Concurrent Programming Notes

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Eduardo Bonelli

Preface

These course notes provide supporting material for CS511.

Contents

Part I

Shared Memory

Chapter 1

Shared Memory Model and Transition Systems

This chapter...

1.1 Shared Memory Model

We begin with an example of a program in Groovy.

```groovy
int x = 0

Thread.start { //P
   x = 1
}

Thread.start { //Q
   x = 2
}
```

ex1.groovy

This program declares a shared variable `x`, sets it to `0` and then spawns two threads. The first thread sets `x` to 1 and the second to `2`. After this program terminates, the value of `x` may either be 1 or 2. The variable `x` is said to be shared in the sense that it is visible to (or its scope includes) both threads[1].

> Semicolons are optional in Groovy

Assuming this program is stored in a file called `ex1.groovy`, it may be executed using the terminal as follows:

[1] From the point of view of Groovy it is actually a local variable. In Groovy, global variables are declared by omitting the type annotation.

```
$ groovy ex1
$
```
bash

Since our program contains no output statements, there is no visible effect from its execution. The following example, waits for P and Q to terminate using the built-in method `join` and then prints the value of `x`:

```
int x = 0

P = Thread.start { //P
      x = 1
}

Q = Thread.start { //Q
      x = 2
}

P.join()  // Wait for P to terminate
Q.join()  // Wait for Q to terminate
println x
```
ex2.groovy

Assuming this program is stored in a file called `ex2.groovy`, it may be executed using the terminal as follows:

```
$ groovy ex2
2
$
```
bash

Repeated execution will most likely produce 2 since P is spawned before Q and runs immediately. It is entirely possible, however, to obtain 1 as a result.

The following example is a Groovy program that prints characters.

```
Thread.start { //P
   print "A"
   print "B"
}

Thread.start { //Q
   print "C"
}
```

What are the possible outputs one may obtain from executing it? It can print three possible sequences of characters, namely `ABC`, `ACB`, `CAB`. What about the following program?

```
Thread.start { //P
    print "A"
    print "B"
}

Thread.start { //Q
    print "C"
    print "D"
```

```
}
```

Clearly the number of possible executions, also called interleavings, grows exponentially with the number of instructions in each thread. Indeed, if P has m instructions and Q has n instructions, then there are

$$\binom{m+n}{m} = \frac{(m+n)!}{m!n!}$$

This makes it difficult to reason about concurrent programs: there are simply too many interleavings to consider; we never know whether one such interleaving might lead our code to produce an unwanted result. We clearly need a rigorous notation to be able to model all such possible interleavings and check whether they satisfy the intended properties. This notation should thus describe the run-time execution of a concurrent program. There is a further, equally important reason, why we need such a notation. Consider the following program:

```
int x=0

P = Thread.start {
      x = x+1
}
Q = Thread.start {
      x = x+1
}

P.join() // wait for P to terminate
Q.join() // wait for Q to terminate
println x
```

Its execution can produce 1 as output!

```bash
$ groovy ex1
1
$
```

How is that possible?

1.2 Transition Systems

This section introduces transition systems, a device we use to model the run-time behavior of concurrent programs. After defining transition systems, we illustrate how to associate a transition system to Groovy programs. By doing so, we assign "meaning" to our concurrent programs. It should be mentioned that we will associate transition systems only to a subset of simple Groovy programs, not arbitrary ones.

A **Transition System** $\mathcal{A}$ is a tuple $(S, \rightarrow, I)$ where

- S is a set of states;
- $\rightarrow \subseteq S \times S$ is a transition relation; and
- $I \subseteq S$ is a set of initial states.

We say that $\mathcal{A}$ is finite if S is finite. Also, we write $s \to s'$ for $(s, s') \in \to$.

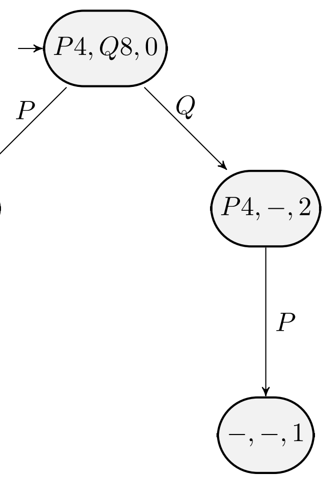
We illustrate, in this first example, how to model the runtime execution of Example 1.1, repeated below:

```
int x = 0

Thread.start { //P
   x = 1
}

Thread.start { //Q
   x = 2
}
```

The states of our transition system will consist of 3-tuples containing the instruction pointer for `P`, the instruction pointer for `Q` and the value of `x`. The initial state is signalled with a small arrow. The hyphen indicates that there are no further instructions to be executed by that thread.

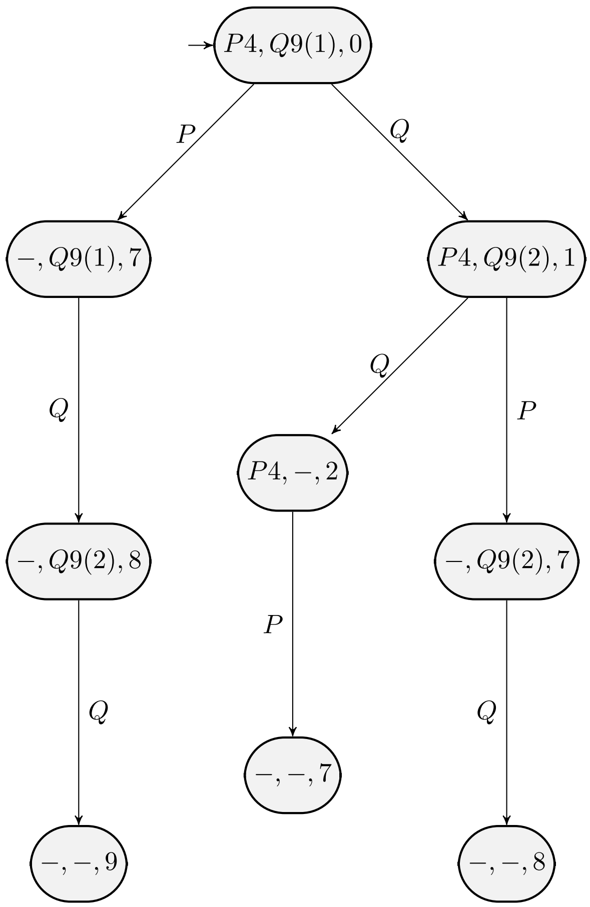


How we hardcode "for"-loops with a constant upper bound.

```
int x = 0

Thread.start { //P
   x = 7
}

Thread.start { //Q
   2.times {
     x = x+1
   }
}
```



How we distinguish local variables with the same name using ”local_P” and ”local_Q” in the state format.

```
int x = 0 // shared variable

Thread.start { //P
   int local = x
   x = local+1 // atomic
}

Thread.start { //Q
   int local = x
   x = local+1 // atomic
}
```

How we deal with “while”-loops.

```
int x=0 // shared variable

Thread.start { //P
    while (x<1) {
      print x
    }
```

```
}

Thread.start { //Q
    x = x + 1
}
```

How we decorate transitions with the output string of a print

```
int x = 0  // shared variable

Thread.start { //P
  x = x + 1
  x = x + 1
}

Thread.start { //Q
  while (x >= 2)
    print x
}
```

```
int counter=0 // shared variable

P = Thread.start {
      50.times {
        counter = counter+1
      }
}
Q = Thread.start {
      50.times {
        counter= counter+1
      }
    }

P.join() // wait for P to finish
Q.join() // wait for Q to finish

println counter // print value of counter
```

1.3 Atomicity

Consider the following program:

```
x=0

Thread.start { //P
    x = x + 1
    println x
}

Thread.start { //Q
    x = x + 1
    println x
}
```

One would expect 1 and 2, or 2 and 2 to be printed. These are indeed possible outputs. However, 1 and 1 is also possible:

```bash
$ groovy ex3
1
1
$
```

bash

The reason is that assignment is not an atomic operation, rather it is decomposed into more fine grained (bytecode) operations. It is the latter that are interleaved. Let's take a closer look at those fine grained operations. Consider the following Java class that spawn two threads, each of which updates a shared variable:

```java
class A implements Runnable {

    static int x=0;

    public void run() {
       x=x+1;
    }

    public static void main(String[] args) {
       new Thread(new A()).start();
       new Thread(new A()).start();
    }
}
```

