4yp

Thomas Aston

May 19, 2024

Contents

1 Introduction **4**

1.1 Contributions 6

2 Related Work **6**

3 Modelling and analysing implementations of locks **9**

3.1 External interfaces 9

3.1.1 Mutual exclusion 10

3.1.2 Deadlock-freedom 11

3.1.3 Livelock-freedom 11

3.2 A simple lock specification 12

3.3 Test-and-Set lock 13

3.3.1 Analysis 15

3.4 Test-and-Test-and-Set lock 16

3.5 Peterson lock 17

3.5.1 Starvation-Freedom 19

3.6 First-come-first-served 21

4 Monitors **23**

4.1 The JVM monitor 24

4.1.1 Modelling the JVM monitor 24

4.2 The SCL monitor 26

4.2.1 The SCL monitor implementation 28

4.2.2 The SCL monitor model 30

4.2.3 The functions and interface of the monitor 36

4.2.4 Correctness 39

4.2.5 Limitations of natural model of the queue 43

5 Barrier synchronisation **45**

5.1 The signalling object 46

5.1.1 Modelling the Signal objects 48

5.2 The Barrier object 50

5.2.1 Modelling the Barrier object 51

5.3 Correctness of the model 52

5.4 Specification processes for the Signal objects 54

6 Conclusions and future work **57**

- Change figure linkings
- Lineariser spelling??
- wait-free? etc
- Process names
- Consistency wrt spurious

- Font colours
- table formatting

1 Introduction

In a world reliant on computer systems, the correctness of those systems is vital. Indeed, simple programming errors can lead to major incidents; examples of these include an automated trader losing $460 million [8] and the inaugural Ariane 5 flight breaking up after launch due to an overflow error [5].

In order to achieve better performance, concurrency can often be introduced to improve the performance of programs or systems, especially those with semi-independent tasks or components. Concurrent systems, be this on a single computer or distributed across a network, achieve these performance improvements at the cost of additional complexity; the design now needs to consider the interactions between threads. Each of possible interactions between threads could potentially lead to a *race condition* in a poorly designed systems; this is where two non-independent actions can occur in an order which produces an incorrect or unwanted outcome. Race conditions can be very damaging in practice: the Therac-25 radiation therapy machine killed three of its patients by radiation overexposure as a result of a race condition [25]. This was caused by the operator quickly changing from the high radiation beam mode to select the lower radiation beam instead; the race condition resulted in the machine erroneously still using the high radiation beam. This highlights the importance of thorough system validation; had more through system verification been completed, these deaths would have likely been avoided [2].

There are two main approaches to developing correct software: testing and verification. Testing can only establish the presence of a bug, not the absence of any; this can be somewhat addressed by writing exhaustive tests to cover every possible edge case, however this imposes severe restrictions on the complexity of such systems. Though thorough unit testing can be effective in reducing software bugs [14], this form of testing is significantly less effective in concurrent contexts. This is due to the inherent non-determinism of event scheduling; this make accuractely testing all possible interactions between threads a significant challenge.

Linearizability testing is an effective alternative approach, although this this relies on the random testing of edge cases; clearly this is not exhaustive either [24]. Explain

By contrast, formal verification can be used to show that systems satisfy some desired properties [3]. This, however, is a complex process and it is often impossible to model check the complete behaviour of a large system simply due to the size of the resulting state space; we instead focus on modelling the concurrent interactions between threads via a variety of synchronisation objects Explain synch objects.

There are two main benefits of this. Firstly, we prove that the synchronisation objects function correctly; debugging concurrent programs is a complex task and bugs due to issues with synchronisation objects can often be particularly challenging to resolve. The second benefit is that we can significantly optimise the model checking of systems that use these primitives. We prove that the synchronisation objects fulfil a specification with the same properties but without all of the internal workings. We can therefore optimise model checking of whole systems by replacing the original synchronisation objects with their respective specification process without changing system behaviour. This allows us to significantly reduce the possible state space of the system, making formal verification of complex systems significantly more feasible.

We choose to use the process algebra Communicating Sequential Processes (CSP) [30] as our tool for modelling these interactions and the accompanying FDR model checker [**GibsonFDR**]. CSP is a language for describing processes that can interact both with their environment and other parallel processes. Since CSP is covered in the Part B Concurrency course [9], we assume familiarity with it (as described in [30]) throughout.

1.1 Contributions

The contributions of this project are as follows:

- We examine a variety of locks from [26] and a number of desirable properties of locks, using CSP refinement checks to determine which properties each lock satisfes. We also discuss the feasibility of modelling infinite liveness properties using CSP, presenting a novel proof that starvation-freedom cannot be captured in CSP.
- We model both the standard JVM monitor and the Scala Concurrency Libraray (SCL) [19] implementation of a monitor, proving that the SCL monitor provides the same mutual exclusion and correctness properties as the JVM monitor but without the same unwanted behaviours.
- We produce a CSP model of a 2-thread synchronisation object and how multiple synchronisation objects can be organised into an arbitrary n-thread barrier synchronisation object. We then use the CSP model to prove the correctness of the barrier synchronisation object.

2 Related Work

Current literature highlights three main approaches to formal verification of software. Such verification can either be done via verification tests written during development, through automated translation of code after development or alternatively through modelling by hand.

Writing verification proofs throughout development allows developers to ensure that their code meets their specification during development. AWS provide an example of this approach, using formal verification methods in code development in order to ensure that their code always meets its specifications [1, 32]. This process involve writing a specification for each function in the form of a number of pre- and post-conditions, with these properties validated automatically. Though similar in style to standard unit-tests, these actual proofs that are continually checked during development, with routine checking of these proofs indicating the correctness (or otherwise) of the code. Though this approach requires more effort during the development and writing process, the ability to detect system design issues during implementation is significantly more helpful than via system testing at the end of development. To aid with this, some languages such as Dafny [16] have been developed with built in model checkers as an extension of this approach; these are however yet to reach mainstream adoption.

Automated code translation is similar, but tends to focus on more generic properties such as detecting deadlocks. NASA developed the Java PathFinder (JPF) in 1999 as one of the first examples of automated verification of code [4]. This was able to detect and alert on deadlocks, unhandled exceptions and assertions, but could not check for correctness against some specification [12]. This limits its utility significantly; code not deadlocking is require but not sufficient for correctness. More modern tools such as Stainless are able to verify some further system properties when given some additional information by the developer [7]. These approaches tend to be inefficient; automated translation has no inherent knowledge about restrictions on the usage of parameters or datatypes, resulting in a potentially very inefficient model.

The final approach to formal verification is to write a model of the code by hand and then verify that model. This approach is more involved and limited in scope than the two alternative methods, but can lead to a larger range of results and additional proofs that the code fulfils certain properties beyond just correctness. It also has the benefit that it is less affected by the state space explosion problem than automated tools.

The state space explosion problem is that adding an additional process or parameter often leads to an exponential increase in the number of states generated by model checkers such as FDR or SPIN [30] better description. Indeed, a single process with a parameter $t : S$ and k states can have k^t states; a network of N of these processes can have N^{k^t} total states. This quickly becomes infeasible to check for even relatively small values of N, k and t. Additionally, a queue can have a potentially infinite number of possible permutations, leading to FDR being unable to generate the complete state space to model check. Insights and smart design can be used to create a smaller, but still correct, model than automated translation methods. This allows for model checking of system with more threads or a wider range of parameter values, leading to greater confidence in their correctness. We therefore focus on this approach.

We choose to use CSP for this task. CSP is very suitable for modelling concurrent systems with tightly restricted communications between threads [15] and allows for natural modeling of system behaviour. Through this, we can effectively use CSP and FDR to model and then check a range of primitives and desired properties. This led to significant verification results previously, most prominently being Lowe's detection of a man-in-the-middle attack on the Needham-Schroeder protocol [17]. It has also been used previously to model software running on the International Space Station, proving that such systems were free of deadlocks[6].

Indeed, CSP has also been successfully used to find bugs in concurrency primitives. Lowe used CSP to model an implementation of a concurrent channel, with FDR returning that the implementation was not deadlock free [20]. This bug was a very niche edge case that required a trace of 37 separate events which had yet to be spotted by hand. The produced trace allowed for a straightforward fix to the code to made to remove the deadlock; this makes it well suited to our needs here as we can both accurately model concurrent datatypes and then easily interpret any resulting error traces.

There are three main styles of concurrent programming as highlighted in [26]: lock-based, message passing and dataype-based concurrent programming. There exists literature on formal verification of the latter two; Lowe has previously proved the correctness of a lock-free queue[18] and also an implementation of a generalised alt operator [21]. There is also more general work on the verification of lock-free algorithms, such as Schellhorn and Bäumler [31]. Their work uses an extended form of linear temporal logic (LTL) and the rely-guarantee paradigm (introduced by [13]) to prove linearizability and lock-freeness properties.

By contrast, there is an lack of research into lock-based concurrency primitives; we therefore focus on this area. better ending

3 Modelling and analysing implementations of locks

In this section we will analyse a number of different lock implementations.

The primary purpose of locks is to provide *mutual exclusion* between threads; that is to avoid two threads from operating concurrently on the same section of code, referred to as the *critical region*. A good lock should also fulfil some *liveness* requirements, essentially that something good will eventually happen. We will present a few models of locks and examine how we can model certain liveness and safety properties using CSP.

3.1 External interfaces

The most straightforward interface of a lock can be seen in Figure 1. This provides a `lock` function for a thread to attempt to gain the lock (blocking if some other thread currently hold the lock) and an `unlock` function for a thread to release the lock.

```
trait Lock{
  /** Acquire the Lock. */
  def lock : Unit
  /** Release the Lock. */
  def unlock : Unit
  ...
}
```

Figure 1: A Scala interface for a simple lock

When a thread t uses a lock l with there are four main events of importance to model in CSP:

- callLock.l.t : The thread calls the lock function;
- lockAcquired.l.t : The thread exits the lock function, now holding the lock;
- lockReleased.l.t : The thread has called the unlock function and the unlock function has been executed to the point where a thread can now reobtain the lock
- end.t : The thread will make no further calls to the lock; this can be used to indicate that the thread has terminated, been permanently descheduled

Throughout the paper, we will use callX to represent a thread calling function X and end.t to represent a thread terminating. The set of all threads is $\mathsf{ThreadID} :: \mathsf{T}.\{0 .. \mathsf{NTHREADS} - 1\}$. We will now specify some ideal properties of locks using these channels:

3.1.1 Mutual exclusion

Mutual exclusion is a safety property which states that at most one thread can hold the lock at any point; i.e. that once thread A acquires the lock, no other thread can obtain the lock until thread A unlocks. We can therefore deduce that a lock l with model X satisfies the trace refinement:

```
Mutex = lockAcquired.l?t → lockReleased.l.t → Mutex
assert  Mutex ⊑T  X \ (Σ − {|lockAcquired.l, lockReleased.l|})
```

3.1.2 Deadlock-freedom

This specifies that if some thread attempts to acquire the lock then a thread will succeed in acquiring the lock[10].

We can express this in the stable-failures model by ensuring that lockAcquired.l is always available to be communicated when some thread has called the lock but not yet obtained it.

```
AcquireLock(l, ts) =
     callLock.l?t:(diff(ThreadID, ts)) → AcquireLock(l, union(ts, {t}))
  □ lockAcquired.l?t:ts → AcquireLock(l, diff(ts, {t}))

assert  AcquireLock(l, {}) ⊑F
    X \ (Σ − {|callLock.l, lockAcquired.l|})
```

AcquireLock takes two parameters: l is the identity of the lock and ts is the set of threads currently which have communicated a callLock but haven't yet acquired the lock. In our refinement check, we will assume that no lock events have occurred prior; ie. no threads have already attempted to acquire the lock.

