



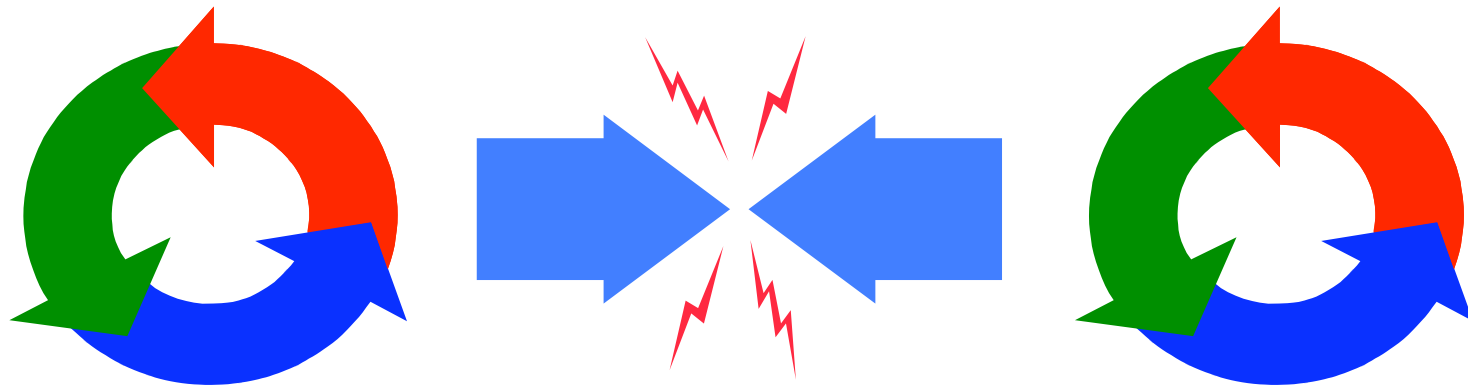
CSCI 5828: Foundations of Software Engineering

Lecture 12: Concurrent Execution

Slides created by Magee and Kramer for the Concurrency textbook

Chapter 4

Shared Objects & Mutual Exclusion



Shared Objects & Mutual Exclusion

Concepts: process interference.
mutual exclusion.

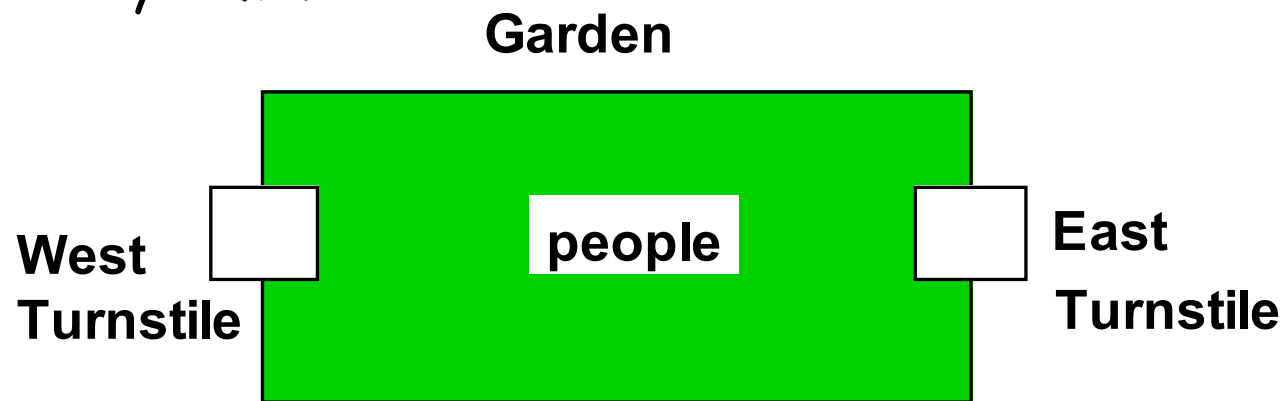
Models: model checking for interference
modeling mutual exclusion

Practice: thread interference in shared Java objects
mutual exclusion in Java
(**synchronized** objects/methods).