A.java

We compile it and look at the resulting bytecode by using `javap`, the Java class file disassembler:

```
$ javac A.java
$ javap -c A
Compiled from "A.java"
class A implements java.lang.Runnable {
  static int x;

  A();
    Code:
       0: aload_0
       1: invokespecial #1                  // Method java/lang/Object."<init>":()V
       4: return

  public void run();
    Code:
       0: getstatic     #7                  // Field x:I
       3: iconst_1
       4: iadd
       5: putstatic     #7                  // Field x:I
       8: return

  public static void main(java.lang.String[]);
    Code:
       0: new           #13                 // class java/lang/Thread
       3: dup
```

```
         4: new           #8                  // class A
26       7: dup
         8: invokespecial #15                 // Method "<init>":()V
28      11: invokespecial #16                 // Method java/lang/Thread."<init>":(Ljava
        14: invokevirtual #19                 // Method java/lang/Thread.start:()V
30      17: new           #13                 // class java/lang/Thread
        20: dup
32      21: new           #8                  // class A
        24: dup
34      25: invokespecial #15                 // Method "<init>":()V
        28: invokespecial #16                 // Method java/lang/Thread."<init>":(Ljava
36      31: invokevirtual #19                 // Method java/lang/Thread.start:()V
        34: return
38
    static {};
40    Code:
         0: iconst_0
42       1: putstatic     #7                  // Field x:I
         4: return
44  }
```

bash

The only lines we are interested are lines 15 to 18. Each thread has a JVM stack. Every time a method is called, a new frame is created (heap-allocated) and stored on the JVM stack for that thread. Each frame has its own array of local variables, its own operand stack, and a reference to the run-time constant pool of the class of the current method. The instruction `x=x+1` is compiled to four bytecode instructions whose meaning can be read off from their opcodes:

```
       0: getstatic     #7                  // Field x:I
       3: iconst_1
       4: iadd
       5: putstatic     #7                  // Field x:I
```

It is these operations, for each thread, that get interleaved. Thus, it is possible to have the following interleaving:

```
       0(P): getstatic     #7                  // Field x:I
       0(Q): getstatic     #7                  // Field x:I
       3(P): iconst_1
       3(Q): iconst_1
       4(P): iadd
       4(Q): iadd
       5(P): putstatic     #7                  // Field x:I
       5(Q): putstatic     #7                  // Field x:I
```

These instructions end up storing 1 in `x`.

1.4 The Mutual Exclusion Problem

Chapter 2

Semaphores

2.1 Introduction

2.2 The MEP Problem Revisited

Consider the following solution to the MEP problem using a binary semaphore presented in listing 2.1[1].

```
1  Semaphore mutex= new Semaphore(1)
2
3  Thread.start { //P
4      while (true) {
5          mutex.acquire()
6          mutex.release()
7      }
8  }
9  Thread.start { //Q
10     while (true) {
11         mutex.acquire()
12         mutex.release()
13     }
14 }
```

Listing 2.1: Solution to MEP using a binary semaphore

One easy way to verify that all three properties of MEP are upheld is to construct its transition system and then analyze these properties. This requires a means for representing semaphores. Since a semaphore is an object with state and the latter includes the number of permits and the set of blocked processes, we shall model `mutex` using the expression `mutex[i,S]` where `i` is the number of permits and `S` is a set of blocked processes. Moreover, we use the "!" symbol as instruction pointer in the states of our transition systems to indicate that there are no instructions ready to execute. For example, a state such as $P6, !, mutex[0, \{Q11\}]$, reflects that only P can be scheduled for execution, there are no permits available in `mutex` and one thread is blocked on

[1] Groovy requires that you import the Semaphore class in order to be able to use it. All code excerpts involving semaphores should thus include, at the top, the line `import java.util.concurrent.Semaphore`. This is typically omitted in our examples.

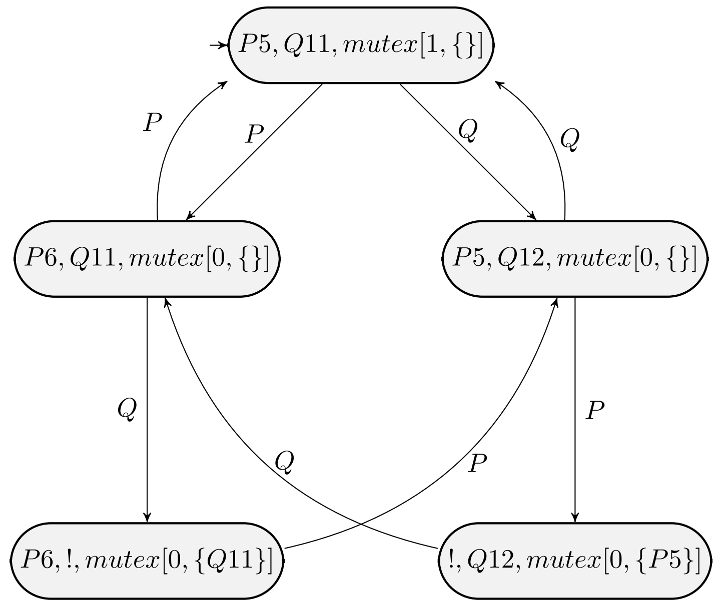


Figure 2.1: Transition System for the solution to MEP using a binary semaphore

`mutex` waiting for a permit to become available, namely Q. Figure **??** is the transition system for the listing in Figure 2.1.

Consider the setting where the above solution is applied to three threads wanting to access their CS. This is illustrated in Listing 2.2. Although Mutex and Absence of Livelock are upheld, Freedom From Starvation is not. Indeed, consider the scenario where `P` goes in and `Q` and `R` try to get in and are both blocked and placed in the set of blocked processes for `mutex`. [COMPLETE]**??**

This is easily solved by having the set of blocked processes in `mutex` be a queue. Such semaphores are called fair semaphores. This is achieved by using an alternative constructor for semaphores that includes a fairness parameter

```
Semaphore(int permits, boolean fair)
```

Replacing line 1 in Listing 2.2 with `Semaphore mutex= new Semaphore(1,true)` suffices to obtain a correct solution to the MEP for any number of threads.

```
1  Semaphore mutex= new Semaphore(1)
2
3  Thread.start { //P
4      while (true) {
5          mutex.acquire()
6          mutex.release()
7      }
8  }
9  Thread.start { //Q
10     while (true) {
11         mutex.acquire()
12         mutex.release()
13     }
```

```
  }
Thread.start { //R
    while (true) {
        mutex.acquire()
        mutex.release()
    }
}
```

Listing 2.2: Attempt at solving the MEP using a binary semaphore for N=3

2.3 More Examples

```
Thread.start {
    println "A"
    println "B"
}
Thread.start {
    println "C"
    println "D"
}
```

```
Semaphore cAfterA = new Semaphore(0)

Thread.start {
    println "A"
    mutex.release()
    println "B"
}
Thread.start {
    mutex.acquire()
    println "C"
    println "D"
}
```

Consider the following example which prints any (infinite) sequence of "a"s and "b"s:

```
Thread.start { //P
    while (true) {
    print "a"
    }
}

Thread.start { //Q
    while (true) {
    print "b"
    }
}
```

Using semaphores, how would you ensure that only the infinite sequence "aabaabaab..." is printed? Hint: make use of two semaphores, `a` and `b`, enabling the execution of an iteration in P and an iteration in Q, respectively.

Here is a solution.

```
import java.util.concurrent.Semaphore

```

```
Semaphore a = new Semaphore(2)
Semaphore b = new Semaphore(0)

Thread.start { //P
    while (true) {
    a.acquire()
    print "a"
    b.release()
    }
}

Thread.start { //Q
    while (true) {
    b.acquire(2)
    print "b"
    a.release(2)
    }
}
```

2.3.1 Thread Dumps

We can check the current thread dump of the our Groovy/Java application as follows. Let's use the example above. First we modify our code so that we give our threads an easy to spot name and remove the lines that print. The result is below; we'll call it `ex1.groovy`.

```
import java.util.concurrent.Semaphore

Semaphore a = new Semaphore(2)
Semaphore b = new Semaphore(0)

Thread.start { //P
    Thread.currentThread().setName("P Thread");
    while (true) {
    a.acquire()
    // print "a"
    b.release()
    }
}

Thread.start { //Q
    Thread.currentThread().setName("Q Thread");
    while (true) {
    b.acquire()
    b.acquire()
    // print "b"
    a.release()
    a.release()
    }
}
```