3.1.3 Livelock-freedom

This requirement specifies that the number of internal actions on a lock must be bounded while no thread holds the lock; i.e. threads can't indefinitely repeat actions whilst the lock is unheld. This can be captured in the failures-divergences model, using a specification process parametised over lock l and a failures-divergences refinement against a system that only has lockAcquired and lockReleased as visible communications.

```
LockSpec(l, ts) = SpecLock(l) [|{|lockAcquired.l, lockReleased.l|}|]
                    (||| t ← ThreadID • SpecThread(l, t))
SpecThread(l, t) =
      callLock.l.t → lockAcquired.l.t → lockReleased.l.t → SpecThread(l, t)
   □ end.t → STOP
SpecLock(l) = lockAcquired.l?t → lockReleased.l.t → SpecLock(l)
```

Figure 2: A non-starvation-free trace specification for a lock

```
LiveUnlocked(l) =    lockAcquired.l?t → LiveLocked(l)
                   ⊓ STOP
LiveLocked(l) =      lockReleased.l?t → LiveUnlocked
                   ⊓ DIV

assert LiveUnlocked(l) ⊑FD X \ (Σ − {|lockAcquired.l, lockReleased.l|})
```

This specification allows the lock to diverge only when it is held by some thread and to be divergence free otherwise. This forces the number of internal actions when the lock is not held to be finite (else it could diverge and the refinement would fail), indicating that no livelock has occured. We allow the specification to non-deterministically STOP when the lock is unheld; this models the effective behaviour of the lock after all threads terminate.

These are three almost essential properties of useful locks; we will consider starvation-freedom later.

3.2 A simple lock specification

Figure 2 shows a simple trace specification for a lock, where l is the identity of the lock and ts is the set of threads that can interact with the lock.

This specification has the properties of mutual exclusion, livelock-freedom and deadlock-freedom; we have verified this by running the three assertions from 3.1.1, 3.1.2 and 3.1.3. As a result, any process which failures-refines this specification also

```
import java.util.concurrent.atomic.AtomicBoolean

/** A lock based upon the test−and−set operation
  * Based on Herlihy & Shavit, Chapter 7. */
class TASLock extends Lock{
  /** The state of the lock: true represents locked */
  private val state = new AtomicBoolean(false)

  /** Acquire the Lock */
  def lock = while(state.getAndSet(true)){ }

  /** Release the Lock */
  def unlock = state.set(false)
}

```

Figure 3: Test-and-set lock from [26]

has these three properties. $\boxed{\text{explanation of why?}}$

3.3 Test-and-Set lock

The Test-and-Set (TAS) lock implementation is based on using an AtomicBoolean called state to capture whether the lock is currently held, with true indicating that some thread holds the lock and false otherwise. The AtomicBoolean, has atomic get and set operations to read and write values respectively. It also has a getAndSet operation which atomically sets the value of the Boolean and returns the old value. The Scala code can be seen in Listing 3. state being false is equivalent to the lock being unlocked; a communication of getAndSet(true) with previous value false indicates that that thread has now obtained the lock.

In order to model the TAS lock, we first need a process that acts as an AtomicBoolean to model the state variable. Figure 4 introduces a process AtomicVar than takes an initial value, and channels get, set : ThreadID.T and getAndSet : ThreadID.T.T for some arbitrary type T.

```
AtomicVar(value, get, set, gAS) =
      get?_!value → AtomicVar(value, get, set, gAS)
   □ set?_?value' → AtomicVar(value', get, set, gAS)
   □ gAS?_!value?value' → AtomicVar(value', get, set, gAS)

```

Figure 4: A process encapsulating an Atomic variable with get, set and getAndSet operations

We therefore represent the `state` variable from the Scala implementation by the following CSP:

```
channel get, set: ThreadID . Bool
channel getAndSet: ThreadID . Bool . Bool
State = Var(false, get, set, getAndSet)
InternalChannels = {|get, set, getAndSet|}
```

A communication on any of the channels is equivalent to a thread calling the corresponding operation in Scala. We use `false` to indicate that no thread holds the lock initially.

We next model the operations of the lock itself. Both operations are trivial to convert, and we can linearize `Lock(t)` when the communication `getAndSet.t.False.True` occurs, indicating that `t` has obtained the lock.

```
Unlock(t) = setState.t! False → SKIP -- def unlock = state.set(false)

Lock(t) = getAndSet.t?v!True → if v == False then SKIP
                                 else Lock(t)
```

We model the threads that are attempting to obtain the lock by a process `Thread(x)`, where `x` is the identity of the thead. Each thread can non-deterministically chooses to either terminate or obtain the lock, release the lock and repeat. Here we use `L.0` as the identity of the lock.

```
Thread(t) =   callLock.L.0.t → Lock(t); Unlock(t); Thread(t)
            □ end.t → SKIP
```

Finally, we construct the lock from its components. We first synchronise all the threads over the get, set and getAndSet channels with the State process. Since getAndSet.t.False.True and setState.t.False are the linearisation points of thread t obtaining and releasing the lock, we can rename these communications to lockAcquired.L.0.t and lockReleased.L.0.t respectively to produce ActualSystemR. Finally, to obtain a system that only visibly communicates the four previously identified events, we hide the internal channels of the lock to produce ActualSystemRExtDiv.

Diagram?

```
-- All initially  do not hold the lock
AllThreads = ||| t : ThreadID • Thread(t)
-- Allow all threads to peform actions on the state variable
ActualSystem = (AllThreads [|InternalChannels|] State)
-- Rename lock acquisition and releasing and hide internal events
ActualSystemR = ActualSystem
                  [[getAndSet.t.False.True \ lockAcquired.L.0.t,
                    set.t.False            \ lockReleased.L.0.t | t <- ThreadID]]
ActualSystemRExtDiv = ActualSystemR \ InternalChannels
```

3.3.1 Analysis

We firstly examine whether this model fulfils the aforementioned properties. The mutual exclusion, deadlock-freedom and livelock-freedom tests from sections 3.1.1, 3.1.2 and 3.1.3 respectively pass. The model also does not diverge before it is first held or when it is not held; these are all expected results. The TAS lock is also equivalent under traces with the earlier lock specification. However, the model can diverge whenever the lock is held. This occurs when a thread (or threads) attempting to obtain the lock perform an infinite number of getAndSet operations. An example trace of this behaviour where T.0 obtains the lock l follows

```
⟨callLock.l.T.0, callLock.l.T.1, getAndSet.T.0.False.True⟩^
  ⟨getAndSet.T.1.True.True⟩^ω
```

```
class TTASLock extends Lock{
  ...
  /** Acquire the lock */
  def lock =
    do{
      while(state.get()){ } // spin until state = false
    } while(state.getAndSet(true)) // if state = true, retry
  ...
}

```

Figure 5: Test-and-test-and-set lock from [26]

This behaviour is expected; thread T.1 is trying to obtain the lock and is being blocked by T.0 which holds the lock. This behaviour is, however, problematic for low-level performance. Any getAndSet operation causes a broadcast on the shared memory bus between the processors, delaying all processors [10]. This also forces each thread to invalidate the value of state from the caches, regardless of whether the value has actually been changed. Since the above trace never results in thread T.1 successfully setting state, it is preferrable to limit the number of getAndSet operations without unneccessarily delaying a thread from obtaining the lock. As a result, we use less costly get operations in order to limit the usage of getAndSet operations; these getAndSet operations are instead limited to situations where they are likely to obtain the lock. Since get does not change the underlying value of a variable, the read will result in at most one cache-miss per set/getAndSet on state; this is a marked improvement.

3.4 Test-and-Test-and-Set lock

The Test-and-Test-and-Set (TTAS) lock makes use of this improvement, whilst otherwise remaining similar to the TAS lock. The sole change is to the lock function, as can be seen in Figure 5, which we then specify in our CSP model as the following:

```
Lock(t) = getState.t?s → if s = True then Lock(t)
```

```
                                        else  gASState.t?v!True → if v = False then SKIP
                                        else  delay ! t  → Lock(t)
```

The TTAS lock can still produce traces with threads performing an unbound number of consecutive operations, however these are now get operations instead of getAndSet operations. The TTAS lock has performs at most one getAndSet operation per thread when the lock becomes available. This is the case when each thread's last communication was get.t.False, indicating that the lock is available and hence leading to a getAndSet communication to attempt to gain the lock.

We now have a linear bound on the number of unsuccessful getAndSet operations, resulting in much more efficient usage of caching and shared memory. This has been verified by synchronising with a regulator process which outputs on an error channel if n getAndSets occur in one locking cycle; this regulator acts as a watchdog. Since the trace refinement is satisfied, we have that no error event has been communicated and hence at most n getAndSets can occur every time the lock is released.

```
channel error
Reg(x) =     gASState?_ → if (x < card(ThreadID)) then Reg(x+1)
                          else  error  → STOP
          □ lockReleased?_ → Reg(0)

assert  LockSpec(L.0, {}, ThreadID)
          ⊑T  ActualSystemR [|{|gASState, lockReleased|}|] Reg(0)
```

3.5 Peterson lock

The Peterson lock is a lock implementation for two threads that provides mutual exclusion, deadlock-freedom and starvation-freedom between threads [28].

Listing 1: The PetersonLock code, adapted from [26]

```
import ox.cads.util.ThreadID
import java.util.concurrent.atomic.AtomicIntegerArray

```

```
class PetersonLock extends Lock{
  private val flag = new AtomicIntegerArray(2)
  @volatile private var victim = 0

  def lock = {
    val me = ThreadID.get; val other = 1−me
    assert(me==0 || me==1,
      "ThreadID needs to be 0 or 1.  Try calling ThreadID.reset first")
    flag.set(me, 1); victim = me
    while(flag.get(other) == 1 && victim == me){ } // spin
  }

  def unlock = { val me = ThreadID.get; flag.set(me, 0) }
}
```

We now consider the CSP model of the Peterson Lock. We first introduce IntArray; this is similar to the Var process earlier but has an index allowing it to store multiple values simultaneously. We also have arguments l and u which specify the lower and upper bounds of the integers stored by IntArray; without this each Entry could theoretically store 2^{32} values, which results in an infeasibly large state space. We do not include the getAndSet operation here as we do not use it in the PetersonLock; it could however be modelled similarly to in Var.

```
IntArray(Ind, init, getI, setI, l, u) =
  let Entry(index, value) =
                get!index?_!value → Entry(index, value)
            □ setI!index?_?value': {l..u} → Entry(index, value')
  within ||| index : Ind • Entry(index, init)
```

We also make a couple of changes to the CSP model compared to the direct translation. Firstly, we store all three variables in the IntArray; this allows us to use the same get and set channels throughout without type errors. victim is now at index 2. WE also bound the IntArray to store values in the range {0..1}; as explained above this allows for efficient model checking in FDR. The rest of the model is a fairly natural translation of the Scala code and we model threads as before.