4.1 Interference

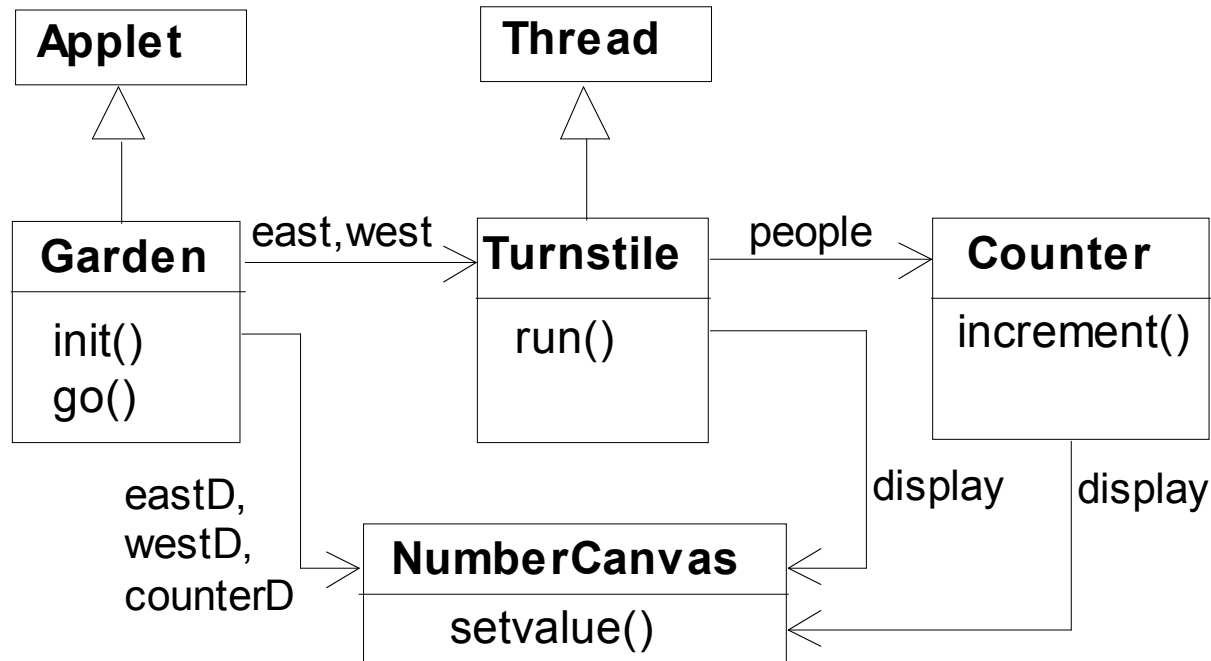
Ornamental garden problem:

People enter an ornamental garden through either of two turnstiles. Management wish to know how many are in the garden at any time.



The concurrent program consists of two concurrent threads and a shared counter object.

ornamental garden Program - class diagram



The **Turnstile** thread simulates the periodic arrival of a visitor to the garden every second by sleeping for a second and then invoking the **increment()** method of the counter object.

ornamental garden program

The **Counter** object and **Turnstile** threads are created by the `go ()` method of the Garden applet:

```
private void go() {  
    counter = new Counter(counterD);  
    west = new Turnstile(westD, counter);  
    east = new Turnstile(eastD, counter);  
    west.start();  
    east.start();  
}
```

Note that `counterD`, `westD` and `eastD` are objects of **NumberCanvas** used in chapter 2.

Turnstile class

```
class Turnstile extends Thread {
    NumberCanvas display;
    Counter people;

    Turnstile(NumberCanvas n, Counter c)
        { display = n; people = c; }

    public void run() {
        try{
            display.setvalue(0);
            for (int i=1;i<=Garden.MAX;i++){
                Thread.sleep(500); //0.5 second between arrivals
                display.setvalue(i);
                people.increment();
            }
        } catch (InterruptedException e) {}
    }
}
```

The `run()` method exits and the thread terminates after `Garden.MAX` visitors have entered.