Now we run it in the background, use `jstack` to obtain the stack trace of the bash job and send the output to a text file `thead-dump.txt`

```
$ groovy ex1 &
[1] 23275
$ jstack -l 23275 > thread-dump.txt
```

```bash
$ kill %1
[1]  + 23275 exit 143   groovy ex1
$ emacs thread-dump.txt
```

bash

The dump contains information on all threads involved in our application. We'll just show an exerpt that mentions `P` and `Q`. We can see that the former is in a RUNNABLE state and the latter is in a WAITING state. We can also see the current instruction being executed in each thread.

```
"P Thread" #17 prio=5 os_prio=31 cpu=5910.73ms elapsed=10.91s tid=0x00007f7d9412b400 nid=27655 runnable
   java.lang.Thread.State: RUNNABLE
    at jdk.internal.misc.Unsafe.unpark(java.base@18.0.1.1/Native Method)
    at java.util.concurrent.locks.LockSupport.unpark(java.base@18.0.1.1/LockSupport.java:177)
    at java.util.concurrent.locks.AbstractQueuedSynchronizer.signalNext(java.base@18.0.1.1/AbstractQueue
    at java.util.concurrent.locks.AbstractQueuedSynchronizer.releaseShared(java.base@18.0.1.1/AbstractQu
    at java.util.concurrent.Semaphore.release(java.base@18.0.1.1/Semaphore.java:432)
    at java.lang.invoke.LambdaForm$DMH/0x0000000800d28000.invokeVirtual(java.base@18.0.1.1/LambdaForm$DM
    at java.lang.invoke.LambdaForm$MH/0x0000000800e32c00.invoke(java.base@18.0.1.1/LambdaForm$MH)
    at java.lang.invoke.LambdaForm$MH/0x0000000800e2b400.guardWithCatch(java.base@18.0.1.1/LambdaForm$MH
    at java.lang.invoke.DelegatingMethodHandle$Holder.delegate(java.base@18.0.1.1/DelegatingMethodHandle
    at java.lang.invoke.LambdaForm$MH/0x0000000800e27800.guard(java.base@18.0.1.1/LambdaForm$MH)
    at java.lang.invoke.DelegatingMethodHandle$Holder.delegate(java.base@18.0.1.1/DelegatingMethodHandle
    at java.lang.invoke.LambdaForm$MH/0x0000000800e27800.guard(java.base@18.0.1.1/LambdaForm$MH)
    at java.lang.invoke.Invokers$Holder.linkToCallSite(java.base@18.0.1.1/Invokers$Holder)
    at ex1$_run_closure1.doCall(ex1.groovy:12)
    at ex1$_run_closure1.doCall(ex1.groovy)
    at java.lang.invoke.DirectMethodHandle$Holder.invokeSpecial(java.base@18.0.1.1/DirectMethodHandle$Ho
    at java.lang.invoke.LambdaForm$MH/0x0000000800c1c800.invoke(java.base@18.0.1.1/LambdaForm$MH)
    at java.lang.invoke.Invokers$Holder.invokeExact_MT(java.base@18.0.1.1/Invokers$Holder)
    at jdk.internal.reflect.DirectMethodHandleAccessor.invokeImpl(java.base@18.0.1.1/DirectMethodHandleA
    at jdk.internal.reflect.DirectMethodHandleAccessor.invoke(java.base@18.0.1.1/DirectMethodHandleAcces
    at java.lang.reflect.Method.invoke(java.base@18.0.1.1/Method.java:577)
    at org.codehaus.groovy.reflection.CachedMethod.invoke(CachedMethod.java:343)
    at groovy.lang.MetaMethod.doMethodInvoke(MetaMethod.java:328)
    at org.codehaus.groovy.runtime.metaclass.ClosureMetaClass.invokeMethod(ClosureMetaClass.java:279)
    at groovy.lang.MetaClassImpl.invokeMethod(MetaClassImpl.java:1009)
    at groovy.lang.Closure.call(Closure.java:418)
    at groovy.lang.Closure.call(Closure.java:412)
    at groovy.lang.Closure.run(Closure.java:500)
    at java.lang.Thread.run(java.base@18.0.1.1/Thread.java:833)

   Locked ownable synchronizers:
    - None

"Q Thread" #18 prio=5 os_prio=31 cpu=6110.53ms elapsed=10.91s tid=0x00007f7d9411fa00 nid=28163 runnable
   java.lang.Thread.State: WAITING (parking)
    at jdk.internal.misc.Unsafe.park(java.base@18.0.1.1/Native Method)
    - parking to wait for  <0x00000006180b9960> (a java.util.concurrent.Semaphore$NonfairSync)
    at java.util.concurrent.locks.LockSupport.park(java.base@18.0.1.1/LockSupport.java:211)
    at java.util.concurrent.locks.AbstractQueuedSynchronizer.acquire(java.base@18.0.1.1/AbstractQueuedSy
    at java.util.concurrent.locks.AbstractQueuedSynchronizer.acquireSharedInterruptibly(java.base@18.0.1
    at java.util.concurrent.Semaphore.acquire(java.base@18.0.1.1/Semaphore.java:318)
    at java.lang.invoke.LambdaForm$DMH/0x0000000800d28000.invokeVirtual(java.base@18.0.1.1/LambdaForm$DM
    at java.lang.invoke.LambdaForm$MH/0x0000000800e32c00.invoke(java.base@18.0.1.1/LambdaForm$MH)
    at java.lang.invoke.LambdaForm$MH/0x0000000800e2b400.guardWithCatch(java.base@18.0.1.1/LambdaForm$MH
    at java.lang.invoke.DelegatingMethodHandle$Holder.delegate(java.base@18.0.1.1/DelegatingMethodHandle
```

```
    at java.lang.invoke.LambdaForm$MH/0x0000000800e27800.guard(java.base@18.0.1.1/LambdaForm$MH
    at java.lang.invoke.DelegatingMethodHandle$Holder.delegate(java.base@18.0.1.1/DelegatingMet
    at java.lang.invoke.LambdaForm$MH/0x0000000800e27800.guard(java.base@18.0.1.1/LambdaForm$MH
    at java.lang.invoke.Invokers$Holder.linkToCallSite(java.base@18.0.1.1/Invokers$Holder)
    at ex1$_run_closure2.doCall(ex1.groovy:19)
    at ex1$_run_closure2.doCall(ex1.groovy)
    at java.lang.invoke.DirectMethodHandle$Holder.invokeSpecial(java.base@18.0.1.1/DirectMethod
    at java.lang.invoke.LambdaForm$MH/0x0000000800c1c800.invoke(java.base@18.0.1.1/LambdaForm$M
    at java.lang.invoke.Invokers$Holder.invokeExact_MT(java.base@18.0.1.1/Invokers$Holder)
    at jdk.internal.reflect.DirectMethodHandleAccessor.invokeImpl(java.base@18.0.1.1/DirectMeth
    at jdk.internal.reflect.DirectMethodHandleAccessor.invoke(java.base@18.0.1.1/DirectMethodHa
    at java.lang.reflect.Method.invoke(java.base@18.0.1.1/Method.java:577)
    at org.codehaus.groovy.reflection.CachedMethod.invoke(CachedMethod.java:343)
    at groovy.lang.MetaMethod.doMethodInvoke(MetaMethod.java:328)
    at org.codehaus.groovy.runtime.metaclass.ClosureMetaClass.invokeMethod(ClosureMetaClass.jav
    at groovy.lang.MetaClassImpl.invokeMethod(MetaClassImpl.java:1009)
    at groovy.lang.Closure.call(Closure.java:418)
    at groovy.lang.Closure.call(Closure.java:412)
    at groovy.lang.Closure.run(Closure.java:500)
    at java.lang.Thread.run(java.base@18.0.1.1/Thread.java:833)

   Locked ownable synchronizers:
    - None
```

One could also make use of online tools that analyse these thread dumps to help identify potential issues. For example, you can try and upload `thread-dump.txt` to this site `fastthread.io` and click on "analyze".

2.4 Classical Synchronization Problems

This section addresses some classical synchronization problems using semaphores.

