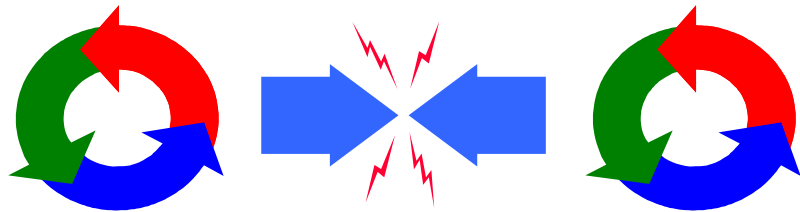


# Shared Objects & Mutual Exclusion



**Concepts:** process interference.  
mutual exclusion.

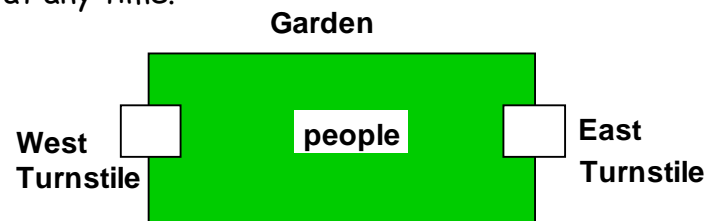
**Models:** model checking for interference  
modeling mutual exclusion

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

### 4.1 Interference

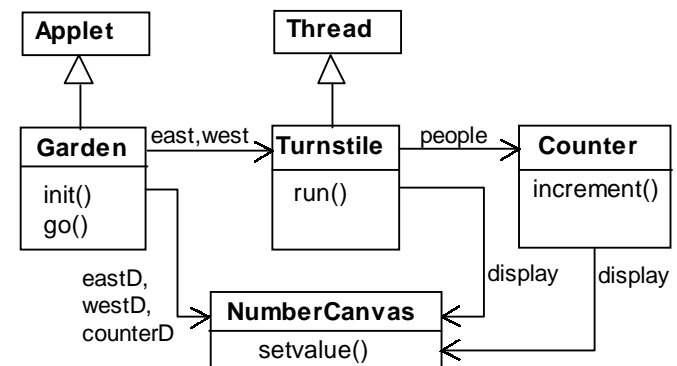
#### Ornamental garden problem:

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.

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## 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.

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## 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.yield()** to force a thread switch.

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## 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?**

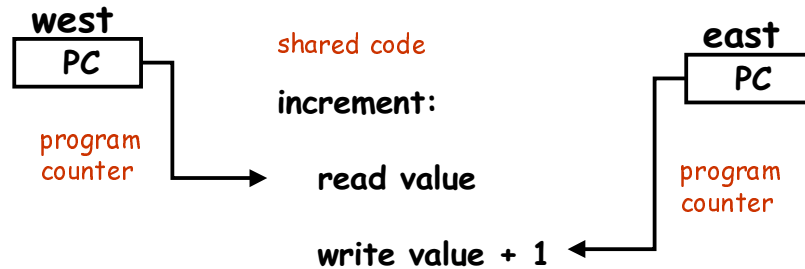
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## concurrent method activation

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

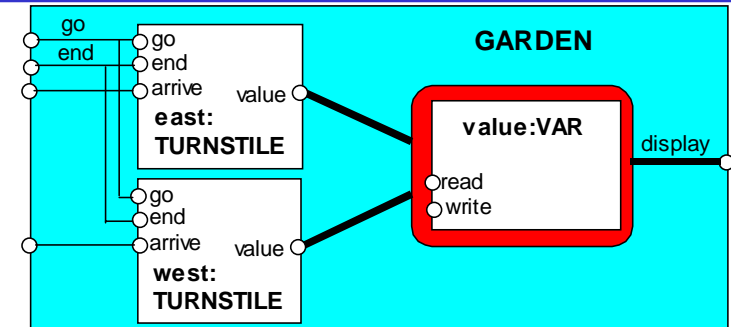


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## ornamental garden Model



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.

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## 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 process `VAR` is declared explicitly as a `set` constant, `VarAlpha`.

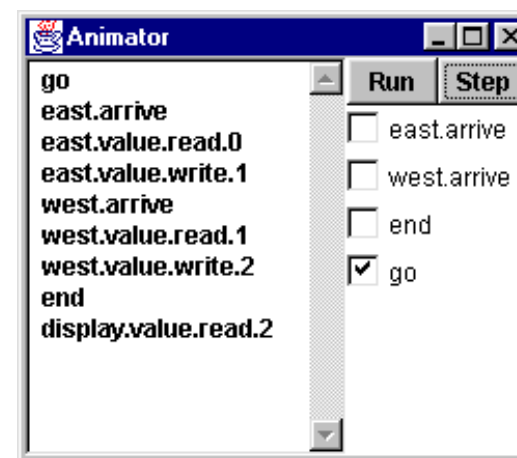
The alphabet of `TURNSTILE` is extended with `VarAlpha` to ensure no unintended free actions in `VAR` i.e. all actions in `VAR` must be controlled by a `TURNSTILE`.

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## checking for errors - animation



Scenario checking - use animation to produce a trace.

*Is this trace correct?*

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## 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.

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## 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**.

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## 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.

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## 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**.

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

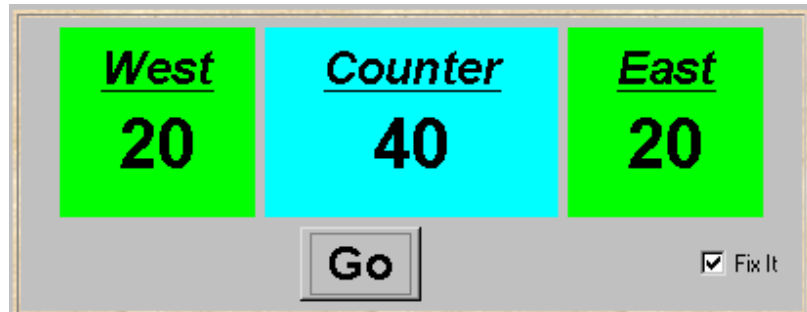
```
class SynchronizedCounter extends Counter {
    SynchronizedCounter(NumberCanvas n)
    {super(n);}
    synchronized void increment() {
        super.increment();
    }
}
```

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## 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.

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## 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(counter) {counter.increment();}
```

*Why is this “less elegant”?*

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

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## 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.
```

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## 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.

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*Is TEST satisfied?*

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## 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.

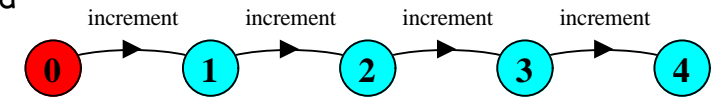
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## COUNTER: Abstraction using action hiding

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.

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## 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).

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