Construction and Verification of Software

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MIEI - Integrated Master in Computer Science and Informatics

Consolidation block

Lecture 8 - Concurrent Abstract Data Types

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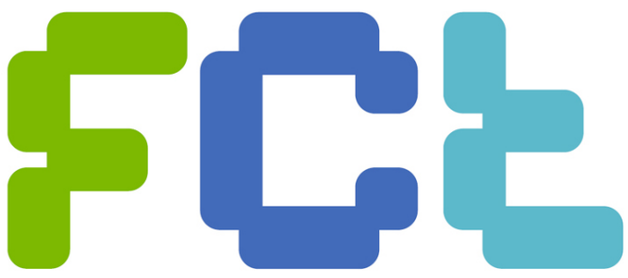

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Concurrent Abstract Data Types

Concurrency

Concurrency

- Several threads of control **share** the same state
- **Interference:**
  - the local view of a thread may change without notice (another thread may act “under the hood”).
- “No-sharing concurrency” (a.k.a. “parallelism”)
  - not treated in this course
- Interference is **the essence** of concurrency
- **Key issue**
  - how to keep state consistency in the presence of sharing and interference
- Reasoning about concurrency is **challenging**!

Verification of Concurrent ADTs

- Check the consistency of stateful objects, when subject to (concurrent) operation requests.
- Any method call must preserve consistency of the ADT
- Consistency is precisely expressed by the representation invariant (and abstraction mapping).
- Every method body *mbody* of an ADT operation must preserve the RepInv

  { RepInv && requires-cond } *mbody* { RepInv && ensures-cond}
- This line of reasoning works well under the assumption of sequentiality. What if methods overlap in time?
- **Challenge**: how to program and reason about ADTs with interfering methods

Interference

- Consider a Stack ADT
  - **– push(v), pop(), isEmpty()**
  - – push() interferes with pop() ?
  - – pop() interferes with isEmpty() ?
  - – pop() interferes with pop() ?
- Consider a Dictionary ADT
  - **– assoc(key,data), find(key)**
  - – assoc() interferes with find() ?
  - – assoc() interferes with assoc() ?
  - – find() interferes with find() ?

Operation Level Behaviour

- It is more useful to reason at the level of ADT operations, not about unstructured low level code and state
- Each ADT operation is performed in three steps
  - The operation is called (by the client thread)
  - The operation is executed (inside the ADT)
  - The operation returns
- Example:
  - push_call(2)
    - ... execute (internally to the ADT)
  - push_return
  - pop_call()
    - .... execute (internally to the ADT)
  - pop_return(2)

Operation Level Behaviour

- We may consider several levels of concurrency
  - Several threads are invoking ADT operations but only one may actually be executing the operation
    - strict serialisation, easier to implement and reason about
    - less chances of “unsound” interference
  - Several threads are invoking ADT operations but more than one may be executing an operation
    - more parallelism, more concurrency, harder to implement and reason about
    - more chances of “unsound” interference
- How does the concurrent object behaviour relate to the intended sequential object specification ?

Two Basic Models

- **Serializability**
  - The global trace is always consistent with some sequential serialisation of previous operations (no overlaps of calls and returns), compatible with the sequential specification.
- **Linearizability**
  - The global trace is always consistent with a view in which previous operations appear to occur instantaneously between calls and returns, and the obtained serialisation is compatible with the sequential specification.
- Linearizability is more flexible than serializability, as it allows for more parallel behaviour.

Desired properties of op execution

- Let us reinterpret the “classical” ACID story:
- **Atomicity**
  - No intermediate states are visible (clearly, they are not compatible with the representation invariant)
- **Consistency**
  - Operations lead from a sound state to a sound state (invariant and soundness are preserved)
- **Isolation**
  - This is another word for “no unsafe interference”
- **Durability** (this goes without saying)
  - Effects are undoable (N.B: this is more useful to highlight in the context of database transactions)

Correctness of Concurrent ADTs

- With naive concurrency, it is hard (or impossible) for client code to be sure if a specific **post-condition** holds.
- E.g: two clients modify the concrete state at the same time, bringing the state inconsistent, breaking the representation invariant, or even crashing the code.
- Solution using serialisation:
  - **serialize** usages of concrete states, so that just a **single** thread may be accessing the state at each given moment
    (mutual exclusion of concrete state)
  - We may then safely reason about such mutually exclusive code fragments as we have done for sequential code.