2.4.1 Producers/Consumers

Buffer of size 1, one producer and one consumer. The code below also works if there were multiple producers and multiple consumers.

```
Integer buffer

Semaphore consume = new Semaphore(0)
Semaphore produce = new Semaphore(1)

Thread.start { // Prod
    Random r = new Random()
    while (true) {
    produce.acquire()
    buffer = r.nextInt(10000) // produce()
    println "produced "+buffer
    Thread.sleep(1000)
    consume.release()
    }
}

Thread.start { // Cons

```

```
    while (true) {
    consume.acquire()
    println "consumed "+buffer
    buffer = null // consume(buffer)
    produce.release()
    }
}
```

Buffer of size `N` with one producer and one consumer. Also known as a blocking queue.

```
final int N=10
Integer[] buffer = [0] * N

Semaphore consume = new Semaphore(0)
Semaphore produce = new Semaphore(N)
int start = 0
int end = 0

Thread.start { // Prod
    Random r = new Random()
    while (true) {
    produce.acquire()
    mutexP.acquire()
    buffer[start] = r.nextInt(10000) // produce()
    println id+" produced "+buffer[start] + " at index "+start
    start = (start + 1) % N
    mutexP.release()
    consume.release()
    }
}

Thread.start { // Cons
    while (true) {
    consume.acquire()
    mutexC.acquire()
    println id+ " consumed "+buffer[end] + " at index "+end
    buffer[end] = null // consume(buffer)
    end = (end + 1) % N
    mutexC.release()
    produce.release()
    }
}
```

Buffer of size `N` with multiple producers and multiple consumers.

> The static method `currentMethod()` returns a reference to the currently executing thread object. Every thread has a unique id. It may be obtained by using the `getId()` method.

```
final int N=10
Integer[] buffer = [0] * N

Semaphore consume = new Semaphore(0)
Semaphore produce = new Semaphore(N)
Semaphore mutexP = new Semaphore(1) // mutex to avoid race conditions on start
Semaphore mutexC = new Semaphore(1) // mutex to avoid race conditions on end
```

```
int start = 0
int end = 0

5.times {
    Thread.start { // Prod
      Random r = new Random()
      while (true) {
          produce.acquire()
          mutexP.acquire()
          buffer[start] = r.nextInt(10000) // produce()
          println Thread.currentThread().getId()+" produced "+buffer[start] + " at index "+star
          start = (start + 1) % N
          mutexP.release()
          consume.release()
      }
    }
}

5.times{
    Thread.start { // Cons
      while (true) {
          consume.acquire()
          mutexC.acquire()
          println Thread.currentThread().getId()+ " consumed "+buffer[end] + " at index "+end
          buffer[end] = null // consume(buffer)
          end = (end + 1) % N
          mutexC.release()
          produce.release()
      }
   }
}
```

2.4.2 Readers/Writers

2.4.3 Barrier Synchronization

```
// One-time use barrier
// Barrier size = N
// Total number of threads in the system = N

final int N=3
N.times {
  Thread.start {
    while (true) {
      // barrier arrival protocol

      // barrier
    }
  }
}
```

```
import java.util.concurrent.Semaphore
// One-time use barrier
// Barrier size = N
// Total number of threads in the system = N
```

```
final int N=3
int t=0
Semaphore barrier = new Semaphore(0)
Semaphore mutex = new Semaphore(1)
N.times {
  Thread.start {
     while (true) {
        // barrier arrival protocol
        mutex.acquire()
        if (t<N) {
           t++
           if (t==N) {
            N.times { barrier.release() }
           }
        } else {
            barrier.release()
        }
        mutex.release()
        // barrier
        barrier.acquire()
       }
   }
}
```

Using cascaded signalling:

```
import java.util.concurrent.Semaphore
// One-time use barrier
// Barrier size = N
// Total number of threads in the system = N

final int N=3
int t=0
Semaphore barrier = new Semaphore(0)
Semaphore mutex = new Semaphore(1)
N.times {
  Thread.start {
    while (true) {
      // barrier arrival protocol
      mutex.acquire()
      if (t<N) {
        t++
        if (t==N) {
          barrier.release()
        }
      }
      mutex.release()
      // barrier
      barrier.acquire() // Cascaded signalling
      barrier.release()
    }
  }
}
```

Cyclic (or reusable) barrier. Failed attempt:

```
import java.util.concurrent.Semaphore
```

```
// Cyclic (ie. Reusable)  barrier
// Barrier size = N
// Total number of threads in the system = N

Semaphore mutex = new Semaphore(1)
Semaphore barrier = new Semaphore(0)
final int N = 3
int t=0

N.times {
    Thread.start {
    while (true) {
        // arrival
        mutex.acquire()
            t++;
            if (t==N) {
                N.times { barrier.release()}
                t=0 // attempt to reset barrier counter
            }
        mutex.release()

        // barrier
        barrier.acquire()
    }
    }
}
```

One easy way to verify that it is incorrect is to count the number of times a thread cycles passed the barrier. Then, notice that some threads can race far ahead of others in terms of the difference in number cycles; this difference can be larger than 1.

A solution follows. We use a second barrier to wait for all threads to fall through the first barrier, thus avoiding any one thread getting ahead of the others.

```
import java.util.concurrent.Semaphore

// Cyclic (ie. Reusable) barrier
// Barrier size = N
// Total number of threads in the system = N

Semaphore mutex = new Semaphore(1)
Semaphore barrier = new Semaphore(0)
Semaphore barrier2 = new Semaphore(0)
final int N = 3
int t=0

N.times {
  int id = it
  Thread.start {
     while (true) {
       // arrival
       mutex.acquire()
       t++;
       if (t==N) {
          N.times { barrier.release() }
       }
       mutex.release()

```

```
        // barrier
        barrier.acquire()

        mutex.acquire()
        t--
        if (t==0) {
           N.times { barrier2.release() }
        }
        mutex.release()

        barrier2.acquire()
      }
   }

}
```

```
import java.util.concurrent.Semaphore

// Cyclic (ie. Reusable) barrier
// Barrier size = N
// Total number of threads in the system = N

Semaphore mutex = new Semaphore(1)
Semaphore barrier = new Semaphore(0)
Semaphore barrier2 = new Semaphore(0)
final int N = 3
int t=0
int[] c = new int[N]

N.times {
  int id = it
  Thread.start {
    1000.times { //while (true) {
      // arrival
      mutex.acquire()
      c[id]++
      t++
      if (t==N) {
         N.times { barrier.release() }
      }
      mutex.release()

      // barrier
      println id + " reached barrier. c="+c[id]
      barrier.acquire()
      println id + " passed barrier. c="+c[id]

      mutex.acquire()
      t--
      if (t==0) {
         N.times { barrier2.release() }
      }
      mutex.release()

      barrier2.acquire()
    }
  }
```

```
}
```

Chapter 3

Monitors

A monitor is a program module that encapsulates data and operations and, moreover, guarantees mutual exclusion in the execution of the operations.

Listing 3.1 implements two turnstiles each of which accesses a global counter. The counter is implemented using a monitor. This monitor supports operations `inc()`, `dec()` and `read()`. The `synchronized` qualifier ensures mutual exclusion in the execution of these methods. Every object has a built in lock called an intrinsic lock. When a thread invokes a synchronized method, it automatically acquires the intrinsic lock for that method's object and releases it when the method returns. A thread is said to own the intrinsic lock between the time it has acquired the lock and released the lock. As long as a thread owns an intrinsic lock, no other thread can acquire the same lock. The other thread will block when it attempts to acquire the lock.

```
// Monitor declaration
  class Counter {
    private int c

    public synchronized void inc() {
       c++
    }

    public synchronized void dec() {
       c--
    }

    public synchronized int read() {
       return c
    }
}

// Sample use of the monitor
Counter ctr = new Counter()

P = Thread.start {
         10.times {
             ctr.inc()
         }
      }

```

```
Q = Thread.start {
        10.times {
            ctr.inc()
        }
    }

P.join()
Q.join()
println (ctr.read())
```

Listing 3.1: Avoiding race conditions on a shared counter using a monitor

3.1 A monitor implementing a semaphore

```
class Semaphore {
    private int permits

    Semaphore(int init) {
    permits=init
    }

    public synchronized void acquire() {
        while (permits==0) {
            wait()
        }
        permits--
    }

    public synchronized void release() {
        notify()
        permits++
    }
}

Semaphore mutex = new Semaphore(1)
int c=0

P = Thread.start {
      10.times {
          mutex.acquire()
          c++
          mutex.release()
      }
   }

Q = Thread.start {
      10.times {
         mutex.acquire()
         c++
         mutex.release()
      }
    }

P.join()
Q.join()
println c
```

This solution is not fair on the threads that are sleeping since an outside thread could "steal" the permit what is made available through a call to `release`. An alternative that is fair in this sense[1] is given in Listing 3.2. A different approach is followed in [Car96].

```
import java.util.concurrent.Semaphore

class Semaphore {
    private int permits;
    private long startWaitingTime=0;
    private static final long startTime = System.currentTimeMillis();
    private int waiting=0;

    Semaphore(int n) {
       permits=n;
    }

    synchronized protected static final long age() {
       return System.currentTimeMillis() - startTime;
    }

    synchronized void acquire() {
       if (waiting>0 || permits==0) {
           long arrivalTime = age();
           while (arrivalTime>startWaitingTime || permits==0) {
               waiting++;
               wait();
               waiting--;
           }
       }
       permits--;
   }

    synchronized void release() {
       permits++;
       startWaitingTime = age();
       notify();
    }
}
```