Listing 2: The CSP implementation of the Peterson Lock

```
channel get, set: Index.ThreadID.{0,1}

Variables  = IntArray(Index, 0, get, set, 0, 1)
InternalChannels  = {|get, set|}

Lock ::  (ThreadID) → Proc
Lock(T.x) =  set.I.x.T.x.1 → set.I.2.T.x.x → WhileLock(T.x)
WhileLock(T.x) =
    get.I.1−x.T.x.0 → SKIP −− Hold lock
□ get.I.1−x.T.x.1 →  get.I.2.T.x?y →
                        if  x =  y then WhileLock(T.x) −− Spin
                        else  SKIP −− Hold lock

Unlock ::  (ThreadID) → Proc
Unlock(T.x) = set.I.x.T.x.0 → SKIP

Thread(T.x) =     callLock.L.0.T.x → Lock(T.x); Unlock(T.x); Thread(T.x)
              ⊓ end.t → SKIP
```

We can then interleave the two threads, synchronise with the IntArray, rename the lock acquistion and released events, and hide all internal communications. Similarly to before we can show that this lock satisfies the properties of mutual exclusion and deadlock- and livelock-freedom. We now consider showing the propety of starvation-freedom.

3.5.1 Starvation-Freedom

Starvation-freedom is a liveness property that states that, under the assumption that no thread holds the lock indefinitely, every thread that attempts to acquire the lock eventually succeeds [10]. It requires that any thread attempting to gain the lock must can only be bypassed by other threads a finite number of times.

One common approach to checking infinite properties in CSP is to hide some (in this case internal) channels and then check that the model does not diverge. This approach does not work here: consider a starvation-free lock which uses busy waiting (repeatedly testing if the lock is available). We have that hiding the internal communications results in a divergence, however the lock is starvation-free. An example of such a lock is the Peterson lock which we examine in section 3.5.

Roscoe and Gibson-Robinson showed that every infinite traces property that can be captured by CSP refinement can also be captured by a finite-traces refinement check when combined with the satisfaction of a deterministic Büchi automaton [29]. A Büchi automaton is an automaton that takes infinite inputs and accepts an input if an accepting state is visited infinitely often Improve [29]. We can, however, show that no deterministic Büchi automaton can capture starvation-freedom.

We will show by contradiction that no such deterministic automaton B can capture starvation-freedom. Let us without loss of generality consider 2-threaded locks.

By the definition of starvation-freedom, the automaton should be satisfied if T.0 acquires and never releases the lock and T.1 attempts to acquire the lock. The automaton therefore must have some accepting state which is visited an infinite number of times when T.0 holds the lock and T.1 attempts to acquire it; we will call this state q_a.

Now we consider the TAS lock from before. This is clearly not starvation-free as the first thread to communicate on getAndSet once the lock becomes available will acquire it; this allows some thread to infinitely bypass some other waiting thread. Consider an execution where T.0 repeatedly acquires and releases the lock, bypassing T.1 which is repeatedly attempting and failing to obtain the lock. This execution, however, passes through the state q_a of B every time T.0 acquires and later releases the lock. This can occur an infinite number of times, resulting in B accepting this execution. This is a contradiction as this execution is not starvation-free (T.1 never obtains the lock) however it still satisfies B.

Improve We hence have that no deterministic Büchi automaton can accurately capture starvation-freedom and hence we cannot test directly for starvation-freedom through a standard FDR refinement check.

3.6 First-come-first-served

We can instead consider capturing the stronger propety of first-come-first-served. Locks that satisfy this property can be split into a *doorway* section of a bounded number of steps and a folowing *waiting* section of a potentially unbounded number of execution steps. This property states that once thread X has completed the doorway section of the lock it cannot be overtaken by a thread Y that has not yet started its doorway section; i.e. X will acquire the lock before Y acquires the lock. This implies starvation-freedom as once X has completed its doorway section, it can only be bypassed by threads who have started their doorway section prior to X.

Checking this propety requires manual renaming of some communication(s) to a new channel doorwayComplete : LockID . ThreadID. The implementation here requires the user to identify the doorway section manually; an automated doorway detector is left as future work. check

We can capture this through a CSP specification which we define below. This is split into four main processes:

- FCFSNotStarted(l, t, s1, s3) indicates that thread t has not called the lock yet. t can either terminate via an end or call the lock.
- FCFSStarted(l, t, s1, s3) indicates that thread t has called the lock and started, but not completed, its doorway section.
- FCFSCompleted(l, t, s1, s3) indicates that thread t has completed its doorway section and is ready to obtain the lock. When it obtains the lock, it transitions back to FCFSNotStarted(l, t, s1, s3).

- FCFSTerminated(l, t) is used when a thread has terminated. We no longer need to keep track of the actions of the other threads as thread t will not obtain the lock again.

At each point in time s1 is the set of states that have completed their doorway section before t started its doorway section; these threads must acquire the lock before t can acquire it under the definition of first-come-first-served. s3 is used to store the set of threads that completed their doorway section after t; once t acquires the lock it cannot reacquire the lock until all the threads in s3 have obtained the lock. This specification only enforces that t cannot bypass other threads that came first. When the specification is ran in alphabetised parallel across all threads it ensures that no thread can bypass another thread; this therefore ensures that no thread can be bypassed.

```
  FCFSNotStarted(l, t, s1, s3) =
     end.t → FCFSTerminated(l, t)
  □ callLock.l.t → FCFSStarted(l, t, s1, s3)
  □ doorwayComplete.l?t':diff(ThreadID, union({t}, union(s1, s3))) → FCFSNotStarted(l,
    t, union(s1, {t'}), s3)
  □ lockAcquired.l?t':diff (union(s1, s3), {t}) → FCFSNotStarted(l, t, diff (s1, {t'}), s3)


FCFSStarted(l, t, s1, s3) =
     doorwayComplete.l.t → FCFSCompleted(l, t, s1, s3)
  □ doorwayComplete.l?t':diff(ThreadID, union({t}, union(s1, s3))) → FCFSStarted(l, t,
    s1, union(s3, {t'}))
  □ lockAcquired.l?t':diff (union(s1, s3), {t}) → FCFSStarted(l, t, diff (s1, {t'}),
    diff (s3, {t'}))

FCFSCompleted(l, t, s1, s3) =
     empty(s1) & lockAcquired.l.t → FCFSNotStarted(l, t, s3, {})
  □ doorwayComplete.l?t':diff(ThreadID, union({t}, union(s1, s3))) → FCFSCompleted(l, t,
    s1, union(s3, {t'}))
  □ lockAcquired.l?t':diff (union(s1, s3), {t}) → FCFSCompleted(l, t, diff(s1, {t'}),
    diff (s3, {t'}))

FCFSTerminated(l, t) =
     doorwayComplete.l?t':diff(ThreadID, {t}) → FCFSTerminated(l, t)
  □ lockAcquired.l?t':diff (ThreadID, {t}) → FCFSTerminated(l, t)
```

We can now verify this property against the Peterson lock implementaion from section 3.5. We place each of the specification processes in parallel, ellowing each to communicate their respective thread's callLock and end events and forcing all of the specifications to synchronise on a doorwayComplete or lockAcquired event on the lock l.

```
FCFSCheck(l) =
  ‖ t ← ThreadID • [union({callLock.l.t, end.t}, {|doorwayComplete.l, lockAcquired.l|})]
        FCFSNotStarted(l, t, {}, {})

PetersonLockDoorway =
  ActualSystemR [[set.l.2.T.0.x \ doorwayComplete.L.0.T.x | x ← {0, 1}]] \
    InternalChannels

assert FCFSCheck(L.0) ⊑F PetersonLockDoorway \ {|lockReleased|}
```

This refinement check passes, indicating that the Peterson lock is indeed first-come-first-served and therefore starvation-free. Testing with the TAS and TTAS lock returns that they are not first-come-first-served; this is as expected as they are not starvation-free.

Mention other locks?? In table?

4 Monitors

This is intended to be used in an earlier background section

A monitor can be used to ensure that certain operations on an object can only be performed under mutual exclusion. Here we first consider the implementation of a monitor used by the Java Virtual Machine (JVM), before considering an alternative implementation that addresses some of the limitations of the JVM monitor.

4.1 The JVM monitor

Mutual exclusion between function calls is provided inside the JVM via synchronized blocks. Only one thread is allowed to be active inside the synchronized blocks of an object at any point; a separate thread trying to execute a synchronized expression will have to wait for the former to release the lock before proceeding. Inside a synchronized block, a thread can also call wait() to suspend and give up the lock. This waits until a separate thread (which can now proceed) executes a notify(), which will wake the waiting thread and allow it to proceed once the notifying thread has released the lock.

It is important to note that the implementation of wait() is buggy. Sometimes a thread that has called wait() will wake up even without a notify(); this is called a *spurious wakeup*.

4.1.1 Modelling the JVM monitor

For our model of a monitor in CSP we have extended the JVMMonitor provided by Lowe [22].

Lowe's module previously provided a single monitor; this is problematic in case we have multiple objects which each require their own monitor. We instead introduce a datatype MonitorID, with this type containing all possible 'objects' that could require their own monitors. The JVMMonitor module is then changed to be parameterised over some subset of MonitorID. The internal channels and processes now also take some MonitorID value to identify which object is being reffered to at any point.

Internally, the model uses one lock per MonitorID. These also have an additional parameter storing the identities of any waiting threads full code in an appendix?. So that it is a faithful model of an actual JVMMonitor we also model spurious wakeups via the spuriousWakeup channel. We therefore run the the lock process in parallel with a regulator process $\mathsf{Reg} = \mathsf{CHAOS}(\{\text{spuriousWakeup}\})$; this is used to non-deterministically allow or block spurious wakeups where appropriate. This is important as when we hide spuriousWakeup events we have that every state in FDR that allows a spuriousWakeup has a pair which blocks the spuriousWakeup. This allows us to perform refinement checks in the stable-failures model instead of just the failures-divergences model, allowing us to write more natural specification processes.

Our model of the monitor provides the following exports:

Listing 3: The interface of the JVMMonitor module; changes are underlined

```
module JVMMonitor(MonitorID)
    ...
    Reg = CHAOS({|spuriousWakeup|})
exports

    -- All events except spuriousWakeup
    events = {| acquire, release , wait, notify , notifyAll |}

    channel spuriousWakeup : MonitorID . ThreadID

    InitialiseAll =
      ||| mon <- MonitorID • (Unlocked(mon, {}) [| {|spuriousWakeup|} |] Reg)

    runWith(obj, P) = P [| events |] (Unlocked(obj, {}) [| {|spuriousWakeup|} |] Reg)

    runWithMultiple(objs, P) =
    P [| events |] (||| obj <- objs • (Unlocked(obj, {}) [| {|spuriousWakeup|} |] Reg))

    -- Interface to threads.

    -- Lock the monitor
    Lock(obj, t) = ...

    -- Unlock the monitor
    Unlock(obj, t) = ...

    -- Perform P under mutual exclusion
    Synchronized(obj, t, P) = ...

    -- Perform P under mutual exclusion, and apply cont to the result.
```

```
    -- MutexC :: (ThreadID, ((a) → Proc) → Proc, (a) → Proc) → Proc
    SynchronizedC(obj, t, P, cont) = ...

    -- Perform a wait(), and then regain the lock.
    Wait(obj, t) = ...

    -- perform a notify()
    Notify(obj, t) = ...

    -- perform a notifyAll()
    NotifyAll (obj, t) = ...

endmodule
```

Each monitor provides Wait(obj, t), Notify(obj, t) and Synchronized(o, t, Proc) methods to model the equivalent functions/blocks in SCL. The Proc parameter is used to specify the process that will be run inside the Synchronized block; the intended usage of this is of the form callFunc.o.t -> Synchronized(o, t, syncFunc) where the process communicates that it is calling the model of fucntion Func before completing the rest of the function whilst holding the monitor lock. runWith(obj, threads) and runWithMultiple(objs, threads) are used to initalise a single monitor with identity obj or multiple monitors with identities objs respectively to synchronise threads that interact with a single object and multiple objects respectively.