Correctness of Concurrent ADTs

- With naive concurrency, it is hard (or impossible) for client code to be sure if a specific **pre-condition** holds.
- E.g: client checks that a buffer is not empty, but other thread empties it under the hood.
- Solution:
  - Concurrency control replaces pre-condition checking (on the client side) by explicit waiting for the precondition to hold (inside the ADT).
  - The pre-condition for some ADT op can only be enabled by executing some other ADT op
  - So waiting for a pre-condition must be managed by special programming language or system support, in a coordinated way with other ADT operations

Concurrent Programming

- Reasoning about concurrency is **hard**
- Making sure the code is right is much more difficult than in sequential code
- Trying to simulate the program running in your head and debug it does not work anymore :-)
  - It does not work in the sequential case either, actually..., although you may still believe.
- We will now study how to design and construct correct concurrent code, based on **monitors**
- monitor = invariant preserving concurrent ADT
- Nicely supported by java.concurrent.util

Monitors

Operating Systems
C. Weissman Editor

Monitors: An Operating System Structuring Concept

C.A.R. Hoare
The Queen's University of Belfast

This paper develops Brinch-Hansen's concept of a monitor as a method of structuring an operating system. It introduces a form of synchronization, describes a possible method of implementation in terms of semaphores and gives a suitable proof rule. Illustrative examples include a single resource scheduler, a bounded buffer, an alarm clock, a buffer pool, a disk head optimizer, and a version of the problem of readers and writers.

Key Words and Phrases: monitors, operating systems, scheduling, mutual exclusion, synchronization, system implementation languages, structured multiprogramming
CR Categories: 4.31, 4.22

Monitors

- An ADT where operations may be called concurrently
- **2 key mechanisms** provided for ensuring consistency:

  synchronization (a.k.a. mutual exclusion)

  – only a single thread may “own” the shared state at any time object, and has permission to change it

  – All that client code may expect from shared state is **the invariant, and nothing more than the invariant**

  – any context switches must preserve the invariant (observable states)

concurrency control

  – pre-condition checking must be usually replaced by explicit waiting for the pre-condition to hold.

  – conditions refine the invariant into finer partitions.

Implementation of monitors

- To implement monitors in Java, we will use locks
  - You have already heard about locks (FSO, CP)
  - A lot harder to reason about programs if we just think of using locks in an unstructured way
- We may latter refine the borders of serialisability to get more concurrency (approach linearisability)
  - Still, useful to only use locks as delimiters of abstract operations on the shared state, thought of as a ADT
  - We will use the **java.util.concurrent** API (Doug Lea)
  - We will learn how to design concurrent ADTs without thinking "operationally", but rather in terms of (partitioned) ownership, invariants. and conditions.

Example (Bounded Counter)

```
class BCounter {
  int N;
  int MAX;
  BCounter(int max) { N = 0 ; MAX = max; }
  void inc() { N++; }
  void dec() { N--; }
  int get() { return N; }
}
```

Example (Bounded Counter)

```
/*@
    predicate BCounterInv(BCounter c; int v,int m) =
        c.N |-> v &*& c.MAX |-> m &*& v>=0 &*& v<=m;
@*/
class BCounter {
  int N;
  int MAX;
  BCounter(int max)
  //@ requires 0 <= max;
  //@ ensures BCounterInv(this,0,max);
  { N = 0 ; MAX = max; }

  void inc()
  //@ requires BCounterInv(this,?n,?m) &*& n < m;
  //@ ensures BCounterInv(this,n+1,m);
  { N++; }

  void dec()
  //@ requires BCounterInv(this,?n,?m) &*& n > 0;
  //@ ensures BCounterInv(this,n-1,m);
  { N--; }

  int get()
  //@ requires BCounterInv(this,?n,?m);
  //@ ensures BCounterInv(this,n,m) &*& 0<=result &*& result<=m;
  { return N; }
}
```

Example (Bounded Counter)

```
public static void main(String[] args)
//@ requires true;
//@ ensures true;
{
      int MAX = 100;
      BCounter c = new BCounter(MAX);
      //@ assert BCounterInv(c,0,MAX);
       if (c.get() < MAX) {
           c.inc(); // this is ok, precondition satisfied
       }
}
```

Example (Bounded Counter)

```
public static void main(String[] args)
//@ requires true;
//@ ensures true;
{
      int MAX = 100;
      BCounter c = new BCounter(MAX);
      //@ assert BCounterInv(c,0,MAX);
      giveaway(c); // potentially give other thread access to c
       if (c.get() < MAX) {
            //@ assert BCounterInv(c,?v,MAX) &*& v < MAX;
            c.inc();
            // not safe any more as other thread may have acted
      }
}
```