Listing 3.2: Fair semaphores

3.2 Producers/Consumers

```
class PC {
    private Object buffer;

    public synchronized void produce(Object o) {
      while (buffer!=null) {
          wait()
      }
      buffer = o
      notifyAll()
```

[1] The idea of using age is from [Har98] which uses it in an attempt to propose a fair solution for readers/writers. Unfortunately, the proposed solution is not fair (after an `endWrite` operation, a writer could steal the lock even though there are waiting readers).

```
    }

    public synchronized Object consume() {
      while (buffer==null) {
          wait()
      }
      Object temp = buffer
      buffer=null
      notifyAll()
      return temp
    }
}

PC pc = new PC()

10.times {
    Thread.start {
      println (Thread.currentThread().getId()+" consumes")
      pc.consume()
    }}

10.times {
    Thread.start {
      println (Thread.currentThread().getId()+" produces")
      pc.produce((new Random()).nextInt(33))
    }}
```

Replacing each of the two `notifyAll()` with `notify()` leads to an incorrect solution where one can end up having a producer and consumer both blocked in the wait-set. Hint: C1,C2,P1,P2. This pitfall is called the lost-wakeup problem.

Disadvantages:

Use multiple condition variables

Condition variables.

3.3 Readers/Writers

Naive solution. Correct but unfair on writers.

```
import java.util.concurrent.locks.*

class RW {
    private int readers;
    private int writers;
    static final Lock lock = new ReentrantLock();
    static final Condition okToRead = lock.newCondition();
    static final Condition okToWrite = lock.newCondition();

    RW() {
    readers=0;
    writers=0;
    }

    void start_read() {
    lock.lock();
    try {
```

```
        while (writers>0) {
        okToRead.await();
        }
        readers++;
    } finally {
        lock.unlock();
    }
    }

    void stop_read() {
    lock.lock();
    try {
        readers--;
        if (readers==0) {
        okToWrite.signal();
        }
    } finally {
        lock.unlock();
    }
    }

    void start_write(Object item) {
    lock.lock();
    try {
        while (readers>0 || writers>0) {
        okToWrite.await();
        }
        writers++;
    } finally {
        lock.unlock();
    }
    }

    void stop_write() {
    lock.lock();
    try {
        writers--;
        okToWrite.signal();
        okToRead.signalAll();
    } finally {
        lock.unlock();
    }
    }

}

RW rw = new RW();

r =  { //R
    Random r = new Random();
    rw.start_read();
    println Thread.currentThread().getId()+" reading..."
    Thread.sleep(r.nextInt(1000));
    println Thread.currentThread().getId()+" done reading..."

    rw.stop_read();
}
```

```
w = { //W
    Random r = new Random();
    rw.start_write();
    println Thread.currentThread().getId()+" writing..."
    Thread.sleep(r.nextInt(1000));
    println Thread.currentThread().getId()+" done writing..."
    rw.stop_write();
}

200.times {
    Thread.start(r)
    Thread.start(w)
}
```

Checking for waiting writers. Places priority on writers but unfair on readers.

```
  import java.util.concurrent.locks.*

class RW {
    private int readers;
    private int writers;
    private int writers_waiting;
    static final Lock lock = new ReentrantLock();
    static final Condition okToRead = lock.newCondition();
    static final Condition okToWrite = lock.newCondition();

    RW() {
    readers=0;
    writers=0;
    writers_waiting=0;
    }

    void start_read() {
    lock.lock();
    try {
        while (writers>0 || writers_waiting>0) {
        okToRead.await();
        }
        readers++;
    } finally {
        lock.unlock();
    }
    }

    void stop_read() {
    lock.lock();
    try {
        readers--;
        if (readers==0) {
        okToWrite.signal();
        }
    } finally {
        lock.unlock();
    }
    }

    void start_write(Object item) {
    lock.lock();
```

```java
    try {
        while (readers>0 || writers>0) {
        writers_waiting++;
        okToWrite.await();
        writers_waiting--;
        }
        writers++;
    } finally {
        lock.unlock();
    }
    }

    void stop_write() {
    lock.lock();
    try {
        writers--;
        okToWrite.signal();
        okToRead.signalAll();
    } finally {
        lock.unlock();
    }
    }
}
```

An attempt at a fair solution to RW is presented in Listing 3.3. One situation that may lead to deadlock is: W1,R1,W2. Another is: R1, W1, R2.

```java
  import java.util.concurrent.locks.*

class RW {
    private int readers;
    private int writers;
    private int writers_waiting;
    private int readers_waiting;
    static final Lock lock = new ReentrantLock();
    static final Condition okToRead = lock.newCondition();
    static final Condition okToWrite = lock.newCondition();

    RW() {
    readers=0;
    writers=0;
    writers_waiting=0;
    readers_waiting=0;
    }

    void start_read() {
    lock.lock();
    try {
          while (writers>0 || writers_waiting>0) {
                readers_waiting++;
        okToRead.await();
                readers_waiting--;
        }
        readers++;
    } finally {
        lock.unlock();
    }
    }
```

```
    void stop_read() {
    lock.lock();
    try {
        readers--;
        if (readers==0) {
        okToWrite.signal();
        }
    } finally {
        lock.unlock();
    }
    }

    void start_write(Object item) {
    lock.lock();
    try {
        while (readers>0 || writers>0 || readers_waiting>0) {
        writers_waiting++;
        okToWrite.await();
        writers_waiting--;
        }
        writers++;
    } finally {
        lock.unlock();
    }
    }

    void stop_write() {
    lock.lock();
    try {
        writers--;
        okToWrite.signal();
        okToRead.signalAll();
    } finally {
        lock.unlock();
    }
    }
}
```

Listing 3.3: Incorrect attempt at a fair solution to RW; may deadlock

If we replace `stop_write` with the following code, then our solution may deadlock. Hint: Consider W1,R1,W2.

```
void stop_write() {
    lock.lock();
    try {
        writers--;
        if (readers_waiting==0) {
        okToWrite.signal();
        } else {
        okToRead.signalAll();
        }
    } finally {
        lock.unlock();
    }
    }
```

Part II

Message Passing

Chapter 4

Message Passing in Erlang

4.1 Examples

4.1.1 Semaphores

```
-module(sem).
-compile(nowarn_export_all).
-compile(export_all).

make(N) ->
    spawn(?MODULE,sem_loop,[N]).

acquire(S) ->
    S!{acquire,self()},
    receive
    {ok} ->
      ok
    end.

release(S) ->
   S!{release}.

sem_loop(0) ->  %% no permits available
    receive
      {release} ->
        sem_loop(1)
    end;
sem_loop(N) when N>0 ->  %% permits available
    receive
      {acquire,From} ->
        From ! {ok},
        sem_loop(N-1);
    {release} ->
        sem_loop(N+1)
end.
```

sem.erl

```
-module(semcl).
```

```
-compile(nowarn_export_all).
-compile(export_all).

start() ->
    S = sem:make(0),
    spawn(?MODULE,client1,[S]),
    spawn(?MODULE,client2,[S]),
    ok.

client1(S) ->
    sem:acquire(S),
    io:format("a"),
    io:format("b").

client2(S) ->
    io:format("c"),
    io:format("d"),
    sem:release(S).
```

semcl.erl

4.1.2 A Cyclic Barrier

```
-module(barr).
-compile(nowarn_export_all).
-compile(export_all).

make(N) ->
    spawn(?MODULE,coordinator,[N,N,[]]).

reached(B) ->
    B!{reached,self()},
    receive
    ok ->
        ok
    end.

% coordinator(N,M,L)
% N is the size of the barrier
% M is the number of processes YET to arrive at the barrier
% L is a list of the PIDs of the processes that have already arrived at the barrier

coordinator(N,0,L) ->
    [ PID!ok || PID <- L],
    coordinator(N,N,[]);
coordinator(N,M,L) when M>0 ->
    receive
    {reached,From} ->
        coordinator(N,M-1,[From|L])
    end.
```