4.2 The SCL monitor

There are two main limitations to the standard JVM monitor: it suffers from spurious wakeups and does not allow targeting of notify calls. Spurious wakeups are obviously undesirable and are a common source of bugs where not adequately protected against. Targeting of signals can also be very beneficial to the performance of a program; take for example the one-place buffer shown below in Listing 4. Suppose we have significantly more threads wanting to get a value than put a value. Each notifyAll will awake every thread waiting on a get, even if gets are blocked by ! available. This results in the majority of the threads immediately sleeping again, adding significant overhead. A notifyAll is also required since the JVM monitor makes no guarantees as to which thread is awoke by a notify; as a result repeated notifys could potentially just wake up two thread alternatively, both of which are waiting to perform the same process.

Listing 4: Single placed buffer as an example of the inefficiency of untargeted signals

```
class OneBuff[T] {
  private var buff = null.asInstanceOf[T]
  private var available = false

  def put(x: T) = synchronized {
    while(available) wait()
    buff = x
    available = true
    notifyAll()
  }

  def get : T = synchronized {
    while(! available) wait()
    available = false
    notifyAll()
    return x // not overwritable as we still hold the lock
  }
}
```

The SCL monitor implementation solves both of these issues with a single monitor offering multiple distinct Conditions to allow for more targeted signalling. It is worth noting that these improvements result in the SCL monitor being more computationally expensive than the JVM Monitor. Each individual condition offers the following operations:

- await() is used to wait for a signal on the condition
- signal() is used to signal to a thread waiting on the condition
- signalAll() is used to signal to all the threasd waiting on the condition

Each of these operations should be performed while holding the lock. We can note that these operations are similar to the JVM monitor wait(), notify() and notifyAll() respectively. This functionality is also similar to the java.util.concurrent.locks.Condition class; the primary difference is that the SCL monitor blocks spurious wakeups whereas they are allowing by the JAVA class.

Considering the single-placed buffer, we can use two conditions to separate the threads attempting to get and those trying to put. We can then modify the program above to only perform a single signal towards the threads that are attempting to perform the opposing function, resulting in significant efficiency gains as no threads need to immediately sleep after being woken up.

The implementation of the SCL Monitor [23], makes use of the Java LockSupport class; we explore the implementations of these in the next section and present CSP models. Wording

4.2.1 The SCL monitor implementation

The SCL monitor is implemented in two sections: these are a central Lock and conditions associated with the central Lock. The Lock definition is a re-entrant lock (i.e. one thread can acquire the acquire the lock multiple times whilst it holds it) with a variable locker: Thread which indicates which thread currently holds the Lock. The lock implementation is quite simple and for modelling we will instead use a non-reentrant Lock; this will reduce the size of the FDR model significantly for model checking without removing functionality.

We instead focus on the Condition class. This internally uses a queue of ThreadInfo objects to store the identities of the waiting threads and a Boolean indicating if that thread has been singalled. When a thread calls await() it releases the lock and enqueues a ThreadInfo object into the queue of the respective condition. A signalling thread dequeues a ThreadInfo object from the queue (if non-empty), sets the ThreadInfo's ready value to true indicatign that it has been signalled and then unparks the corresponding thread. signalAll acts similaly to signal, but repeats the above process for all ThreadInfo objects in the queue. We note that we have excluded all code regarding interruptions from the SCL code below: this is to reduce the complexity of the resulting CSP model. The interruption handling is also quite simple - it stops the thread from parking again once it has been interrupted and throws a InterruptedException.

Listing 5: A subset of the Condition class from [23]

```
import java.util.concurrent.locks.LockSupport

/** A condition associated with ‘lock‘. */
class Condition(lock: Lock){
  /** Information about waiting threads. */
  private class ThreadInfo{
    val thread = Thread.currentThread //the waiting thread
    @volatile var ready = false // has this thread received a signal?
  }

  /** Check that the current thread holds the lock. */
  @inline private def checkThread =
    assert(Thread.currentThread == lock.locker,
      s"Action on Condition by thread ${Thread.currentThread}, but the "+
        s"corresponding lock is held by ${lock.locker}")

  /** Queue holding ThreadInfos for waiting threads.
    * This is accessed only by a thread holding lock. */
  private val waiters = new scala.collection.mutable.Queue[ThreadInfo]()

  /** Wait on this condition. */
  def await(): Unit = {
    checkThread
    // record that I'm waiting
    val myInfo = new ThreadInfo; waiters.enqueue(myInfo)
    val numLocked = lock.releaseAll                // release the lock
    while(!myInfo.ready){
      LockSupport.park()                           // wait to be woken
    }                                // reacquire the lock
    lock.acquireMultiple(numLocked)
  }

```

```
  /** Signal to the first waiting thread. */
  def signal(): Unit = {
    checkThread
    if (waiters.nonEmpty){
      val threadInfo = waiters.dequeue()
      if (!threadInfo.ready){
        threadInfo.ready = true; LockSupport.unpark(threadInfo.thread)
      }
      else signal() // try next one; that thread was interrupted or timed out
    }
  }

  /** Signal to all waiting threads. */
  def signalAll() = {
    checkThread
    while(waiters.nonEmpty){
      val threadInfo = waiters.dequeue()
      threadInfo.ready = true; LockSupport.unpark(threadInfo.thread)
    }
  }
}
```

4.2.2 The SCL monitor model

DIAGRAM

We now consider our model of the SCL monitor. This consists of three main components:

- The monitor lock: as described above, we model the re-entrant lock of the implementation with a single entry lock here. This is because a thread could obtain the lock an unbounded number of times, resulting in a potentially unbounded state space in FDR.

  The lock we use is a simple process $\mathsf{Lock(m) = acquire.m?t} \rightarrow \mathsf{release.m.t} \rightarrow \mathsf{Lock(m)}$ which specifies that only one thread can hold the lock and that same thread must release the lock before some other thread can obtain it. This provides mutual exclusion between threads as required.

- The LockSupport module, described in section 4.2.2.1.
- The queue of ThreadInfo values, desribed in section 4.2.2.2.

4.2.2.1 LockSupport

The Java LockSupport [27] class offers two main operations: park and unpark, which are used to suspend and resume a thread respectively. A thread t typically calls LockSupport.park() to suspend itself until a permit becomes available by another thread calling LockSupport.unpark(t). As this is a permit-based system, a permit is stored if a thread calls unpark(t) and t is not yet parked. This allows t to immediately resume when it does call park. It is also important to note that LockSupport is also affected by spurious wakeups where some parked thread can resume without an unpark.

Threads interact with the LockSupport module via three main events: a thread can park itself, a thread can unpark another thread and a parked thread can wake up. We therefore introduce channels park, unpark and wakeUp to represent these three synchronisations. We also use the spurious channel to indicate that the following wake-up is spurious; this will allow us to check that LockSupport can only diverge when an infinite numebr of spurious wake-ups occur.

Internally, the model stores two sets of threads: waiting stores the parked threads and permits stores the threads with permits available. A thread that is parking is either added to the waiting set if no permit is available or it is immediately re-awoken is a permit is available. A thread that is performing an unpark(t) will either awake t if it is currently waiting or store a permit for t. We split our definition into two processes: LockSupport can either nondeterministically allow a waiting thread to spuriously wake-up, or it can act as the deterministic LockSupport1 which initially only communicates park or unpark events. $\boxed{\text{GAVIN???}}$

Listing 6: The CSP model of the Java LockSupport module

```
module LockSupport

  channel park: ThreadID
  channel unpark: ThreadID.ThreadID
  channel wakeUp: ThreadID.Bool

  LockSupport1(waiting, permits) =
    park?t→ (
      if  member(t, permits)
        then wakeUp.t → LockSupport(waiting, diff(permits, {t}))
      else  LockSupport(union(waiting, {t}), permits) )
    □
    unpark?t?t2→ (
      if  member(t2, waiting)
        then wakeUp.t2 → LockSupport(diff(waiting, {t2}), permits)
      else  LockSupport(waiting, union(permits, {t2})))
  LockSupport(waiting, permits) =
    if  waiting = {} then LockSupport1(waiting, permits)
    else  (LockSupport1(waiting, permits)
           ⊓ spurious → wakeUp$t:waiting → LockSupport(diff(waiting, {t}), permits))


  LockSupportDet :: ({ThreadID}, {ThreadID}) → Proc
  LockSupportDet(waiting, permits) = LockSupportDet1(waiting, permits)
  LockSupportDet1(waiting, permits) = ... −− Analogous to LockSupport1

exports

  channel spurious

  InitLockSupport = LockSupport({}, {})

  InitLockSupportDet = LockSupportDet({}, {})

  Park(t) = park.t → wakeUp.t?_ → SKIP

  Unpark(t, t') = unpark.t.t' → SKIP


endmodule
```

4.2.2.2 The ThreadInfo Queue

As seen in listing 5, each Condition maintains a queue of ThreadInfo objects which have a thread id and a variable ready indicating whether the corresponding thread has been unparked. The natural method of modelling this queue in CSP is with a sequence of nodes, a number of processes each corresponding to a node $\boxed{\text{Wording etc}}$ and some co-ordinator processes.

We first consider the ThreadInfo process. Each ThreadInfo process has a corresponding Node which remains unchanged throughout; this allows us to use the Node datatype to specify which ThreadInfo process a thread is interacting with. The ThreadInfo(n) process communicates over five channels:

- channel initialiseNode : Node . ThreadID. A communication of initaliseNode.n.t is used to indicate that ThreadInfo(n) will act as thread t's threadInfo object until it is released.
- channel releaseNode : Node . ThreadID. A communication on this will stop ThreadInfo(n) from acting as t's threadInfo object, it can now be reinitialised by some thread.
- channel setReady : Node . ThreadID . ThreadID is used by some thread to indicate that thread t has been signalled; this is only allowed to occur once per initialisation.
- channel isReady : Node . ThreadID . ThreadID . Bool is used to indicate whether or not thread t has been signalled yet. It is used by t to protect against spurious wake-ups, reparking itself it is has awoken without being signalled.
- channel nodeThread : Node . ThreadID . ThreadID. A communication on this channel of the form nodeThread.n.t.t2 indicates to thread t2 that ThreadInfo(n) is currently initialised by thread t.

The lifecycle of the ThreadInfo process is that some thread t will initialise the ThreadInfo process with its identity after it is performing an await. The ThreadInfo process will then act as that thread's threadInfo object from the Scala implementaion. Its corresponding Node value will then be enqueued in the condition's queue. A thread may then dequeue that Node value vis either a signal or signalAll call; in both cases it will then call setReady.n.t?_ to indicate that that the corresponding thread has been signalled. Once thread t has been unparked and awoken, it checks that it has been signalled via a communication on isReady. When this indicates that t has been signalled, t then communicates a releaseNode event to indicate that it has finished using the corresponding ThreadInfo process. It can then be re-initialised by some other thread and the above lifecycle repeated. We always allow ThreadInfo(n) to communicate on any of its channels, however we diverge whenever some communication occurs that should not be possible in the original Scala code. This allows us to easily check that if the ThreadInfo processes are used correctly; any incorrect usage will lead to a divergence which we can find by checking for divergence-freedom later.