Counter class

```
class Counter {
    int value=0;
    NumberCanvas display;

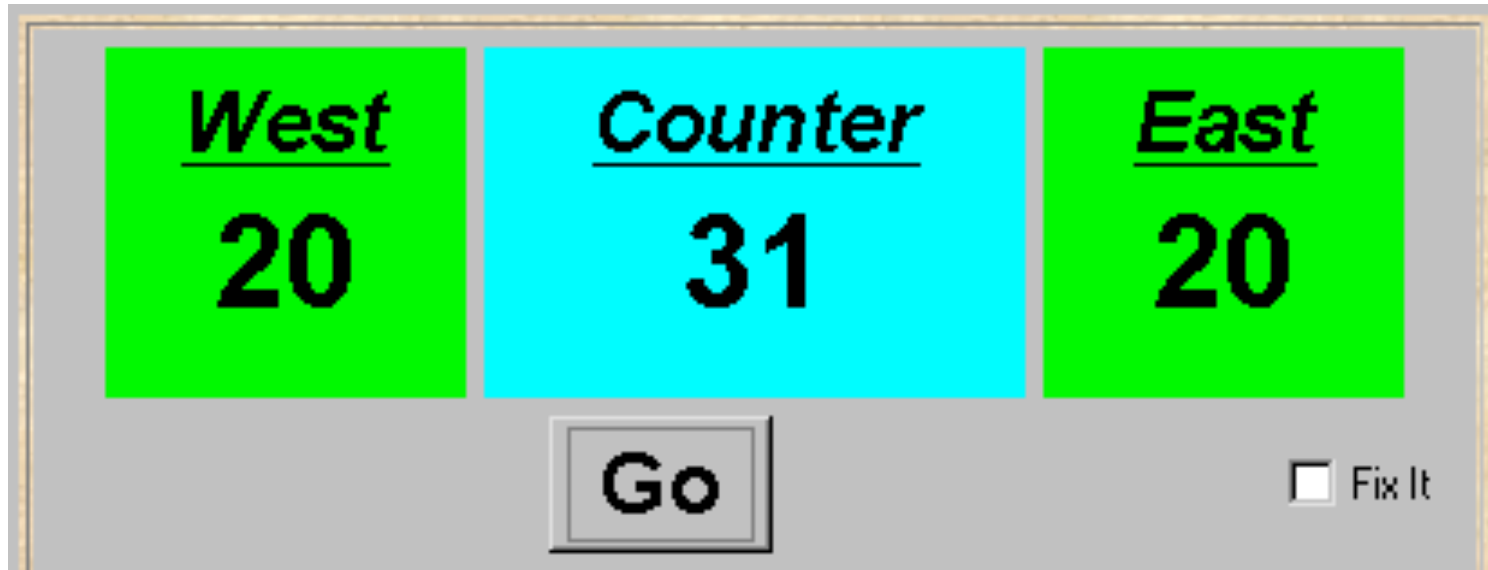
    Counter(NumberCanvas n) {
        display=n;
        display.setvalue(value);
    }

    void increment() {
        int temp = value;    //read value
        Simulate.HWinterrupt();
        value=temp+1;        //write value
        display.setvalue(value);
    }
}
```

Hardware interrupts can occur at **arbitrary** times.

The **counter** simulates a hardware interrupt during an **increment()**, between reading and writing to the shared counter **value**. Interrupt randomly calls **Thread.sleep()** to force a thread switch.