barr.erl

```
-module(barrcl).
-compile(nowarn_export_all).
-compile(export_all).
```

```
start() ->
    B = barr:make(3),
    spawn(?MODULE,client1,[B]),
    spawn(?MODULE,client2,[B]),
    spawn(?MODULE,client3,[B]),
    ok.

client1(B) ->
    io:format("a"),
    barr:reached(B),
    io:format("1"),
    client1(B).

client2(B) ->
    io:format("b"),
    barr:reached(B),
    io:format("2"),
    client2(B).

client3(B) ->
    io:format("c"),
    barr:reached(B),
    io:format("3"),
    client3(B).
```

barrcl.erl

4.1.3 Guessing Game

```
-module(gg).
-compile(nowarn_export_all).
-compile(export_all).

start() ->
    S = spawn(?MODULE,server_loop,[]),
    [ spawn(?MODULE,client,[S]) || _ <- lists:seq(1,100)].

client(S) ->
    S!{self(),start},
    receive
    {ok,Servlet} ->
        client_loop(Servlet,rand:uniform(100))
    end.

client_loop(Servlet, G) ->
    Servlet!{G,self()},
    receive
    {youGotIt,T} ->
        io:format("~w got it in ~w tries~n",[self(),T]);
    {tryAgain} ->
        client_loop(Servlet,rand:uniform(100))
    end.

server_loop() ->
    receive
    {From,start} ->
        ServLet = spawn(?MODULE,servlet,[rand:uniform(100),0]),
```

```
        From!{ok,ServLet},
        server_loop()
    end.

servlet(N,T) ->
    receive
    {Guess,From} when Guess==N ->
        From!{youGotIt,T};
    {Guess,From} when Guess/=N ->
        From!{tryAgain},
        servlet(N,T+1)
end.
```

gg.erl

4.1.4 Producers/Consumers

```
-module(pc).
-compile(nowarn_export_all).
-compile(export_all).

start(Cap,NofP,NofC) ->
    RS = spawn(?MODULE,resource,[0,Cap,0,0]),
    [ spawn(?MODULE,producer,[RS]) || _ <- lists:seq(1,NofP)],
    [ spawn(?MODULE,consumer,[RS]) || _ <- lists:seq(1,NofC)],
    ok.

%% client code
producer(RS) ->
    startProduce(RS),
    %% produce
    timer:sleep(rand:uniform(100)),
    stopProduce(RS).

consumer(RS) ->
    startConsume(RS),
    %% consume
    timer:sleep(rand:uniform(100)),
    stopConsume(RS).

%% PC code
startProduce(RS) ->
    RS!{startProduce,self()},
    receive
    {ok} ->
        ok
    end.

stopProduce(RS) ->
    RS!{stopProduce}.

startConsume(RS) ->
  RS!{startConsume,self()},
    receive
    {ok} ->
        ok
    end.
```

```
stopConsume(RS) ->
    RS!{stopConsume}.

resource(Size,Cap,SP,SC) ->
    receive
    {startProduce,From} when Size + SP < Cap ->
        From!{ok},
        resource(Size,Cap,SP+1,SC);
    {stopProduce} ->
        resource(Size+1,Cap,SP-1,SC);
    {startConsume,From} when Size - SC > 0 ->
        From!{ok},
        resource(Size,Cap,SP,SC+1);
    {stopConsume} ->
        resource(Size-1,Cap,SP,SC-1)
    end.
```

pc.erl

Part III

Model Checking

Chapter 5

Promela

5.1 Syntax

We begin with a brief introduction to Promela through a series of examples.

5.1.1 Shared Variable in Promela

```
byte n=0;

active proctype P() {
  n=1;
  printf("P has pid %d. n=%d\n",_pid,n)
};

active proctype Q() {
  n=2;
  printf("Q has pid %d. n=%d\n",_pid,n)
}
```

Executing Promela code is referred to as a "simulation run of the model".

```bash
$ spin eg.pml
          Q has pid 1. n=2
      P has pid 0. n=2
2 processes created
```

bash

Each process is a assigned a pid, starting from 0, By default, during simulation runs, Spin arranges for the output of each active process to appear in a different column: the pid number is used to set the number of tab stops used to indent each new line of output that is produced by a process. You can use the `-T` option to supress indentation.

```bash
$ spin -T eg.pml
P has pid 0. n=1
Q has pid 1. n=1
2 processes created
```

bash

Semicolon is a separator, not a terminator.

5.1.2 Examples involving Loops

```
byte sum=0;

active proctype P() {
  byte i=0;
  do
   :: i>10 -> break
   :: else ->
        sum = sum + i;
        i++
  od;

  printf("The sum of the first 10 numbers is %d\n",sum)
}
```

The following example is one of an infinite loop. Run it and note also how Spin reports overflows errors.

```
byte i=0;

active proctype P() {
 do
  :: i++;
     printf("Value of i: %d\n. ",i)
 od
}
```

An example using a for loop:

```
byte sum=0;

active proctype P() {
  byte i;
  for (i:1..10) {
    sum = sum + i
  }

  printf("The sum of the first 10 numbers is %d\n",sum)
}
```

5.1.3 Expressions as blocking commands

```
byte c=0;
finished = 0;
proctype P() {
  c++;
  finished++
}

proctype Q() {
  c++;
  finished++
}

init {
  atomic {
    run P();
    run Q()
  };
  finished==2;
  printf("c is %d\n",c)
}
```

Equivalently, one may do the following:

```
byte c=0;

proctype P() {
  c++
}

proctype Q() {
  c++
}

init {
  atomic {
    run P();
    run Q()
  };
  _nr_pr==1;
  printf("c is %d\n",c)
}
```

However, the following variation does not have the expected outcome. When a process terminates, it can only die and make its `_pid` number available for the creation of another process, if and when it has the highest `_pid` number in the system. This means that processes can only die in the reverse order of their creation (in stack order).

```
active proctype P() {
  printf("A");
}

active proctype Q() {
  printf ("B");
}

```

```
init {
10   printf("Pr %d",_nr_pr);
      _nr_pr==1;
12    printf("Done")
}
```

termination.pml

For example, consider what happens if we simulate a run:

```
$ spin termination.pml
      A           B                Pr 3       timeout
#processes: 3
  3:    proc  2 (:init::1) termination.pml:11 (state 2)
  3:    proc  1 (Q:1) termination.pml:7 (state 2) <valid end state>
  3:    proc  0 (P:1) termination.pml:3 (state 2) <valid end state>
3 processes created
```

bash

It deadlocks at line 11 (`_nr_pr==1`) of the file termination.pml. This boolean expression is blocked since processes 0 and 1 cannot terminate until 2 does. If we attempt to verify this program we will obtain an invalid end-state error at line 11.

5.1.4 Macros

Semaphores can be modeled in Promela using an `inline` definition. An inline definition works much like a preprocessor macro, in the sense that it just defines a replacement text for a symbolic name, possibly with parameters.

```
byte s=0;

inline acquire(s) {
 atomic {
  s>0 -> s--
 }
}

inline release(s) {
 s++
}

/* AB after CD */
proctype P() {
 acquire(s);
 printf("A");
 printf("B")
}

proctype Q() {
 printf("C");
 printf("D");
 release(s)
}

init {
 atomic {
```

```
28    run P();
      run Q()
30   }
    }
```

Problems if you drop the "atomic" in "acquire":

```
1   byte s=1;
    byte c=0;
3
    inline acquire(s) {
5     s>0 -> s--
    }
7
    inline release(s) {
9    s++
    }
11
    proctype P() {
13   acquire(s);
     c++;
15  }

17  proctype Q() {
     acquire(s);
19   c++;
    }
21  / /\ AB after CD *\/ */
    /* proctype P() { */
23  /* acquire(s); */
    /* printf("A"); */
25  /* printf("B") */

27  /* } */

29  /* proctype Q() { */

31  /* printf("C"); */
    /* printf("D"); */
33  /* release(s) */
    /* } */
35
    init {
37   atomic {
      run P();
39    run Q()
     }
41   (_nr_pr==1);
     printf("C is %d ",c)
43
    }
```

Exercise: would executing lines 7-8 and 18-19 in atomic block avoid deadlock? What about inverting lines 7 and 8 and then placing them in an atomic block (and likewise with lines 18 and 19)?

```
bool wantP = false;
bool wantQ = false;
byte cs=0;

proctype P() {
 do
  :: wantP = true;
     !wantQ;
     cs++;
     assert (cs==1);
     cs--;
     wantP=false
 od
}

proctype Q() {
 do
  :: wantQ = true;
     !wantP;
     cs++;
     assert (cs==1);
     cs--;
     wantQ=false
 od
}

init {
 atomic {
  run P();
  run Q()
 }
}
```

