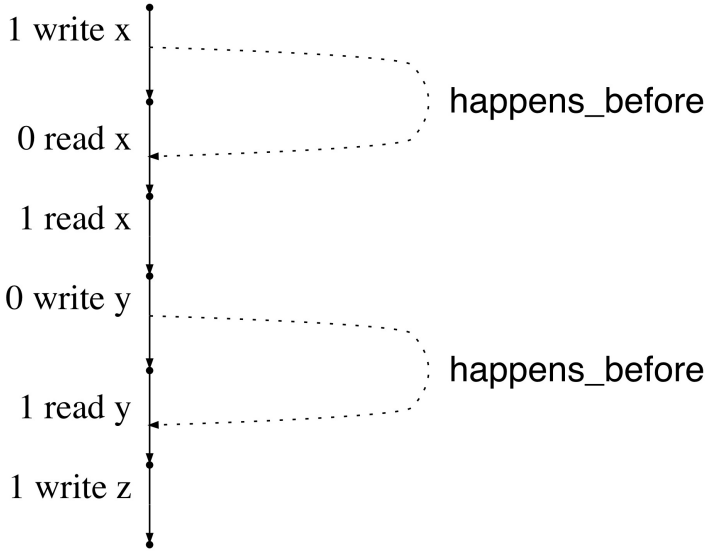
Dependence Relation

```
bool dependent(memory_instr1, memory_instr2)
{
   return same_thread(memory_instr1, memory_instr2) ||
          ( same_operand(memory_instr1, memory_instr2) &&
            memory_instr1.is_write() || memory_inst2.is_write() );
}
```

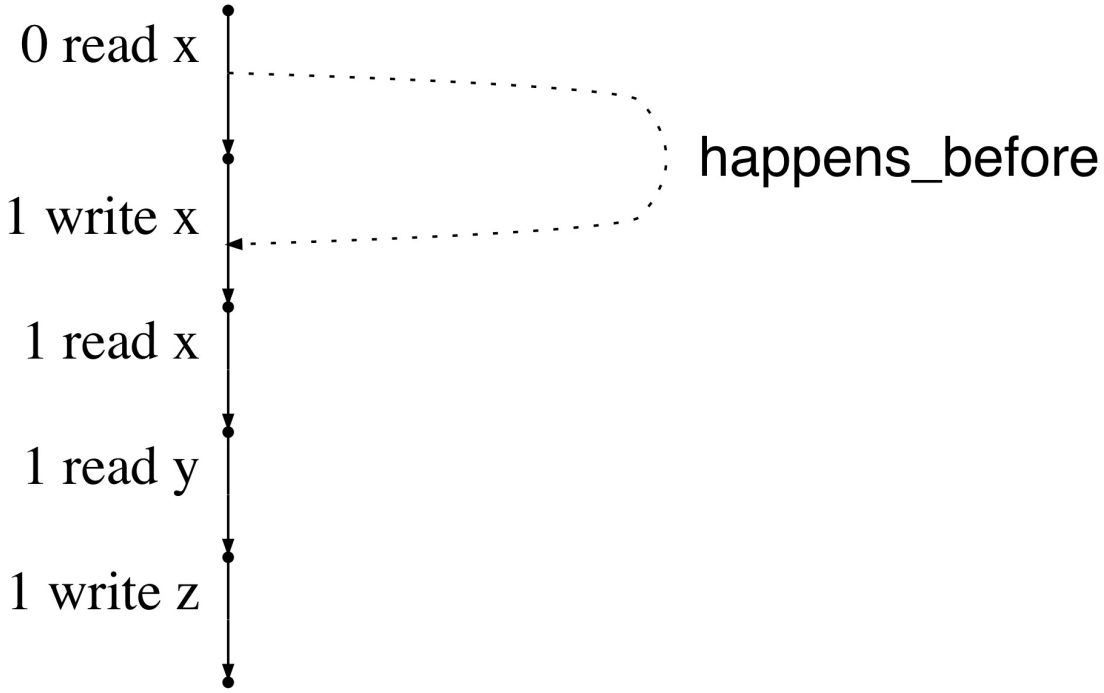
```
bool dependent(lock_instr1, lock_instr2)
{
   return same_thread(lock_instr1, lock_instr2) ||
          ( same_operand(lock_instr1, lock_instr2) &&
            lock_instr1.is_lock() && lock_inst2.is_lock() );
}
```