Listing 7: The definition of a ThreadInfo process

```
ThreadInfo :: (Node) → Proc
ThreadInfo(n) =
      initialiseNode .n?t → ThreadInfoF(n, t)
  □ isReady.n?t?t2.true → DIV
  □ setReady.n?t?t2 → DIV
  □ nodeThread.n?t?t' → DIV
  □ releaseNode.n?t → DIV
ThreadInfoF(n, t) =
      isReady.n! t?t2.false → ThreadInfoF(n, t)
  □ setReady.n!t?t2:diff (ThreadID, t) → ThreadInfoT(n, t)
  □ initialiseNode .n! t → DIV
  □ nodeThread.n.t?t' → ThreadInfoF(n, t)
  □ releaseNode.n?t → DIV
ThreadInfoT(n, t) =
      isReady.n! t?t2.true → ThreadInfoT(n, t)
  □ setReady.n!t?t2 → DIV
  □ initialiseNode .n! t → DIV
```

```
□ nodeThread.n.t?t' → ThreadInfoT(n, t)
□ releaseNode.n.t → ThreadInfo(n)
```

Since we are handling n threads and all of them can be waiting at the same time, we hence need n ThreadInfo processes and hence we define the Node datatype as datatype Node = N.{0..n−1}.

We then use a process called NodeAllocator to allocate the Nodes to threads and also to collect them when they are no longer required. We note that any thread can use any node in this model; this is analogous to the nodes being memory chunks allocated to each thread by NodeAllocator and then garbage collected once they are no longer needed.

We note that neither the NodeAllocator nor the Nodes themselves take a MonitorID as a parameter; this is because each thread can only perform an await on one conition or monitor at any point in time. This choice allows us to use the same Nodes across multiple monitors, leading to significantly smaller FDR state spaces when modelling using multiple monitors.

Listing 8: The NodeAllocator process

```
NodeAllocator(ns) =
  (not(empty(ns))) &
    (initialiseNode $n:ns?t → NodeAllocator(diff(ns, {n})))
□ releaseNode?n:ns?t → DIV
□ releaseNode?n:diff(Node, ns)?t → NodeAllocator(union(ns, {n}))
```

Finally we have the Queue processes, which model the queues maintained inside each Condition. Each Queue keeps a sequence of the Node identities waiting on its condition. The Queue processes have three parameters: m is the identity of the SCL monitor and c is the identity of the condition that the queue belongs to; qs is the current state of the queue.

```
Queue(m, c, qs) =
      (not(null (qs))) & dequeue.m.c?t!head(qs) → Queue(m, c, tail(qs))
  □ (null (qs)) & isEmpty.m.c?t → Queue(m, c, qs)
```

```
   □ enqueue.m.c?t?n:diff(Node, QS) → Queue(m, c, qs^<n>)
```

We have that each Queue is always ready to accept an enqueue (unless all nodes are already in the queue), but will only communicate one of dequeue or isEmpty at any point in time. We note that the restriction on the values of n that can be enqueued is such that the queue is of finite length; this is required for efficient model checking in FDR.

4.2.3 The functions and interface of the monitor

Now we have the components of the model of the monitor, the last step is to place these processes in parallel. The majority of these processes are independent of each other; only the NodeAllocator and the ThreadInfo processes need to synchronise with each other, which occurs when a node is either initialised or released.

```
Queues(m, setC) = ||| c ← setC • Queue(m, c, <>)
NodeSystem =
  NodeAllocator(Node)
    [|{|initialiseNode , releaseNode|}|] (||| n ← Node • ThreadInfo(n))

InitialiseMon (m, setC) =
  (Lock(m) ||| Queues(m, setC) ||| NodeSystem ||| InitLockSupport)
```

The first function we export as part of the interface of our module is runWith(P, mon, setC) which each takes a process P representing program threads, an identity for the monitor and a set of conditions on that monitor. This processes synchronises P with the InitialiseMon(m, setC). This is to allow the threads to 'call' the various functions that act on the monitor correctly and so that mutual exclusion between threads can be obtained using the functions of the monitor. Include spurious in next?

```
  ...
  −− The set of events that are hidden when a thread uses the monitor
  HideSet(m, setC) =
    {|park, unpark, wakeUp, enqueue.m.c, dequeue.m.c, initialiseNode, nodeThread,
      setReady, isReady, isEmpty.m.c, releaseNode | c ← setC|}

```

```
  -- The set of events to synchronise on between a thread and the monitor
    SyncSet2(m, setC) = Union({{|acquire.m|}, {|release.m|}, HideSet(m, setC)})

exports

  channel spurious
  channel acquire, release : MonitorID.ThreadID
  channel callAcquire, callRelease : MonitorID.ThreadID
  channel callAwait, callSignalAll : MonitorID.ConditionID.ThreadID
  channel callSignal : MonitorID.ConditionID.ThreadID

  -- Runs the monitor with internal spurious wakeups
  runWith(P, mon, setC) =
    ((P [|SyncSet(mon, setC)|]
          InitialiseMon (mon, setC)) \ HideSet(mon, setC))

  -- Runs the monitor without internal spurious wakeups
  runWithDet(P, mon, setC) =
    ((P [|SyncSet(mon, setC)|]
          InitialiseMonDet (mon, setC)) \ HideSet(mon, setC))

  ...
```

In the definitions above, SyncSet contains every event that we need to synchronise on between a series of threads and the monitor. We then hide all events except for those representing a thread acquiring and releasing the lock; this is the contents of HideSet.

We now consider the operations offered by the monitor. We have the interface given below, with each of the five operations corresponding to the function of the same name. Each process starts with a communication on the correspondingly named callX channel to indicate that the specified thread has just called that function; this makes examining any traces produced significantly simpler. We will refer to these callX communications as 'external' and all other channels as being 'internal'. Better convention for placeholder values?

```
export
  ...

  -- Operations on the monitor
  Await(mon, cnd, t) = callAwait.mon.cnd.t → Await1(mon, cnd, t)
```

```
Signal (mon, cnd, t) = callSignal .mon.cnd.t → Signal1(mon, cnd, t)

SignalAll (mon, cnd, t) = callSignalAll .mon.cnd.t → SignalAll1(mon, cnd, t)

Lock(mon, t) = callAcquire .mon.t → acquire.mon.t → SKIP

Unlock(mon, t) = callRelease .mon.t → release.mon.t → SKIP

endmodule
```

Both Lock and Unlock both only require a single internal communication (either acquiring or releasing the lock) after the thread's external communication. By contrast Await, Signal and SignalAll are more complex, so the initial external communication is followed by another process, in each case named X1. Each of these processes are natural translations of the Scala code into CSP; the main exception is using Await2 to represent the while loop in the Scala await() function.

```
Signal1(mon, cnd, t) =
      isEmpty.mon.cnd.t → SKIP
  □ dequeue.mon.cnd.t?n → nodeThread.n?t2!t → isReady.n.t2.t?b →
        (if b then Signal1(mon, cnd, t)
        else setReady.n.t2.t → Unpark(t, t2))

SignalAll1 (mon, cnd, t) =
      isEmpty.mon.cnd.t → SKIP
  □ dequeue.mon.cnd.t?n → nodeThread.n?t2!t → setReady.n.t2.t →
          Unpark(t, t2); SignalAll1 (mon, cnd, t)

Await1(mon, cnd, t) =
  initialiseNode ?n!t → enqueue.mon.cnd.t.n → release.mon.t → Await2(mon, cnd, t, n)

Await2(mon, cnd, t, n) =
  isReady.n.t.t?b → (if b then releaseNode.n.t → acquire.mon.t → SKIP
                      else Park(t); Await2(mon, cnd, t, n))
```

4.2.4 Correctness

We now consider the correctness of our model. We present a specification process for a idealised monitor with conditions and perform refinement checks against it. We show that the ordering of awaits is also upheld by a separate refinement check.

We will first consider the specification process of a monitor with multiple conditions. Each monitor process is parameterised over the identity of the monitor and a map of ConditionID => {ThreadID} representing the set of threads waiting on each Condition. We choose to use sets of waiting threads instead of queues of waiting threads to make this a more general specification of a monitor and it is also more efficient. We consider orderings in a later test. initSet is the initial mapping of the waiting threads, with each condition mapping to an empty set. We define valuesSet as a helper function which returns a set of all the threads that are currently waiting on any condition; this allows us to restrict the specification to only allow threads that aren't waiting to obtain the lock.

```
initSet = mapFromList(<(c, {}) | c ← seq(ConditionID)>)
valuesSet (map) = Union({mapLookup(map, cnd) | cnd ← ConditionID})
Spec2Unlocked(m, waiting) =
  SCL::acquire.m?t:diff(ThreadID, values(waiting)) → Spec2Locked(m, t, waiting)

Spec2Locked(m, t, waiting) =
  □ c': ConditionID •
      (
          (mapLookup(waiting, c') = {}) & SCL::callSignal.m.c'.t →
              Spec2Locked(m, t, waiting)
        □ (mapLookup(waiting, c') ≠ {}) &
              ⊓ t': mapLookup(waiting, c') • SCL::callSignal.m.c'.t →
                  Spec2Locked(m, t,
                              mapUpdate(waiting, c', diff (mapLookup(waiting, c'), {t'})))
      )
  □ SCL::callSignalAll.m?c:ConditionID!t →
              Spec2Locked(m, t, mapUpdate(waiting, c, {}))
  □ SCL::callRelease.m.t → SCL::release.m.t →
          Spec2Unlocked(m, waiting)
```

```
  □ SCL::callAwait.m?c:ConditionID!t → SCL::release.m.t →
        Spec2Unlocked(m, mapUpdate(waiting, c, union(mapLookup(waiting, c), {t})))


Spec2Thread(t, m) = SCL::callAcquire.m.t → SCL::acquire.m.t → Spec2Thread2(t, m)
Spec2Thread2(t, m) =
     SCL::callAwait.m?c.t → SCL::release.m.t → SCL::acquire.m.t → Spec2Thread2(t, m)
  □ SCL::callRelease.m.t → SCL::release.m.t → Spec2Thread(t, m)
  □ SCL::callSignalAll .m?c.t → Spec2Thread2(t, m)
  □ SCL::callSignal .m?c.t → Spec2Thread2(t, m)

Spec2SCL = (let m = SigM.S.0 within
  (Spec2Unlocked(m, initSet) [|SpecChans(m, ConditionID)|]
      (||| t ← ThreadID • (Spec2Thread(t, m)))))

```

We first note that the specification process provided is divergence free; we choose this as an idealised monitor should never internally diverge. We use the technique of having multiple threads linear

To test against this specification, we interleave a number of process of ThreadSCL(t), with each of these representing the potential (correct) usage of the monitor that thread t could perform. These are interleaved to form ThreadsSCL and then this is then synchronised with the SCL monitor, via the use of runWith or runWithDet as outlined above.

```
ThreadSCL(t) = SCL::Lock(SigM.S.0, t); ThreadSCL1(t)
ThreadSCL1(t) =
  □ c : ConditionID •
     (
         (SCL::Await(SigM.S.0, c, t); ThreadSCL1(t))
       □ (SCL::Signal(SigM.S.0, c, t); ThreadSCL1(t))
       □ (SCL::Signal(SigM.S.0, c, t); ThreadSCL1(t))
       □ (SCL::SignalAll (SigM.S.0, c, t); ThreadSCL1(t))
     )
  □ (SCL::Unlock(SigM.S.0, t); ThreadSCL(t))

ThreadsSCL = ||| t←ThreadID • ThreadSCL(t)

SCLSystemSpur = SCL::runWith(ThreadsSCL, SigM.S.0, ConditionID)
SCLSystem = SCLSystemSpur \ {spurious}
```

```
assert SCLSystemSpur :[divergence free]
assert not SCLSystem :[divergence free]
```

We have that both the assertions pass: SCLSystemSpur is divergence free, but hiding the spurious channel introduces divergences. Since the system is divergence-free with the spurious channel visible, we can conclude that spurious wake-ups don't lead to a state where the system can diverge without more spurious wake-ups. We can therefore conclude that the divergences of the system with spurious hidden are only due to repeated spurious wakeups

We note that using the stable failures-model is normally inappropriate for a system that can diverge. However, this is valid here as for any state that could be unstable due to repeated hidden spurious wakeups there exists a corresponding stable state where the non-deterministic choice in the LockSupport model blocks the spurious event.

```
assert SpecSCL ⊑_F (SCLSystem)
```

We have that this the assertion holds, indicating that the SCL monitor fulfils the specification of a monitor as required.