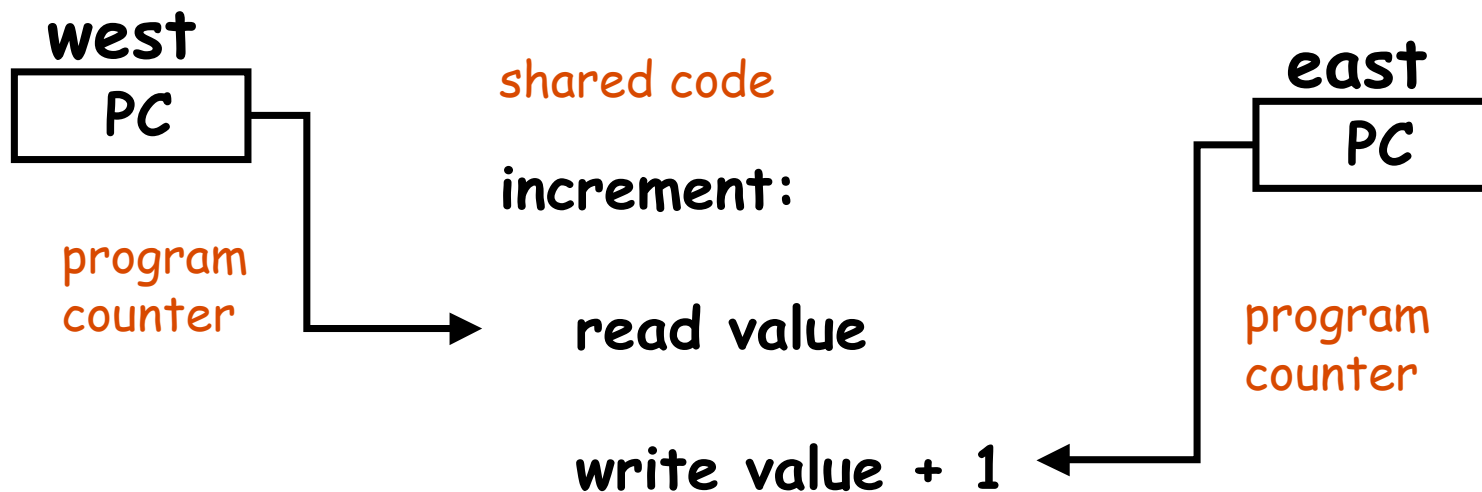
ornamental garden program - display



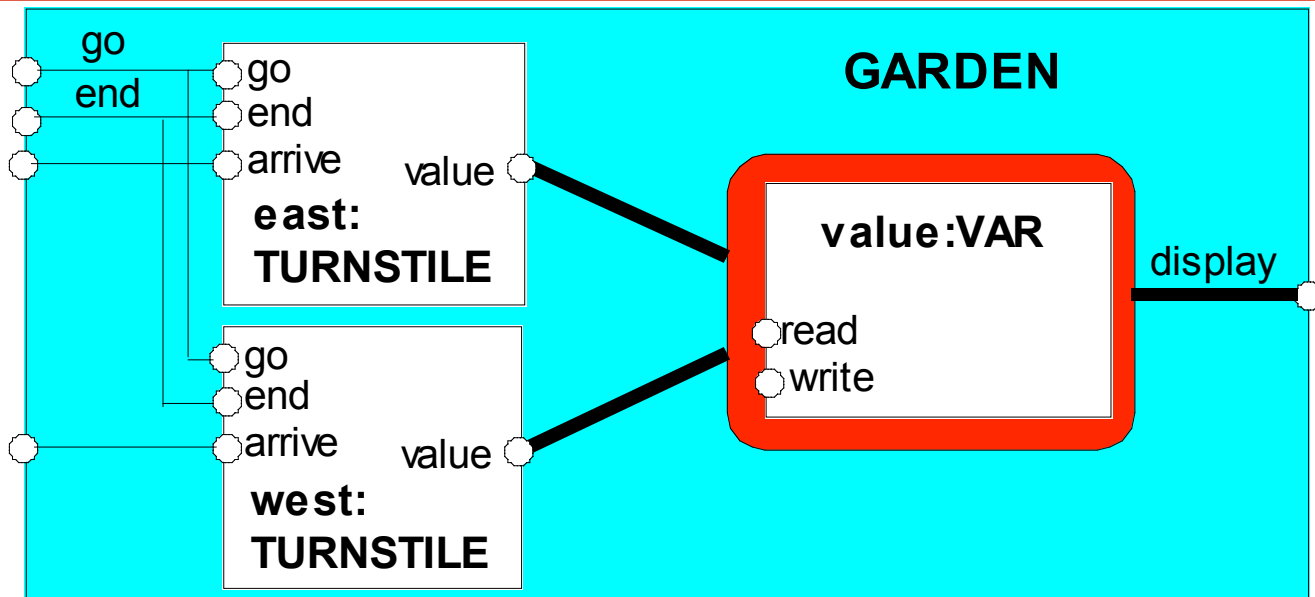
After the East and West turnstile threads have each incremented its counter 20 times, the garden people counter is not the sum of the counts displayed. Counter increments have been lost. *Why?*

concurrent method activation

Java method activations are not atomic - thread objects `east` and `west` may be executing the code for the `increment` method at the same time.



ornamental garden Model



Process VAR models read and write access to the shared counter value.

Increment is modeled inside TURNSTILE since Java method activations are not atomic i.e. thread objects east and west may interleave their read and write actions.