1st: Serialise access to shared state

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

class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;

  BCounter(int max)
  {
        N = 0 ;
        MAX = max;
        mon = new ReentrantLock();
   }
…
```

Example (Bounded Counter)

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

class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
…
  void inc()
{
     mon.enter(); //request permission to the shared state
     N++;
     mon.leave(); //release ownership of the shared state
 }

 void dec()
{
     mon.enter(); //request permission to the shared state
     N--;
     mon.leave(); //release ownership of the shared state
 }
```

Example (Bounded Counter)

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

class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
…
  void inc()
{
     mon.lock(); //request permission to the shared state
     N++;
     mon.unlock(); //release ownership of the shared state
 }

 void dec()
{
     mon.lock(); //request permission to the shared state
     N--;
     mon.unlock(); //release ownership of the shared state
 }
```

Example (Bounded Counter)

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

class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
…
  int get()
  {
      int r;
      mon.enter();
      r = N; // put a copy on the stack, private to the thread
      mon.leave();
      return r;
  }
```

Hoare Rule for enter / leave

{ emp } m.enter () { SharedStateInv }

{ SharedStateInv } m.leave () { emp }

SharedStateInv is the representation invariant.

In our example ...

```
//@ predicate BCounterInv(BCounter c) =
    c.N |-> ?v &*& c.MAX |-> ?m &*& v>=0 &*& v<=m;
```

so:

{ `emp` } m.enter () { `BCounterInv(this)` }

Issue: Red assertions not available!

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;

 void inc()
  //@ requires BCounterInv(this,?n,?m) &*& n < m;
  //@ ensures BCounterInv(this,n+1,m);
  {
      mon.enter(); //@ request permission to the shared state
      //@ assert BCounterInv(this,?n,?m)
      N++;
      //@ assert BCounterInv(this,n+1,m)
      mon.leave(); //@ release ownership of the shared state
  }
```

How can a client check n<m ?

- With naive concurrency, it is hard (or impossible) for client code to be sure a **pre-condition** holds.
- E.g: client checks that a buffer is not empty, but other thread empties it under the hood.
- Solution:
  - Concurrency control replaces pre-condition checking (on the client side) by explicit waiting for the precondition to hold (inside the ADT).
  - The pre-condition for some ADT op can only be enabled by executing some other ADT op
  - So waiting for a pre-condition must be managed by special programming language or system support, in a coordinated way with other ADT operations

“invisible” abstract state

- Many threads may be interfering, so the only thing one may assume is the invariant, only after entering the shared state a client may know extra details about the concrete state.
- In fact, nothing specific about the abstract state may be revealed to client code, and we need to be less informative about the abstract state (e.g., no current val)
- Inside the object, the only unprotected objects are the locks (or the single lock).
- Each lock can be used to ask permission to access a disjoint part of the shared state.
- We must precisely define which part of the shared state is separately owned by each lock.

Example (Bounded Counter)

```
/*@
    predicate_ctor BCounter_shared_state (BCounter c) () =
        c.N |-> ?v &*& v >= 0 &*& c.MAX |-> ?m &*& m > 0 &*& v <= m;
*@/

/*@ predicate BCounterInv(BCounter c) =
    c.mon |-> ?l &*&
    l != null &*& lck(l,1,BCounter_shared_state(c))
    @*/
class BCounter {
   int N;
   int MAX;
   ReentrantLock mon;
   BCounter(int max)
   //@ ensures BCounterInv(this);
   {
     N = 0 ;
     MAX = max;
     mon = new ReentrantLock();
   }
}
```

Example (Bounded Counter)

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;

  void inc()
  //@ requires BCounterInv(this);
  //@ ensures BCounterInv(this);
  {
    mon.enter(); // request permission to the shared state
    //@ open BCounter_shared_state(this)();
    N++;
    //@ close BCounter_shared_state(this)();
    mon.leave(); // release ownership of the shared state
  }
}
```

Example (Bounded Counter)

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;

  void dec()
  //@ requires BCounterInv(this);
  //@ ensures BCounterInv(this);
  {
    mon.enter();
    //@ open BCounter_shared_state(this)();
    N--;
    //@ close BCounter_shared_state(this)();
    mon.leave();
  }
}
```

What if N==0 ?

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;

  void dec()
  //@ requires BCounterInv(this); // no way to reveal a pre-cond!
  //@ ensures BCounterInv(this);
  {
    mon.enter();
    //@ open BCounter_shared_state(this)();
    N--;
    //@ close BCounter_shared_state(this)(); // must ensure N>=0!
    mon.leave();
  }
}
```