We next consider the fairness of the monitor with regards to individual signal calls. In the SCL monitor, queues are used so that each signal wakes the thread that has been waiting for the longest time on the condition (if one exists). We test that this property holds using OrderCheck, a process which maintains a list of the threads waiting on each condition in the order that they started waiting. OrderCheck effectively acts as a watchdog, completing a communication over the new channel error if an error in ordering is detected; we therefore verify this has not occured by a trace refinement against the specification.

We choose to use a watchdog as the left hand side of any assertion has to be normalised by FDR. Normalisation is an expensive process for complex specifications with many states; maintaining queues of waiting threads on each condition is therefore more suited to the right-hand side of an assertion as this does not require normalisation. For further details, see [30].

```
valuesSeq(map) = Union({set(mapLookup(map, cnd)) | cnd ← ConditionID})
channel error : MonitorID
OrderCheck(m, waiting) =
      SCL::acquire.m?t:ThreadID →
      (if member(t, valuesSeq(waiting)) then error.m → STOP--DIV
        else OrderCheck(m, waiting))
   □ SCL::callAwait.m?c?t →
      (if member(t, valuesSeq(waiting)) then error.m → STOP
        else OrderCheck(m, mapUpdate(waiting, c, mapLookup(waiting, c)^<t>)))
   □ SCL::callSignalAll .m?c?_ →
        OrderCheck(m, mapUpdate(waiting, c, <>))
   □ SCL::callSignal .m?c?_ →
      (if null (mapLookup(waiting, c)) then OrderCheck(m, waiting)
        else OrderCheck(m, mapUpdate(waiting, c,
                                    tail (mapLookup(waiting, c)))))
```

This new process only synchronises on the events ; this is sufficient to detect any threads which have non-spuriously woken up before they should.

To run the refinement checks, we place OrderCheck in parallel with SCLSystem. We only synchronise on events that that indicate a thread waking, waiting or acquiring the lock; these are all the communications offered by OrderCheck except for error.m.

We then check that this still trace refines SpecSCL, which it does. We can therefore conclude that no error events occur and no new stable failures are introduced, hence the ordering within the model of the SCL monitor are maintained correctly.

```
assert SpecSCL ⊑T (OrderCheck(SigM.S.0, initSeq)
                   [|{|SCL::callAwait.SigM.S.0,
                       SCL::acquire.SigM.S.0,
                       SCL::callSignal .SigM.S.0,
                       SCL::callSignalAll .SigM.S.0|}|] SCLSystem)
```

4.2.5 Limitations of natural model of the queue

Though the model given above is a natural model of the SCL monitor, this is quite ill-suited to refinement checking in FDR. The current implementation of the ThreadInfo allows any thread to obtain and use any of the Nodes; this leads to exponential blow up in the number of states as the number of threads increases. Considering a case where we have n threads and m are currently waiting with their nodes queued, this has $\binom{n}{m}$, or $O(n^m)$ permutations.

We can instead use the same nodes, but restrict them so that each node N.x can only be used by the respective thread T.x. This forces each thread to use the same ThreadInfo each time, removing this source of blow up. This is most trivially done by changing Await1 to specify the node to initialise and not a random one allocated by NodeAllocator i.e. as follows:

```
Await1(mon, cnd, t) = initialiseNode .N.t → ...

NodeAllocator(ns) =
    (not(empty(ns))) & (initialiseNode ?n:ns?t → NodeAllocator(diff(ns, {n})))
  □ ...
```

We will refer to this version of the queue as the 'Simple' model. This simplified model has one possible bijective mapping of threads to nodes. By contrast, the natural model has $n!$ bijective mappings of threads to nodes. As a result, for every single state that the model with the simplified queue can be in, there are upto $n!$ states of the natural model that are identical in all manners other than the node allocations.

For further performance improvements, we can also remove the node allocator process as each node is pre-allocated. Additionally we can change the type signature of Node to N.ThreadID and simplify many of the channels (removing nodeThread and releaseNode entirely) as node indicates which thread it corresponds to as follows:

```
datatype Node = N.ThreadID
```

```
channel enqueue: MonitorID.ConditionID.Node
channel dequeue: MonitorID.ConditionID.ThreadID.Node
channel setReady: Node.ThreadID
channel isReady: Node.ThreadID.Bool
channel initialiseNode : Node
channel isEmpty: MonitorID.ConditionID.ThreadID
channel await, signalAll : MonitorID.ConditionID.ThreadID
```

All the definitions remain the same apart from removing any nodeThread and releaseNode communications and the required type changes. We keep initialiseNode to so that a thread can use it to indicate it is initialising a 'new' ThreadInfo object and hence to reset the ready value to false. We also change InitialiseMon and InitialiseMonDet to remove the NodeAllocator; each of the individual ThreadInfo processes are still interleaved as before. We will refer to this as the 'optimised' version.

We first need to check that this simplified model remains correct. The refinement checks still all pass, indicating that the monitor model with a modified queue fulfills the specification similarly wording to the natural queue model.

We next verify that the efficiency improvements occurs in practice too. We do this by running the FDR verification of assert SpecSCL [F= SCLSystem for a range of numbers of threads and conditions. We then compare the number of states generated by the different queue models, with the results presented in table 1.

Here we see that the restricted model with each thread allocated a single node to use results in a state space reduced by a factor of at least $n!$ where n is the number of threads. This is as expected due to the reduction in the mappings from threads to nodes as stated above. Though the state space still grows exponentially with the simplified queues, it is exponentially more efficient and makes refinement checks for larger numbers of threads and conditions significantly more feasible.

Table 1: The number of states generated by FDR for the different queue implementations. The improvement value is given as the $\frac{\text{Original number of states}}{\text{Reduced number of states}}$

No. threads	No. conditions	Number of states Natural	Simple	Improvement	optimised	Improvement
2	1	2288	1088	2.10	904	2.53
3	1	239428	36262	6.60	26494	9.04
4	1	3.14×10^7	1180416	26.7	792240	39.7
5	1	5.39×10^9	4.06×10^7	133	2.59×10^7	208
2	2	4932	2382	2.07	2382	2.40
3	2	686896	106672	6.44	82973	8.27
4	2	1.22×10^8	4655652	26.2	3363492	36.3
2	3	8436	4106	2.05	3634	2.32
3	3	1445008	227512	6.35	184276	7.84
4	3	3.15×10^8	1.22×10^7	25.9	9212868	34.2

5 Barrier synchronisation

A *barrier synchronisation* object is used to synchronise some number of threads. This allows for a program with threads working on some shared memory which all threads can update to use a number of rounds of synchronisation in order to ensure thread-safety. Programs which use *global synchronisations* (synchronising all threads) typically operate by instantiating some barrier object and then having each thread call `sync` on the barrier once they have completed their current round. Each call to `sync` only returns after all threads have called `sync`, synchronising all the threads at that point in time and allowing the threads to proceed afterwards [19].

Here we model and analyse an `n` thread barrier synchronisation object which internally uses a binary heap of `n` two-thread signalling objects.

5.1 The signalling object

We first consider the signalling object Signal. This is used to synchronise between a 'parent' and 'child' thread, providing three external methods:

- signalUpAndWait is used by the child to signal to the parent that the child is ready to synchronise and waits until the parent signals back;
- waitForSignalUp is used by the parent to wait for the child to be ready;
- signalDown is used to indicate to the child that the synchronisation has completed.

Internally, the Signal object makes use of a private Boolean variable state with true indicating that a child is waiting and false otherwise. The use of this variable is protected by a monitor. The Scala code for the Signal object can be found in figure 9.

Listing 9: The Scala code for the Signal object

```
private class Signal{
  /** The state of this object. true represents that the child has signalled,
    * but not yet received a signal back. */
  private var state = false

  /** Signal to the parent, and wait for a signal back. */
  def signalUpAndWait = synchronized{
    require(!state,
      "Illegal state of Barrier: this might mean that it is\n"+
      "being used by two threads with the same identity.");
    state = true; notify()
    while(state) wait()
  }

  /** Wait for a signal from the child. */
  def waitForSignalUp = synchronized{ while(!state) wait() }

  /** Signal to the child. */
  def signalDown = synchronized{ state = false; notify() }
}
```

The signalUpAndWait function first asserts that there currently is no other child waiting for the parent to complete a signalDown; this ensures that we do not have more than one child using the same Signal object. It then sets state to true, indicating that the child is now waiting and it notifies the parent, awaking them if they are waiting. It then forces the child thread to wait until the parent sets state to false and notifies the child; the use of the while loop here is to guard against spurious wakeups.

waitForSignalUp is used by a parent to wait for the child node to perform a signalUpAndWait and notify the parent; the while loop again guards against spurious wakeups.

The signalDown function is used to signal to the child that the synchronisation has been completed and that the child can return from its signalUpAndWait call.

5.1.1 Modelling the Signal objects

We use our model for a JVM monitor from $\boxed{\text{REF}}$ in our modelling of the Signal object. $\boxed{\text{Wording}}$ An interacting thread will run the CSP process of the equivalent Scala function, here referred to as Func. In each case these first communicates a callFunc before running the syncFunc process within a Synchronized block as outlined previously in section $\boxed{\text{REF}}$ 3.

$\boxed{\text{From signal-scala.csp}}$

Listing 10: The state variable(s) and the function call channels

```
channel getState, setState : SignalID . ThreadID . Bool
stateChannels(s) = {|getState.s, setState.s|}

State :: (SignalID) -> Proc
State(s) = Var(false, getState.s, setState.s)

channel callSignalUpAndWait, callWaitForSignalUp, callSignalDown : SignalID . ThreadID
signalChannels = {|callSignalUpAndWait, callWaitForSignalUp, callSignalDown|}

```

We first initialise the state variable, with the SignalID parameter in the channels indicating the Signal object the variable corresponds to. We also introduce the function call channels as indicated above.