ornamental garden model

```
const N = 4
range T = 0..N
set VarAlpha = { value.{read[T],write[T]} }

VAR      = VAR[0],
VAR[u:T] = (read[u]  ->VAR[u]
            |write[v:T]->VAR[v]).

TURNSTILE = (go      -> RUN),
RUN        = (arrive-> INCREMENT
            |end    -> TURNSTILE),
INCREMENT  = (value.read[x:T]
            -> value.write[x+1]->RUN
            )+VarAlpha.

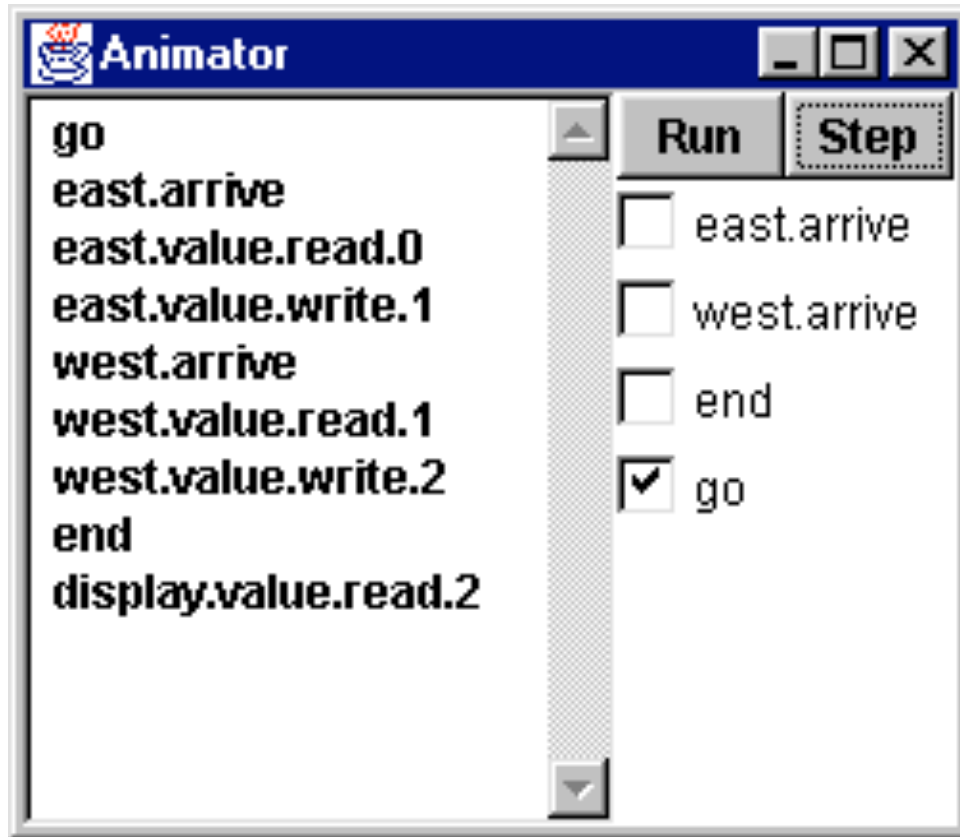
||GARDEN = (east:TURNSTILE || west:TURNSTILE
|| { east,west,display}::value:VAR)
/{ go /{ east,west} .go,
  end/{ east,west} .end} .
```

The alphabet of shared process **VAR** is declared explicitly as a **set** constant, **VarAlpha**.

The **TURNSTILE** alphabet is extended with **VarAlpha** to ensure no unintended **free (autonomous) actions** in **VAR** eg. **value.write[0]**. All actions in the shared **VAR** must be controlled (shared) by a **TURNSTILE**.

Concurrency: shared objects & mutual exclusion

checking for errors - animation



Scenario checking
- use animation to
produce a trace.

*Is this trace
correct?*

checking for errors - exhaustive analysis

Exhaustive checking - compose the model with a TEST process which sums the arrivals and checks against the display value:

```
TEST          = TEST[0],
TEST[v:T]    =
    (when (v<N) {east.arrive,west.arrive}->TEST[v+1]
    |end->CHECK[v]
    ),
CHECK[v:T]   =
    (display.value.read[u:T] ->
    (when (u==v) right -> TEST[v]
    |when (u!=v) wrong -> ERROR
    )
    )+{display.VarAlpha}.
```

Like STOP, **ERROR** is a predefined FSP local process (state), numbered **-1** in the equivalent LTS.

ornamental garden model - checking for errors

```
||TESTGARDEN = (GARDEN || TEST) .
```

Use *LTSA* to perform an exhaustive search for **ERROR**.

```
Trace to property violation in TEST:
```

```
go
east.arrive
east.value.read.0
west.arrive
west.value.read.0
east.value.write.1
west.value.write.1
end
display.value.read.1
wrong
```

LTSA produces
the shortest
path to reach
ERROR.

Interference and Mutual Exclusion

Destructive update, caused by the arbitrary interleaving of read and write actions, is termed *interference*.