Partition shared state using conditions

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
  Condition notzero;
  Condition notmax;

  void dec()
  //@ requires BCounterInv(this);
  //@ ensures BCounterInv(this);
  {
    mon.enter();
    //@ open BCounter_shared_state(this)();
    if (N==0) notzero.wait();
    N--;
    //@ close BCounter_shared_state(this)();
    mon.leave();
  }
}
```

Partition shared state using conditions

```
/*@

predicate_ctor BCounter_shared_state (BCounter c) () =
   c.N |-> ?v &*& v >= 0 &*& c.MAX |-> ?m &*& m > 0 &*& v <= m;

predicate_ctor BCounter_nonzero (BCounter c) () =
   c.N |-> ?v &*& c.MAX |-> ?m &*& v > 0 &*& m > 0 &*& v <= m;

predicate_ctor BCounter_nonmax (BCounter c) () =
   c.N |-> ?v &*& c.MAX |-> ?m &*& v < m &*& m > 0 &*& v >= 0;
```

```
predicate BCounterInv(BCounter c) =
        c.mon |-> ?l
    &*& l != null
    &*& lck(l,1, BCounter_shared_state(c))
    &*& c.notzero |-> ?cc
    &*& cc != null
    &*& cond(cc, BCounter_shared_state(c), BCounter_nonzero(c))
    &*& c.notmax |-> ?cm
    &*& cm != null
    &*& cond(cm, BCounter_shared_state(c), BCounter_nonmax(c));
@*/
```

Partition shared state using conditions

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
  Condition notzero;
  Condition notmax;

  void dec()
  //@ requires BCounterInv(this);
  //@ ensures BCounterInv(this);
  {
    mon.enter();
    //@ open BCounter_shared_state(this)();
    if (N==0) notzero.wait();
    N--;
    //@ close BCounter_shared_state(this)();
    mon.leave();
  }
}
```

Example (Bounded Counter)

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
  Condition notzero;
  Condition notmax;

  BCounter(int max)
  //@ requires max > 0;
  //@ ensures BCounterInv(this);
  {
    MAX = max; mon = new ReentrantLock();
    //@ close BCounter_shared_state(this)();
    //@ close set_cond(BCounter_shared_state(this),BCounter_nonzero(this));
    notzero = mon.newCondition(); // notzero set to mean N > 0  !!
    //@ close set_cond(BCounter_shared_state(this),BCounter_nonmax(this));
    notmax = mon.newCondition();  // notmax set to mean N < MAX !!
  }
}
```

Partition shared state using conditions

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
  Condition notzero; Condition notmax;
  void dec()
  //@ requires BCounterInv(this);
  //@ ensures BCounterInv(this);
  {
    mon.enter();
    //@ open BCounter_shared_state(this)();
    if (N==0) notzero.wait();
    //@ open BCounter_notzero(this)(); // refined state >=0
    N--;
    //@ close BCounter_shared_state(this)();
    mon.leave();
  }
}
```

Partition shared state using conditions

```
class BCounter {
  int N;
  int MAX;
  ReentrantLock mon;
  Condition notzero; Condition notmax;
  void inc()
  //@ requires BCounterInv(this);
  //@ ensures BCounterInv(this);
  {
    mon.enter();
    //@ open BCounter_shared_state(this)();
    if (N==MAX) notmax.wait();
    //@ open BCounter_notmax(this)(); // refined state <= max
    N++;
    //@ close BCounter_shared_state(this)();
    mon.leave();
  }
}
```

Hoare Rule for await

{ SharedStateInv } C.await() { SharedStateInv && cond(C) }

cond(C) is the refined state property denoted by condition C.

In our example:

- cond(**`notzero`**) = (N > 0)
- cond(**`notmax`**) = (N < MAX)

Ensure progress using signalling

```
void inc()
//@ requires BCounterInv(this);
//@ ensures BCounterInv(this);
{
  mon.enter();
  //@ open BCounter_shared_state(this)();
  if (N==MAX) notmax.wait();
  //@ assert BCounter_notmax(this)();
  N++;
  //@ close BCounter_notzero(this)();
  notzero.signal();
  //@ close BCounter_shared_state(this)();
  mon.leave();
}
```

Ensure progress using signalling

```
void dec()
//@ requires BCounterInv(this);
//@ ensures BCounterInv(this);
{
  mon.enter();
  //@ open BCounter_shared_state(this)();
  if (N==0) notzero.wait();
  //@ assert BCounter_notzero(this)();
  N--;
  //@ close BCounter_notmax(this)();
  notmax.signal();
  //@ close BCounter_shared_state(this)();
  mon.leave();
}
```

Hoare Rule for signal

{ SharedStateInv && cond(C) } C.signal() { SharedStateInv }

cond(C) is the refined state property denoted by condition C.