Listing 11: The CSP model of the signalUpAndWait function of the Signal object

```
SignalUpAndWait :: (SignalID, ThreadID) -> Proc
SignalUpAndWait(s, t) =
  callSignalUpAndWait.s.t -> Synchronized(SigM.s, t, syncSignalUpAndWait(s, t))
syncSignalUpAndWait(s, t) =
  getState.s.t?val -> if val == true then DIV -- Required to be false
                      else setState.s.t.true ->
                           Notify(SigM.s, t); SignalWaitingForFalse(s, t)


SignalWaitingForFalse :: (SignalID, ThreadID) -> Proc
SignalWaitingForFalse(s, t) =
  getState.s.t?val -> if val == false then SKIP
                      else Wait(SigM.s, t); SignalWaitingForFalse(s, t)
```

This models entering a synchronized block and checks that state is not true, diverging if so. This divergence is used to model a failed assertion; the rest of the code is a more direct translation.

Listing 12: The CSP model of the waitForSignalUp function of the Signal object

```
WaitForSignalUp :: (SignalID, ThreadID) → Proc
WaitForSignalUp(s, t) =
  callWaitForSignalUp.s.t → Synchronized(SigM.s, t, syncWaitForSignalUp(s, t))
syncWaitForSignalUp(s, t) =
  getState.s.t?val → if val == true then SKIP
                     else Wait(SigM.s, t); syncWaitForSignalUp(s, t)
```

Again this is a fairly natural model of the Scala code presented earlier; we communicate that thread t has called waitForSignalUp on Signal object s, enter a synchronized block and then simulate the while loop used to guard against spurious wakeups.

Listing 13: The CSP model of the signalDown function of the Signal object

```
SignalDown :: (SignalID, ThreadID) → Proc
SignalDown(s, t) = callSignalDown.s.t → Synchronized(SigM.s, t, syncSignalDown(s, t))
syncSignalDown(s, t) = setState.s.t.false → Notify(SigM.s, t); SKIP
```

SignalDown is the most simple function of the three to model; it obtains the monitor's lock, sets the state variable to false and then notifies the child that the synchronisation has completed.

Listing 14: The initialisation of the Signal objects,

```
InitialiseSignal (sig, threads) =
  runWith(SigM.sig, threads [|stateChannels(sig)|] State(sig))
      \ union(stateChannels(sig), events)

allStateChannels(sigs) = {|getState.s, setState.s | s ← sigs|}
States(sigs) = ||| s ← sigs • State(s)
monitors(sigs) = {SigM.s | s ← sigs}

InitialiseSignals (sigs, threads) =
  runWithMultiple(monitors(sigs), threads [|allStateChannels(sigs)|] States(sigs))
```

```
      \ union(allStateChannels(sigs), events)
```

We finally define processes InitialiseSignal and InitialiseSignals to initialise a single signal and multiple signals respectively. This is used to synchronise the threads with the interleaving of the state variables and the monitors and then hiding the internal behaviour of the Signal objects. runWith and runWithMultiple are both used to initialise the monitors for each of the Signal objects that are being modelled, ensuring mutual exclusion between threads on each of the Signal objects.

5.2 The Barrier object

When initialised, the Barrier(n: Int) object creates an array of n Signal objects, with these organised in the structure of a heap. As per the trait of a barrier synchronisation, Barrier only provides a single function sync(me) which takes the thread's identity as an input:

Listing 15: The Scala definition of the Barrier.sync function

```
/** Perform a barrier synchronisation.
  * @param me the unique identity of this thread. */
def sync(me: Int) = {
  require(0 <= me && me < n,
    s"Illegal parameter $me for sync: should be in the range [0..$n).")
  val child1 = 2*me+1; val child2 = 2*me+2
  // Wait for children
  if (child1 < n) signals(child1).waitForSignalUp
  if (child2 < n) signals(child2).waitForSignalUp
  // Signal to parent and wait for signal back
  if (me != 0) signals(me).signalUpAndWait
  // Signal to children
  if (child1 < n) signals(child1).signalDown
  if (child2 < n) signals(child2).signalDown
}
```

This checks that the thread's identity is such that signals(me) does not cause an ArrayIndexOutOfBoundsException. It then waits for the thread's children (if they exist) to signal that they are ready to synchronise, before signalling to its parent that all of its children are ready to synchronise. Once the parent signals back that the synchronisation has occurred the thread notfies its children that the synchronisation has completed befoe returning. The exception to this is thread 0, which has no parent to signal to. Thread 0 reaching line 11 of its sync(0) call can therefore be taken as the linearization point of the barrier synchronisation.

5.2.1 Modelling the Barrier object

Listing 16: The CSP model of a thread interacting with the Barrier object

```
Thread(T.me) = beginSync.T.me → Sync(T.me) ⊓ end.T.me → SKIP

Sync(T.me) =
  let child1 = 2*me+1
      child2 = 2*me+2
  within
      (if (child1 < n) then WaitForSignalUp(S.(child1), T.me) else SKIP);
      (if (child2 < n) then WaitForSignalUp(S.(child2), T.me) else SKIP);
      (if (me ≠ 0) then SignalUpAndWait(S.me, T.me) else SKIP);
      (if (child1 < n) then SignalDown(S.(child1), T.me) else SKIP);
      (if (child2 < n) then SignalDown(S.(child2), T.me) else SKIP);
      endSync.T.me → Thread(T.me)

Threads = ||| t : ThreadID • Thread(t)

BarrierSystem = InitialiseSignals   (Threads)
```

We recall from earlier that datatype ThreadID = T.{0..n−1} and datatype SignalID = S.{0..n−1}. The process Thread(T.me) models the individual behaviour of a specific thread with identity T.me :: ThreadID, with each thread nondeterministically choosing to either communicate an end.T.me and terminate or to call the CSP model of sync(me). In the latter case, a communication of beginSync.T.me is used to indicate the start of the synchronisation. The Sync(T.me) definition is very straightforward, with it mostly following directly from the Scala definition; the only further change is that Sync(T.me) communicates a endSync.T.me event just before it terminates.

The thread processes are then interleaved together to yield Threads. We then initialise the system with Signal objects that can nondeterministically allow or block spurious wakeups to give BarrierSystem. We hide all events of the signal object, so the only visible channels of BarrierSystem are {beginSync, endSync, spuriousWakeup, end}.

5.3 Correctness of the model

We will show that the barrier synchronisation is correct; here correct requires that the synchronisation can be correctly linearised and if a synchronisation is possible then it will always occur.

Correctly linearised in this context means that the barrier synchronisation can be considered to occur at some point between when all n threads have communicated beginSync and when the first thread communicates an endSync event. The requirement that a linearisation must occur means that if all n threads communicate a beginSync then none of the threads can be blocked from communicating their respective endSync.

Listing 17: The lineariser specification for barrier synchronisations

```
Lineariser (t) = beginSync.t → sync → endSync.t → Lineariser(t)
                 ⊓ end.t → STOP
Spec = ( ‖ t ← ThreadID • [{beginSync.t, sync, endSync.t, end.t}]
                 Lineariser (t)) \ {sync}
```

Lineariser(t) allows any thread to beginSync.t followed by an endSync.t, representing the call and return of barrier.sync(). The sync event can be considered to be the point at which the barrier synchronisation occurs since all threads must synchronise on this, fulfilling the requirement above. Additionally, each thread can terminate via end.t, indicating that it will perform no further synchronisations. This blocks all other threads from completing a barrier synchronisation, which is the intended behaviour.

We first note that BarrierSystem is divergence-free, but BarrierSystem \ {spuriousWakeup} is not. BarrierSystem with spurious wakeups visisble being divergence-free is relevant as this means that we never breach the assertion in the SignalUpAndWait function and that no internal divergence can be caused by a finite number of spurious wakeups. This therefore means hiding the spuriousWakeup events must be the cause of the divergences. This is expected behaviour as one thread could spuriously wakeup, check the test condition and wait again before spuriously waking up like this indefinitely. Similarly to before this is not a particular cause for concern; in practice spurious wakeups occur infrequently within the JVM.

We first consider the traces model, where we have that the following holds:

```
assert Spec ⊑_T BarrierSystem \ {|spuriousWakeup|}
```

This means that BarrierSystem fulfils the requirements fulfilled by Spec i.e. that it can be linearised and that the synchronisation between all n threads occurs correctly (if indeed it does occur).

Since Spec cannot diverge we will also consider refinement under the stable failures model. This ensures that if a synchronisation can occur then it must occur and that all threads can then return.

Similarly to 4.2.4 we will check refinement under the stable-failures model even though the model can diverge. This is valid as for every state that could be unstable due to a hidden spuriousWakeup there exists a correspondign stable state where the regulator process Reg blocks the spurious wakeup. FDR yields that both the following hold for systems of upto 6 threads; this can be verified in 1280 seconds.

```
assert Spec ⊑_F BarrierSystem \ {|spuriousWakeup|}
```

As a result, we have that the Barrier object presented earlier is a correct implementation of barrier synchronisation for n upto 6. This gives us significant confidence that the system is corect.

5.4 Specification processes for the Signal objects

Our current model of Signal models the internal workings of the object, modelling the synchronized blocks and the internal state variable. As this is a faithful recreation it is also rather complex; we can only test for correctness on models with upto 6 threads in reasonable time. We can instead construct a specification process which models the use of the Signal object. Though this still results in a model size exponential in the number of threads, the model will be of significantly smaller size allowing us to model the Barrier object for larger numbers of threads in the same approximate time.

By inspecting the usage of Signal we observe that there are two synchronisations between threads performed by each Signal object $\boxed{\text{Diagram}}$

- waitForSignalUp and signalUpAndWait synchronise to indicate that that all threads using objects in this subtree are waiting to synchronise. This synchronisation has the parent waiting on the child to signal, with the child being allowed to signal and progress immediately

- signalDown and signalUpAndWait synchronise, with the parent signalling to the child that the barrier synchronisation has occurred and that signalUpAndWait can return. This synchronisation has the child thread waiting on the parent signalling down to it; the child thread is always waiting first as the child starts waiting on this synchronisation immediately after the previous synchronisation occurs.

We can model this simplified Signal object via the following CSP:

Listing 18: The CSP model of the specification Signal object

```
channel endWaitForSignalUp, endSignalUpAndWait : SignalID . ThreadID
waitChannels = {|endWaitForSignalUp, endSignalUpAndWait|}

-- Simplified spec for a correctly used Signal object
SpecSig(s) =
    callSignalUpAndWait.s?t → callWaitForSignalUp.s?t2 → SpecSig2(s, t, t2)
```

```
  □ callWaitForSignalUp.s?t2 → callSignalUpAndWait.s?t → SpecSig2(s, t, t2)
SpecSig2(s, t, t2) =
  endWaitForSignalUp.s.t2 → callSignalDown.s.t2 → endSignalUpAndWait.s.t → SpecSig(s)

-- The individual functions for the Signal object
SpecSignalUpAndWait(s, t) = callSignalUpAndWait.s.t → endSignalUpAndWait.s.t → SKIP
SpecWaitForSignalUp(s, t) = callWaitForSignalUp.s.t → endWaitForSignalUp.s.t → SKIP
SpecSignalDown(s, t) = callSignalDown.s.t → SKIP

-- Construct the system for each of the SpecSig objects
SpecSignals =
  || s ← SignalID • [{|callSignalUpAndWait.s, callWaitForSignalUp.s,
                        callSignalDown.s, endWaitForSignalUp.s, endSignalUpAndWait.s|}]
                      SpecSig(s)

-- Method for barrier-sync to initialise the two objects
InitialiseSpecSignals (threads) =
  (SpecSignals [|union(signalChannels, waitChannels)|] threads) \ waitChannels
```

We introduce channels endWaitForSignalUp and endSignalUpAndWait to represent the synchronisations between the child and parent, with each of the channels indicating that their respective functions are able to return. SpecSig(s) is used to dictate the order that communications are allowed to occur:

1. Initially, it can either communicate a callSignalUpAndWait from the child thread or a callWaitForSignalUp from the parent. It then communicates the other event.