Partial Order Reduction

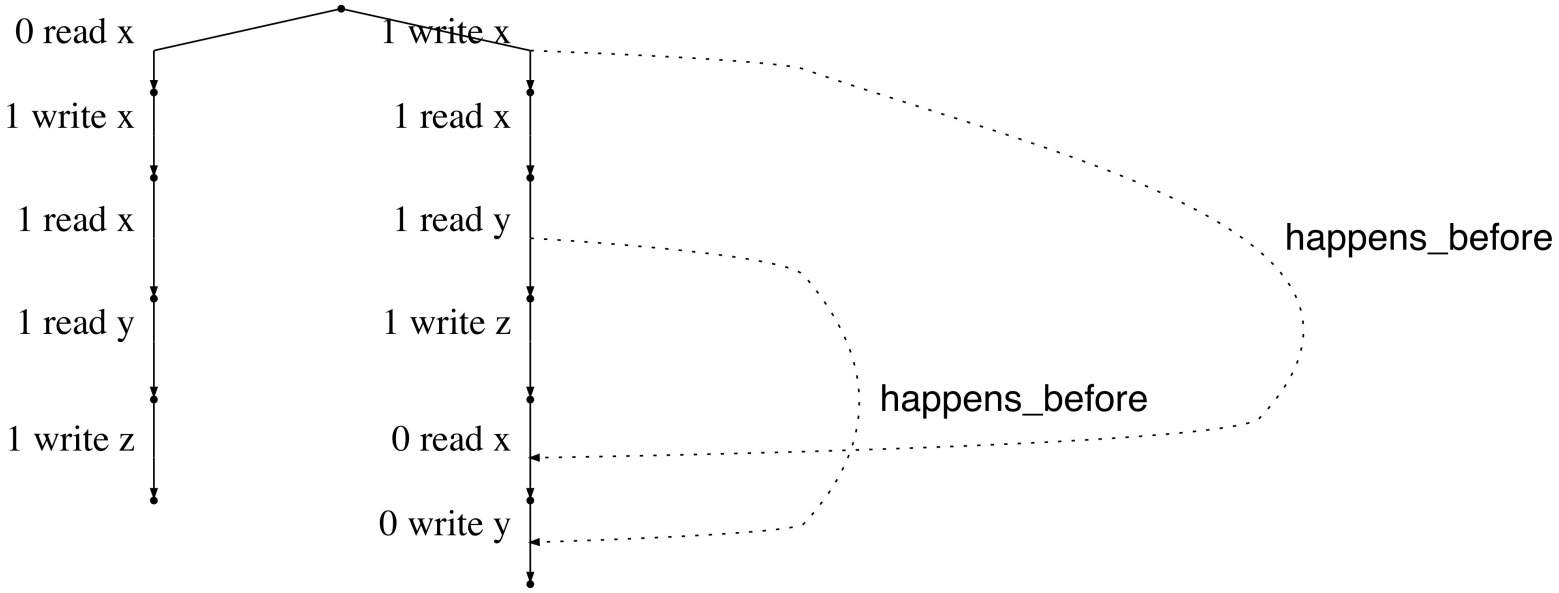




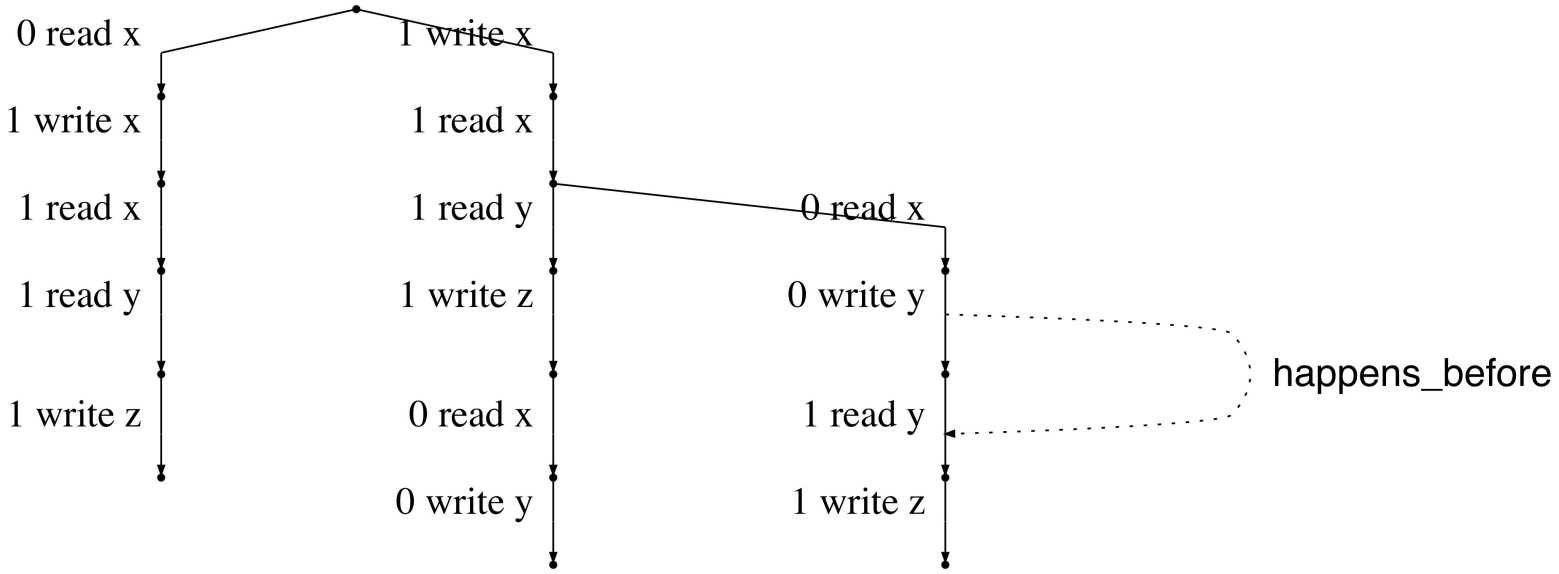
Partial Order Reduction



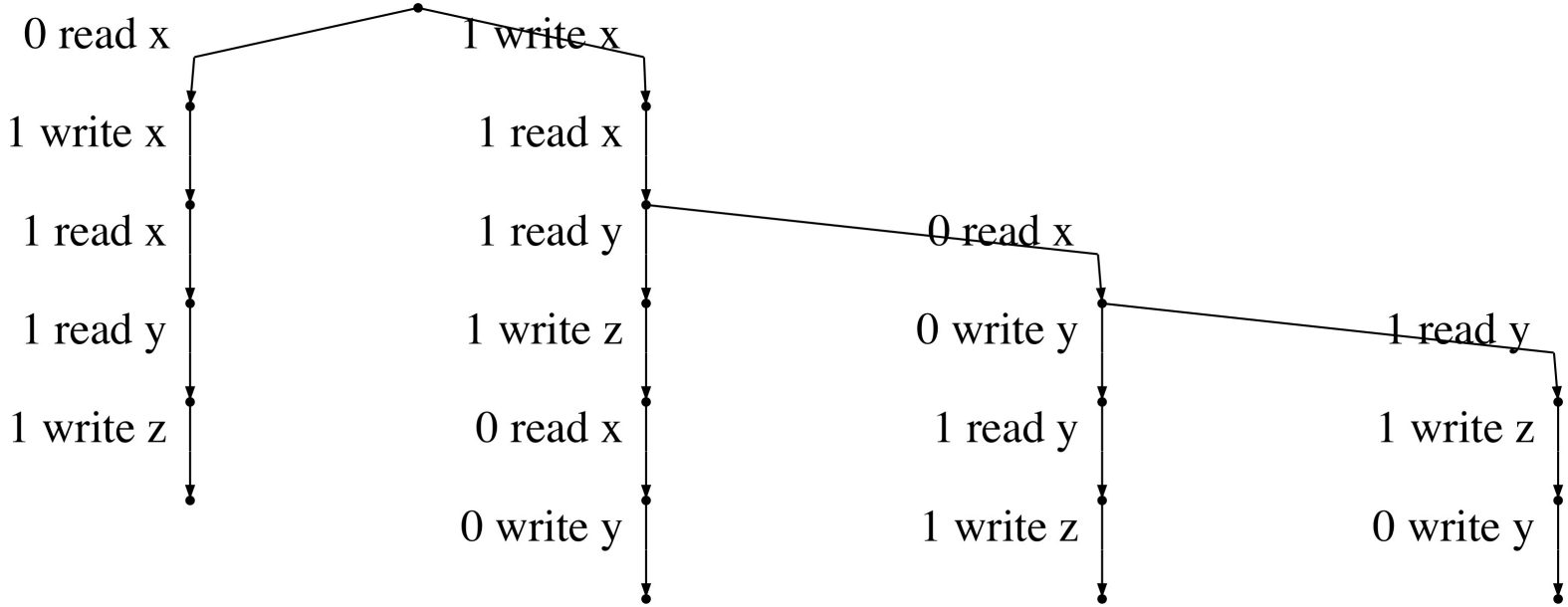
Partial Order Reduction



Partial Order Reduction



Partial Order Reduction



Partial Order Reduction

Advantages:

- Complete coverage

Disadvantages:

- Still infeasible for large state-spaces with many dependencies
- Not incremental

Thank you!

Links

Helgrind

http://valgrind.org/docs/manual/hg-manual.html

ThreadSanitizer:

https://github.com/google/sanitizers/wiki

My Project:

https://github.com/s-vde/record-replay

https://github.com/s-vde/state-space-explorer