In our example:

- cond(**`notzero`**) = (N > 0)
- cond(**`notmax`**) = (N < MAX)

Defending against unsound implementation

Excerpt from Java API documentation:

Implementation Considerations

When waiting upon a *`Condition`*, a "spurious wakeup" is permitted to occur, in general, as a concession to the underlying platform semantics.
This has little practical impact on most application programs as a *`Condition`* should always be waited upon in a loop, testing the state predicate that is being waited for.
An implementation is free to remove the possibility of spurious wakeups but it is recommended that applications programmers always assume that they can occur and so always wait in a loop.

Defending against unsound implementation

```
void inc()
//@ requires BCounterInv(this);
//@ ensures BCounterInv(this);
{
  mon.enter();
  //@ open BCounter_shared_state(this)();
  while(N==MAX) notmax.wait();
  //@ assert BCounter_notmax(this)();
  N++;
  //@ close BCounter_notzero(this)();
  notzero.signal();
  //@ assert BCounter_shared_state(this)();
  mon.leave();
}
```

Defending against unsound implementation

```
void dec()
//@ requires BCounterInv(this);
//@ ensures BCounterInv(this);
{
  mon.enter();
  //@ open BCounter_shared_state(this)();
  while (N==0) notzero.wait();
  //@ assert BCounter_notzero(this)();
  N--;
  //@ close BCounter_notmax(this)();
  notmax.signal();
  //@ assert BCounter_shared_state(this)();
  mon.leave();
}
```

Concurrent ADT Construction Steps

Concurrent ADT Construction Steps

- Associate a monitor to the ADT (mon)
- Determine the CADT Representation Invariant (RI), which now talks about the shared state

  The RI describes the memory footprint of the shared state, subject to other various conditions.

- In the implementation of each operation of the CADT

  To get access to the RI, you must mon.lock()

  When done and only if the RI holds you mon.unlock()

- Replace the ADT op pre-conditions by conditions inside the monitor (this part must be carefully though).

Summary (key monitor primitives)

- mon.enter(); // a.k.a. mon.lock()

  asks for exclusive access to the shared state

  `{ P } mon.enter() { P &*& SSInv }`

- mon.leave(); // a.k.a. mon.unlock()

  releases exclusive access to the shared state

  `{ P &*& SSInv } mon.leave(); { P }`

- cond.wait();

  releases exclusive access to the shared state

  `{ P &*& SSInv} cond.await(); { P &*& SSCond}`

- cond.signal()

  releases exclusive access to the shared state

  `{ P &*& SSCond} cond.signal(); { P &*& SSInv}`

Concurrent ADT Construction Steps

- To replace ADT op pre-conditions by conditions inside the monitor, we must consider the following aspects:
- When a thread enters a CADT op and gets ownership of the RI, it may find that the state does not satisfy the pre-condition (e.g., wants to dec but counter value is zero)
- The thread must then await for the condition to hold (e.g, for the value to be > 0).
- Conversely, whenever a thread running inside the CADT establishes any one of the monitor conditions (e.g., inc establishes value >0), it has the duty to signal the condition (so that the runtime system, may awake a waiting thread)
- Notice: signaling is there to help the system to progress, and simplify the implementation of monitors.

Java Monitors Interface

```
package java.util.concurrent.locks;

interface Lock:

void lock() // Acquires the lock.

void unlock() // Releases the lock.

Condition newCondition() // Returns a new Condition instance that is
bound to this Lock instance.

interface Condition:

void await() // Causes the current thread to wait until the condition
holds (is signaled to hold).

void signal() // Signals to the runtime system that the condition
holds.This may cause a waiting thread on this condition to wakeup.
```

These are just a few hints, read the java docs!