2. It then communicates an endWaitForSignalUp to indicate to the parent that the first synchronisation has occurred.

3. The parent then commmunicates a callSignalDown indicating that the barrier synchronisation has occured.

4. Finally, a endSignalUpAndWait is communicated to indicate to the child that they can now terminate; SpecSig(s) then repeats.

We also define the specification versions of the three external methods offered by a Signal object. SpecSignalUpAndWait and SpecWaitForSignalUp both initially communicate an event indicating that they have been ‘called’ before communicating a endSignalUpAndWait or endWaitForSignalUp respectively before terminating. By contrast, SpecSignalDown immediately terminates after communicating that it has been ‘called’ as it does not require a synchronisation with another thread.

Finally for the Signal specifications, we let SpecSignals be the alphabetised parallel composition of each of the SpecSig(s) processes, with the parallel composition forcing each specification object to only synchronise on events with the matching SignalID. The individual threads and the overall system are defined similaly to the above, with the exception that all calls are to the specification processes and not the originals.

Stuff about how the initial implementation of Signal fulfils this specification?

Listing 19: The implementation of the Barrier based on

```
-- sThread is the same as Thread but uses the spec Signal
sThread(T.me) = beginSync.T.me → sSync(T.me) ⊓ end.T.me → SKIP
sSync(T.me) =
  let child1  = 2*me+1
      child2  = 2*me+2
  within (if (child1 < n) then SpecWaitForSignalUp(S.(child1), T.me) else SKIP);
         (if (child2 < n) then SpecWaitForSignalUp(S.(child2), T.me) else SKIP);
         (if me ≠ 0 then SpecSignalUpAndWait(S.me, T.me) else SKIP);
         (if (child1 < n) then SpecSignalDown(S.(child1), T.me) else SKIP);
         (if (child2 < n) then SpecSignalDown(S.(child2), T.me)else SKIP);
         endSync.T.me → sThread(T.me)

-- Initialise the simple system
sThreads = ||| t : ThreadID • sThread(t)
sBarrierSystem = InitialiseSpecSignals (sThreads)

-- Spec failure-divergences refines it as expected
assert Spec ⊑FD sBarrierSystem
```

Since the simplified Signal object does not use monitors we have that the system should be divergence-free. This is verifed by FDR as the above refinement holds against our (divergence-free) linearization checker.

$\boxed{\text{Proper performance comparison Simplified can run 10 threads in about the same time?}}$

6 Conclusions and future work

In this paper, we have examined a range of concurrency primitives offered by the Java Virtual Machine, Scala Concurrency Library module and a range of different lock designs. We have examined and proved the correctness of each of these whilst also proving complexity results and examining other properties. There are, however, some limitations to our work.

Firstly, by the nature of model checking, we are only able to model a limited number of threads with restrictions on other parameters too. Though model checking with larger numbers of threads is technially possible, the exponential blow up in the number of states renders it practically infeasible. If a model is correct for small numbers of threads, we have significantly more confidence in the model remaining correct for larger numbers of threads; we do however note that this does not necessarily imply correctness.

Take, for example, the SCL monitor which we have previously proved correct for six threads and two conditions in section 4.2. The components of each individual condition are distinct with the exception of the ThreadInfo objects; any flaw with this would be expected to show itself with only two conditions. Likewise any issue due to interfering threads must require at least seven interacting threads; this seems remarkably unlikely due to the simplicity of the system and limited possible interactions between threads.

We have also only considered a number of specific concurrency primitives. Though our approach can be extended to many other primitives, this would still require significant work to verify the correctness of these. An automated translation system from normal code to CSP would aid in this task. Specialised examples do exist, such as SVA for shared variable programs [11], however no mor general models exist. It is worth noting that any general translator would likely suffer from additional complexity blow up due to a lack of insight. An example of this can be seen in the SCL Monitor model, where a more natural implementation of the queue lead to state space- $n!$ times larger than a model with additional insight. Though a naïve translation is very feasible, the utility of such an approach is limited, though non-zero. Implementing an general automated translator, either optimised or naïve, is beyond the scope of the project and therefore left as further work.

References

[1] Chong et al. "Code-Level Model Checking in the Software Development Workflow". In: 2020.

[2] Sara Baase. *A Gift of Fire, 4th Edition*. 2012. URL: https://www.philadelphia.edu.jo/academics/lalqoran/uploads/A-Gift-of-Fire-4thEd-2012.pdf.

[3] Christel Baier and Joost-Pieter Katoen. *Principles of Model Checking*. MIT Press, 2008.

[4] John Bluck and Valerie Williamson. *New NASA Software Detects 'Bugs' in Java Computer Code*. Tech. rep. NASA, 2005. URL: https://web.archive.org/web/20100317110540/https://www.nasa.gov/centers/ames/news/releases/2005/05_28AR.html.

[5] Independent Inquiry Board. *ARIANE 5: Flight 501 Failure*. Report. 1996. URL: http://sunnyday.mit.edu/nasa-class/Ariane5-report.html.

[6] Bettina Buth et al. "Deadlock analysis for a fault-tolerant system". In: *Algebraic Methodology and Software Technology*. Ed. by Michael Johnson. Berlin, Heidelberg: Springer Berlin Heidelberg, 1997, pp. 60–74. ISBN: 978-3-540-69661-2.

[7] Centre for Digital Trust. *Interview with Prof. Viktor Kunçak on Formal Software Verification and Stainless*. Newletter. 2019. URL: https://mailchi.mp/6d0f3c2d3070/c4dt-newsletter-02?e=ec2376a2c8.

[8] Henrico Dolfing. *Case Study 4: The $440 Million Software Error at Knight Capital*. 2019. URL: https://www.henricodolfing.com/2019/06/project-failure-case-study-knight-capital.html.

[9] Bill Roscoe Gavin Lowe. *Concurrency Lecture Slides*. 2020. URL: https://www.cs.ox.ac.uk/teaching/materials19-20/concurrency/.

[10] Maurice Herlihy and Nir Shavit. *The Art of Multiprocessor Programming, Revised Reprint*. 1st. San Francisco, CA, USA: Morgan Kaufmann Publishers Inc., 2012. ISBN: 9780123973375.

[11] David Hopkins and A. W. Roscoe. "SVA, a tool for analysing shared-variable programs". In: (2007). URL: https://www.cs.ox.ac.uk/bill.roscoe/publications/119.pdf.

[12] Andrew Jones. *An Introduction to NASA's Java Pathfinder*. 2010. URL: https://www.doc.ic.ac.uk/~wlj05/ajp/lecture6/slides/slides.pdf.

[13] Cliff Jones. "Tentative steps toward a development method for interfering programs". In: *ACM Transactions on Programming Languages and Systems* 5.4 (1983).

[14] Gunnar Kudrjavets Laurie Williams and Nachiappan Nagappan. *On the Effectiveness of Unit Test Automation at Microsoft*. URL: https://collaboration.csc.ncsu.edu/laurie/Papers/Unit_testing_cameraReady.pdf.

[15] Jonathan Lawrence. "Practical Application of CSP and FDR to Software Design". In: *Communicating Sequential Processes. The First 25 Years: Symposium on the Occasion of 25 Years of CSP, London, UK, July 7-8, 2004. Revised Invited Papers.* Ed. by Ali E. Abdallah, Cliff B. Jones, and Jeff W. Sanders. Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 151–174. ISBN: 978-3-540-32265-8. DOI: 10.1007/11423348_9. URL: https://doi.org/10.1007/11423348_9.

[16] K. Rustan M. Leino. "Dafny: An Automatic Program Verifier for Functional Correctness". In: *Logic for Programming, Artificial Intelligence, and Reasoning*. Ed. by Edmund M. Clarke and Andrei Voronkov. Berlin, Heidelberg: Springer Berlin Heidelberg, 2010, pp. 348–370. ISBN: 978-3-642-17511-4.

[17] Gavin Lowe. "An attack on the Needham-Schroeder public-key authentication protocol". In: *Information Processing Letters* 56.3 (1995), pp. 131–133. ISSN: 0020-0190. DOI: https://doi.org/10.1016/0020-0190(95)00144-2. URL: https://www.sciencedirect.com/science/article/pii/0020019095001442.

[18] Gavin Lowe. *Analysing Lock-Free Linearizable Datatypes using CSP*. 2017. URL: https://www.cs.ox.ac.uk/people/gavin.lowe/LockFreeQueue/lockFreeListAnalysis.pdf.

[19] Gavin Lowe. *Concurrent Programming Lecture Slides*. 2022. URL: https://www.cs.ox.ac.uk/teaching/materials22-23/concurrentprogramming/.

[20] Gavin Lowe. "Discovering and correcting a deadlock in a channel implementation". In: *Formal Aspects of Computing* 31 (4 2019). URL: https://doi.org/10.1007/s00165-019-00487-y.

[21] Gavin Lowe. "Implementing Generalised Alt". In: *Communicating Process Architectures 2011* (2011).

[22] Gavin Lowe. *JVM Monitor Module*. GitHub. 2023. URL: https://github.com/GavinLowe1967/SCL-CSP-analysis/blob/main/JVMMonitor.csp.

[23] Gavin Lowe. *Scala Concurrency Library - lock.scala*. 2022. URL: https://github.com/GavinLowe1967/Scala-Concurrency-Library/blob/main/src/Lock/Lock.scala.

[24] Gavin Lowe. "Testing for linearizability". In: *Concurrency and Computation: Practice and Experience* 29.4 (2017), e3928. URL: https://onlinelibrary.wiley.com/doi/abs/10.1002/cpe.3928.

[25] Jamie Lynch. *The Worst Computer Bugs in History: Race conditions in Therac-25*. Blog. 2017. URL: https://www.bugsnag.com/blog/bug-day-race-condition-therac-25/.

[26] Hanno Nickau and Gavin Lowe. *Concurrent Algorithms and Data Structures Lecture Notes*. 2023. URL: https://www.cs.ox.ac.uk/teaching/courses/2023-2024/cads/.

[27] Oracle. *Class LockSupport*. Manuals. 2017. URL: https://docs.oracle.com/javase%2F9%2Fdocs%2Fapi%2F%2F/java/util/concurrent/locks/LockSupport.html.

[28] Gary L. Peterson. "Myths About the Mutual Exclusion Problem". In: *Inf. Process. Lett.* 12 (1981), pp. 115–116. URL: https://api.semanticscholar.org/CorpusID:45492619.

[29] A. W. Roscoe and Thomas Gibson-Robinson. *The relationship between CSP, FDR and Büchi automata*. 2016. URL: https://www.cs.ox.ac.uk/files/8301/infinitec.pdf.

[30] Andrew (Bill) Roscoe. *Understanding Concurrent Systems*. Springer, 2010.

[31] Gerhard Schellhorn and Simon Bäumler. "Formal Verification of Lock-Free Algorithms". In: *Ninth International Conference on Application of Concurrency to System Design* (2009).

[32] Daniel Schwartz-Narbonne. *How to integrate formal proofs into software development*. 2020. URL: https://www.amazon.science/blog/how-to-integrate-formal-proofs-into-software-development.