Figure 5.1: Attempt III in Promela

```
   byte ticket=0;
2  byte mutex=1;

4  inline acquire(sem) {
    atomic {
6    sem>0 -> sem--
    }
8  }

10 inline release(sem) {
    sem++
12 }

14 active [5] proctype Jets() {
    acquire(mutex);
16  acquire(ticket);
    acquire(ticket)
18  release(mutex)
   }
20
   active [5] proctype Patriot() {
22  release(ticket);
   }
```

Figure 5.2: Solution to Bar Problem in Promela

5.2 Assertion-Based Model Checking

5.2.1 The Bar Problem Revisited

Listing 5.2 presents the solution to the Bar Problem in Promela. We'll verify that this solution is correct in the sense of upholding the problem invariant, namely that there at least two patriots fans for every jets fan. Before doing so, however, let us first run a simulation of this model.

```bash
> spin bar.pml
      timeout
#processes: 5
        ticket = 0
        mutex = 0
 23:    proc  4 (Jets:1) bar.pml:4 (state 4)
 23:    proc  3 (Jets:1) bar.pml:4 (state 4)
 23:    proc  2 (Jets:1) bar.pml:19 (state 15) <valid end state>
 23:    proc  1 (Jets:1) bar.pml:19 (state 15) <valid end state>
 23:    proc  0 (Jets:1) bar.pml:4 (state 12)
10 processes created
```

The `timeout` indicates that the simulation did not run to completion, it got stuck at a state that is not a valid end state. In other words, it reached a deadlock. From the output above we can see that indeed there are three processes that are deadlocked: 0, 3 and 4. The fact that they are all stuck at line 4 means they are blocked at an acquire. Since there are no available permits in `mutex`, clearly processes 3 and 4 are blocked on the `acquire(mutex)` and 0 at the second `acquire(ticket)`.

A process that terminates must do so after executing its last instruction, otherwise it is said to be in an invalid end state. SPIN checks for this by default. One can insert end state labels to indicate that if execution reaches a certain point and fails to terminate, this should not be considered as an invalid end state. Such valid end state labels must be prefixed with the word `end`. For example, if we replaced the acquire operation in 5.2 with the following one:

```
inline acquire(permits) {
  skip;
end1:
  atomic {
    permits>0;
    permits--
  }
}
```

then the end states mentioned above are no longer reported as such:

```
> spin bar.pml
      timeout
#processes: 5
        ticket = 0
        mutex = 0
 34:    proc  4 (Jets:1) bar.pml:7 (state 4) <valid end state>
 34:    proc  3 (Jets:1) bar.pml:7 (state 4) <valid end state>
 34:    proc  2 (Jets:1) bar.pml:22 (state 18) <valid end state>
 34:    proc  1 (Jets:1) bar.pml:7 (state 14) <valid end state>
 34:    proc  0 (Jets:1) bar.pml:22 (state 18) <valid end state>
10 processes created
```

bash

Let us get back to the task of verifying that the solution is correct. In order to do so we add two counters. Listing 5.2.1 exhibits the updated code.

```
byte mutex=1;
byte ticket=0;
byte j=0;
byte p=0;

inline acquire(permits) {
  skip;
end1:
  atomic {
    permits>0;
    permits--
  }
}

inline release(permits) {
  permits++
}

active [5] proctype Jets() {

  acquire(mutex);
```

```
  acquire(ticket);
  acquire(ticket);
  release(mutex)
  j++;
  assert (j*2<=p)
}

active [5] proctype Patriots() {
  release(ticket)
  p++;
  assert (j*2<=p)
}
```

We now verify that our solution is correct.

```bash
$ spin -a bar.pml
$ gcc -o pan pan.c
$ ./pan

pan:1: assertion violated ((j*2)<=p) (at depth 34)
pan: wrote bar.pml.trail

(Spin Version 6.5.1 -- 20 December 2019)
Warning: Search not completed
    + Partial Order Reduction

Full statespace search for:
    never claim             - (none specified)
    assertion violations    +
    acceptance   cycles     - (not selected)
    invalid end states   +

State-vector 92 byte, depth reached 47, errors: 1
    18104 states, stored
    18718 states, matched
    36822 transitions (= stored+matched)
        0 atomic steps
hash conflicts:       147 (resolved)

Stats on memory usage (in Megabytes):
    2.072   equivalent memory usage for states (stored*(State-vector + overhead))
    1.071   actual memory usage for states (compression: 51.69%)
            state-vector as stored = 34 byte + 28 byte overhead
  128.000   memory used for hash table (-w24)
    0.534   memory used for DFS stack (-m10000)
  129.511   total actual memory usage

pan: elapsed time 0.02 seconds
pan: rate    905200 states/second
```

bash

It seems that this is not the case since an assertion violation is reported. An inspection of the offending trail shows that when the patriots perform a `release(ticket)` but before incrementing the p counter, a jets fan can go in. There are two ways we can fix our code. One is to increment the p counter before performing the release. Another one is to perform the release and increment the counter in one atomic block.

5.2.2 The MEP Problem

Consider the code for Dekker's solution to the MEP from Fig. **??**. The Promela code is listed in Fig. **??**. We have inserted a variable cs to help count when a process enters its critical section. Note how the await in line 12 has been coded as a do-loop: we want this loop to cycle while it waits for the condition to hold.

```
   int turn = 1;
2  boolean wantP = false;
   boolean wantQ = false;
4
   Thread.start { //P
6    while (true) {
      // non-CS
8     wantP = true
      while wantQ
10      if (turn == 2) {
          wantP = false
12        await (turn==1)
          wantP = true
14      }
      // CS
16    turn = 2
      wantP = false
18    // non-CS
     }
20 }

22 Thread.start { //Q
     while (true) {
24    // non-CS
      wantQ = true
26    while wantP
        if (turn == 1) {
28        wantQ = false
          await (turn==2)
30        wantQ = true
        }
32    // CS
      turn = 1
34    wantQ = false
      // non-CS
36   }
   }
```

```
bool wantp = false;
bool wantq = false;
byte turn = 1;
byte cs=0;

active proctype P() {
    do
```

```
    ::  wantp = true;
        do
        :: !wantq -> break;
        :: else ->
            if
            :: (turn == 2) ->
                wantp = false;
                do
                :: turn==1 -> break
                :: else
                od;
                wantp = true
            :: else  /* leaves if, if turn<>2 */
            fi
        od;
        cs++;
        assert(cs==1);
        cs--;
        wantp = false;
        turn = 2
    od
}

active proctype Q() {
    do
    ::  wantq = true;
        do
        :: !wantp -> break;
        :: else ->
            if
            :: (turn == 1) ->
                wantq = false;
                do
                :: turn==2 -> break
                :: else
                od;
                wantq = true
            :: else  /* leaves if, if turn<>2 */
            fi
        od;
        cs++;
        assert(cs==1);
        cs--;
        wantq = false;
        turn = 1
    od
}
```

```
$ spin -a dekker.pml
$ gcc -o pan pan.c
$ ./pan

(Spin Version 6.5.1 -- 20 December 2019)
    + Partial Order Reduction

Full statespace search for:
```

```
    never claim             - (none specified)
    assertion violations    +
    acceptance   cycles     - (not selected)
    invalid end states  +

State-vector 28 byte, depth reached 74, errors: 0
      172 states, stored
      173 states, matched
      345 transitions (= stored+matched)
        0 atomic steps
hash conflicts:         0 (resolved)

Stats on memory usage (in Megabytes):
    0.009   equivalent memory usage for states (stored*(State-vector + overhead))
    0.287   actual memory usage for states
  128.000   memory used for hash table (-w24)
    0.534   memory used for DFS stack (-m10000)
  128.730   total actual memory usage


unreached in proctype P
    dekker.pml:29, state 28, "-end-"
    (1 of 28 states)
unreached in proctype Q
    dekker.pml:54, state 28, "-end-"
    (1 of 28 states)

pan: elapsed time 0 seconds
```

bash

5.2.3 The Feeding Lot Problem Revisited

Consider the Feeding Lot Problem discussed in Exercise **??**:

> A farm breeds cats and dogs. It has a common feeding area for both of them. Although the feeding area can be used by both cats and dogs, it cannot be used by both at the same time for obvious reasons. Provide a solution using semaphores. The solution should be free from deadlock but not necessarily from starvation.

A solution in Promela is given in Listing 5.3.