Interference bugs are extremely difficult to locate. The general solution is to give methods *mutually exclusive* access to shared objects. Mutual exclusion can be modeled as atomic actions.

4.2 Mutual exclusion in Java

Concurrent activations of a method in Java can be made mutually exclusive by prefixing the method with the keyword **synchronized**, which uses a lock on the object.

We correct **COUNTER** class by deriving a class from it and making the increment method **synchronized**:

```
class SynchronizedCounter extends Counter {  
    SynchronizedCounter (NumberCanvas n)  
        { super (n) ; }  
    synchronized void increment() {  
        super.increment() ;  
    }  
}
```

acquire
lock

release
lock

mutual exclusion - the ornamental garden



Java associates a *lock* with every object. The Java compiler inserts code to acquire the lock before executing the body of the synchronized method and code to release the lock before the method returns. Concurrent threads are blocked until the lock is released.

Java synchronized statement

Access to an object may also be made mutually exclusive by using the **synchronized** statement:

```
synchronized (object) { statements }
```

A less elegant way to correct the example would be to modify the **Turnstile.run()** method:

```
synchronized(people) {people.increment();}
```

Why is this “less elegant”?

To ensure mutually exclusive access to an object, **all object methods** should be synchronized.

4.3 Modeling mutual exclusion

To add locking to our model, define a `LOCK`, compose it with the shared `VAR` in the garden, and modify the alphabet set :

```
LOCK = (acquire->release->LOCK) .
||LOCKVAR = (LOCK || VAR) .

set VarAlpha = {value.{read[T],write[T],
                    acquire, release}}
```

Modify `TURNSTILE` to acquire and release the lock:

```
TURNSTILE = (go -> RUN) ,
RUN        = (arrive-> INCREMENT
              |end -> TURNSTILE) ,
INCREMENT = (value.acquire
             -> value.read[x:T]->value.write[x+1]
             -> value.release->RUN
             )+VarAlpha.
```

Revised ornamental garden model - checking for errors

A sample animation execution trace

```
go
east.arrive
east.value.acquire
east.value.read.0
east.value.write.1
east.value.release
west.arrive
west.value.acquire
west.value.read.1
west.value.write.2
west.value.release
end
display.value.read.2
right
```

Use TEST and *LTSA* to perform an exhaustive check.

COUNTER: Abstraction using action hiding

```
const N = 4
range T = 0..N

VAR = VAR[0],
VAR[u:T] = ( read[u]->VAR[u]
             | write[v:T]->VAR[v] ) .

LOCK = (acquire->release->LOCK) .

INCREMENT = (acquire->read[x:T]
             -> (when (x<N) write[x+1]
                ->release->increment->INCREMENT
                )
             )+{read[T],write[T]} .

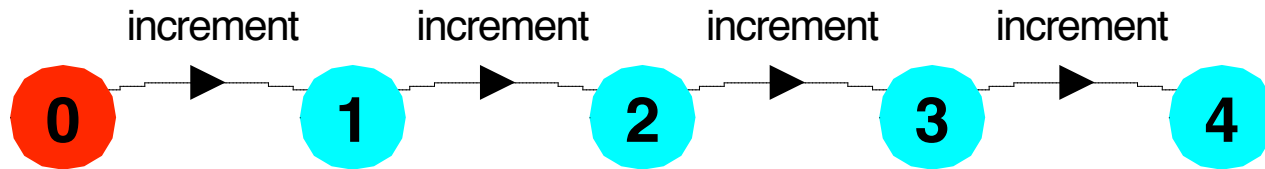
|| COUNTER = (INCREMENT || LOCK || VAR) @ {increment} .
```

To model shared objects directly in terms of their **synchronized** methods, we can abstract the details by hiding.

For SynchronizedCounter we hide read, write, acquire, release actions.

COUNTER: Abstraction using action hiding

Minimized
LTS:



We can give a more abstract, simpler description of a COUNTER which generates the same LTS:

```
COUNTER = COUNTER[0]
COUNTER[v:T] = (when (v<N) increment -> COUNTER[v+1]).
```

This therefore exhibits “**equivalent**” behavior i.e. has the same observable behavior.

Summary

◆ Concepts

- **process interference**
- **mutual exclusion**

◆ Models

- **model checking for interference**
- **modeling mutual exclusion**

◆ Practice

- **thread interference in shared Java objects**
- **mutual exclusion in Java (**synchronized** objects/methods).**