Java Monitors Verifast Interface

```
package java.util.concurrent.locks;

/*@

predicate lck(ReentrantLock s; int p, predicate() inv);

predicate cond(Condition c; predicate() inv, predicate() p);

predicate enter_lck(int p, predicate() inv) = (p == 0 ? emp : inv()) ;

predicate set_cond(predicate() inv, predicate() p) = true;

@*/
```

enter_lock: to associate Representation Invariant to monitor

set_cond: to associate logical assertion to Condition object

Java Monitors Verifast Interface

```
public class ReentrantLock {
    public ReentrantLock();
    //@ requires enter_lck(1,?inv);
    //@ ensures lck(this, 1, inv);

    public void lock();
    //@ requires lck(?t, 1, ?inv);
    //@ ensures lck(t, 0, inv) &*& inv();

    public void unlock();
    //@ requires lck(?t, 0, ?inv) &*& inv();
    //@ ensures lck(t, 1, inv);

    public Condition newCondition();
    //@ requires lck(?t, 1, ?inv) &*& set_cond(inv, ?pred);
    //@ ensures lck(t, 1, inv) &*& result != null &*& cond(result,inv,pred);
}
```

How many threads can access the lock?

In this way we cannot have shared references to a lock.

Java Monitors Verifast Interface

```
public class ReentrantLock {
    public ReentrantLock();
    //@ requires enter_lck(1,?inv);
    //@ ensures lck(this, 1, inv);

    public void lock();
    //@ requires [?f]lck(?t, 1, ?inv);
    //@ ensures [f]lck(t, 0, inv) &*& inv();

    public void unlock();
    //@ requires [?f]lck(?t, 0, ?inv) &*& inv();
    //@ ensures [f]lck(t, 1, inv);

    public Condition newCondition();
    //@ requires lck(?t, 1, ?inv) &*& set_cond(inv, ?pred);
    //@ ensures lck(t, 1, inv) &*& result != null &*& cond(result,inv,pred);
}
```

We need a special mechanism to declared sharing of objects. We will study “fractioned permissions” in the next lecture.

Java Monitors Verifast Interface

```
package java.util.concurrent.locks;

public interface Condition {

    public void await();
        //@ requires cond(this,?inv,?acond) &*& inv();
        //@ ensures cond(this,inv, acond) &*& acond();

    public void signal();
        //@ requires cond(this,?inv,?acond) &*& acond();
        //@ ensures cond(this,inv,acond) &*& inv();

}
```

Counter ADT (Java + Verifast)

```
package CCounterMain;

import java.util.concurrent.*;
import java.util.concurrent.locks.*;

/*@

predicate_ctor CCounter_shared_state (CCounter c) () = c.N |-> ?v &*& v >= 0;

predicate_ctor CCounter_notzero_state (CCounter c) () = c.N |-> ?v &*& v > 0;

predicate CCounterInv(CCounter c;) =
        c.mon |-> ?l
    &*& l!=null
    &*& lck(l,1, CCounter_shared_state(c))
    &*& c.notzero |-> ?cc
    &*& cc != null
    &*& cond(cc, CCounter_shared_state(c),CCounter_notzero_state(c));

@*/
```

Counter ADT (Java + Verifast)

```
public class CCounter {

int N;
ReentrantLock mon;
Condition notzero;

public CCounter()
//@ requires true;
//@ ensures CCounterInv(this);
{
//@ close CCounter_shared_state(this)();
//@ close enter_lck(1,CCounter_shared_state(this));
 mon = new ReentrantLock();
 //@ close set_cond(CCounter_shared_state(this),CCounter_notzero_state(this));
notzero = mon.newCondition();
//@ close CCounterInv(this);
}
...
}
```

Counter ADT (Java + Verifast)

```
public class CCounter {

  int N;
  ReentrantLock mon;
  Condition notzero;

public void inc()
//@ requires [?f]CCounterInv(this);
//@ ensures [f]CCounterInv(this);
  {
  //@ open CCounterInv(this);
mon.lock();
//@ open [f] CCounter_shared_state(this)();
N++;
//@ close CCounter_notzero_state(this)();
notzero.signal();
mon.unlock();
//@ close [f]CCounterInv(this);
}
```

Counter ADT (Java + Verifast)

```
public class CCounter {
...
public void dec()
//@ requires [?f]CCounterInv(this);
//@ ensures [f]CCounterInv(this);
{
  try {
//@ open [f]CCounterInv(this);
   mon.lock();
//@ open CCounter_shared_state(this)();
   if (N==0) {
//@ close CCounter_shared_state(this)();
    notzero.await(); }
//@ open CCounter_notzero_state(this)();
    N--;
  } catch (java.lang.InterruptedException e){}
//@ close CCounter_shared_state(this)();
  mon.unlock();
//@ close [f]CCounterInv(this);
  }
}
```