Exercise 5.2.1. *Show that if lines 20, 28, 44 and 52 are removed, then deadlock is possible. Explain the deadlock situation that can arise.*

Exercise 5.2.2. *Show, using assertions, that there cannot be felines feeding, if there are dogs feeding and, likewise, there cannot be dogs feeding, if there are felines feeding.*

Exercise 5.2.3. *Show that the following is an alternative solution to the problem by introducing assertions and checking them in Spin.*

```
byte dogs=0;
byte cats=0;
byte mutexDogs=1;
byte mutexCats=1;
byte mutex=1;

inline acquire(sem) {
  atomic {
    sem>0;
    sem--
  }
}

inline release(sem) {
 sem++
}

active [3] proctype Dog() {
  acquire(mutex);
  acquire(mutexDogs);
  dogs++;
  if
  :: dogs==1 -> acquire(mutexCats);
  :: else -> skip;
  fi
  release(mutexDogs);
  release(mutex);
  // Feed
  acquire(mutexDogs);
  dogs--;
  if
  :: dogs==0 -> release(mutexCats);
  :: else -> skip;
  fi
  release(mutexDogs);
}

active [3] proctype Cat() {
  acquire(mutex);
  acquire(mutexCats);
  cats++;
  if
  :: cats==1 -> acquire(mutexDogs);
  :: else -> skip;
  fi
  release(mutexCats);
  release(mutex);
  // Feed
  acquire(mutexCats);
  cats--;
  if
    :: cats==0 -> release(mutexDogs);
    :: else -> skip;
  fi
  release(mutexCats);
}
```

Figure 5.3: Feeding Lot Problem in Promela

```
byte mutexCats=1;
byte mutexDogs=1;
byte mutex=1;
byte resource=1;
byte cats=0;
byte dogs=0;

// Code for acquire and release omitted for brevity

active [3] proctype Cat(){
  acquire(mutex);
  acquire(mutexCats);
  if
  :: cats==0 -> acquire(resource)
  :: else -> skip
  fi;
  cats++;
  release(mutexCats);
  release(mutex);

  acquire(mutexCats);
  cats--;
  if
  :: cats==0 -> release(resource)
  :: else -> skip
  fi;
  release(mutexCats);
}

active [3] proctype Dog(){
  acquire(mutex);
  acquire(mutexDogs);
  if
    :: dogs==0 -> acquire(resource)
    :: else -> skip
  fi;
  dogs++;
  release(mutexDogs);
  release(mutex);

  acquire(mutexDogs);
  dogs--;
  if
    :: dogs==0 -> release(resource)
    :: else -> skip
  fi;
  release(mutexDogs);
}
```

5.3 Non-Progress Cycles

SPIN can check for some simple liveness properties without the need to use Temporal Logic. An infinite computation that does not include infinitely many occurrences of a progress state is called a non-progress cycle. We illustrate this feature by showing that Dekker's algorithm enjoys absence of livelock.

Consider

```
byte x=1;

active proctype P() {

  do
    :: x==1 -> x=2;
    :: x==2 -> x=1;
  od
}
```

Consider

```
byte x=1;

active proctype P() {

  do
    :: x==1 -> x=2;
    :: x==2 -> progress1: x=1;
  od
}
```

Consider

```
byte x=1;

active proctype P() {

  do
    :: x==1 -> x=2;
    :: x==2 -> progress1: x=1;
    :: x==2 -> x=1;
  od
}
```

We would like to verify that this attempt at solving the MEP problem does not enjoy absence of livelock. For that we insert progress labels just before entering the CS.

```
bool wantP=false;
bool wantQ=false;

proctype P() {
  do
    :: wantP=true;
       do
     :: wantQ==false -> break
     :: else
       od;
progress1:
       wantP=false
  od
}

proctype Q() {
  do
```

```
    :: wantQ=true;
       do
     :: wantP==false -> break
     :: else
       od;
progress2:
       wantQ=false
  od
}

init {
  atomic {
    run P();
    run Q()
  }
}
```

Selecting Non-Progress in the drop down list and then verifying, Spin reports a non-progress cycle:

```
2 Q:1   1)  wantQ = 1
Process Statement          wantQ
1 P:1   1)  wantP = 1      1
Process Statement          wantP      wantQ
2 Q:1   1)  else           1          1
<<<<<START OF CYCLE>>>>>
2 Q:1   1)  else           1          1
1 P:1   1)  else           1          1
2 Q:1   1)  else           1          1
spin: trail ends after 15 steps
```

spin

```
bool wantp = false;
bool wantq = false;
byte turn = 1;

active proctype P() {
    do
    ::  wantp = true;
        do
        :: !wantq -> break;
        :: else ->
            if
            :: (turn == 2) ->
                wantp = false;
                do
                :: turn==1 -> break
                :: else
                od;
                wantp = true
            :: else  /* leaves if, if turn<>2 */
            fi
        od;
progressP:
        wantp = false;
        turn = 2
```

```
    od
}

active proctype Q() {
    do
    ::  wantq = true;
        do
        :: !wantp -> break;
        :: else ->
            if
            :: (turn == 1) ->
                wantq = false;
                do
                :: turn==2 -> break
                :: else
                od;
                wantq = true
            :: else  /* leaves if, if turn<>2 */
            fi
        od;
progressQ:
        wantq = false;
        turn = 1
    od
}
```

"Weak Fairness" should be enabled. Weak fairness means that each statement that becomes enabled and remains enabled thereafter will eventually be scheduled. Consider the example below [**?**]:

```
byte x=0;

active proctype P() {
  do
    :: true -> x = 1 - x;
  od
}

active proctype Q() {
  do
    :: true -> progress1: x = 1 - x;
  od
}
```

It is possible that `Q` makes no progress if `Q` is never scheduled for execution. Weak fairness guarantees that it eventually will. Verify this in SPIN by first enabling weak fairness and then disabling it. In the former case no errors are reported, but in the latter a non-progress cycle is reported:

```
  0 P:1   1)  1
<<<<<START OF CYCLE>>>>>
0 P:1   1)  x = (1-x)
Process Statement          x
0 P:1   1)  1              1
0 P:1   1)  x = (1-x)      1
0 P:1   1)  1              0
```

spin

Consider the code for Attempt IV

```
bool wantP = false, wantQ = false;

active proctype P() {
  do
  :: wantP = true;
     do
     :: wantQ -> wantP = false; wantP = true
     :: else  -> break
     od;
     wantP = false
    od
}

active proctype Q() {
   do
   :: wantQ = true;
      do
      :: wantP -> wantQ = false; wantQ = true
      :: else -> break
      od;
   wantQ = false
   od
}
```

We know that it does not enjoy freedom from starvation. Freedom from starvation would mean that both P and Q enter their CS infinitely often. We can verify that it does not enjoy freedom from starvation by inserting a progress label in the critical section of P, selecting Non-Progress in the drop down list and then verifying.

```
  bool wantP = false, wantQ = false;

active proctype P() {
  do
  :: wantP = true;
     do
     :: wantQ -> wantP = false; wantP = true
     :: else  -> break
     od;
progress1:
     wantP = false
    od
}

active proctype Q() {
   do
   :: wantQ = true;
      do
      :: wantP -> wantQ = false; wantQ = true
      :: else -> break
      od;
progress2:
   wantQ = false
```

```
    od
}
```

Here is the output from Spin

```
1 Q:1   1)  wantQ = 1
Process Statement           wantQ
1 Q:1   1)  else            1
1 Q:1   1)  wantQ = 0       1
0 P:1   1)  wantP = 1       0
Process Statement           wantP       wantQ
1 Q:1   1)  wantQ = 1       1           0
1 Q:1   1)  wantP           1           1
0 P:1   1)  wantQ           1           1
<<<<<START OF CYCLE>>>>>
1 Q:1   1)  wantQ = 0       1           1
1 Q:1   1)  wantQ = 1       1           0
1 Q:1   1)  wantP           1           1
0 P:1   1)  wantP = 0       1           1
1 Q:1   1)  wantQ = 0       0           1
1 Q:1   1)  wantQ = 1       0           0
1 Q:1   1)  else            0           1
0 P:1   1)  wantP = 1       0           1
0 P:1   1)  wantQ           1           1
1 Q:1   1)  wantQ = 0       1           1
0 P:1   1)  wantP = 0       1           0
1 Q:1   1)  wantQ = 1       0           0
1 Q:1   1)  else            0           1
1 Q:1   1)  wantQ = 0       0           1
0 P:1   1)  wantP = 1       0           0
1 Q:1   1)  wantQ = 1       1           0
1 Q:1   1)  wantP           1           1
Process Statement           wantP       wantQ
0 P:1   1)  wantQ           1           1
spin: trail ends after 50 steps
```

Chapter 6

Solution to Selected Exercises

Section ??

Answer 6.0.1 (Exercise **??**). jj

Section ??

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