# Shared Objects

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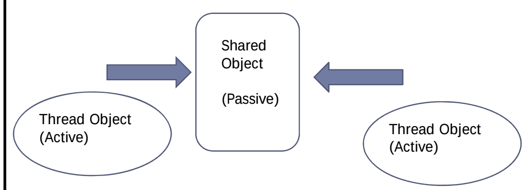
Modified from Kramer and Magee's lecture notes.
Reading material: Chapter 4 of Textbook.



## Thread Communication




Arbitrary interleaving of accesses possible.



## Interference between threads

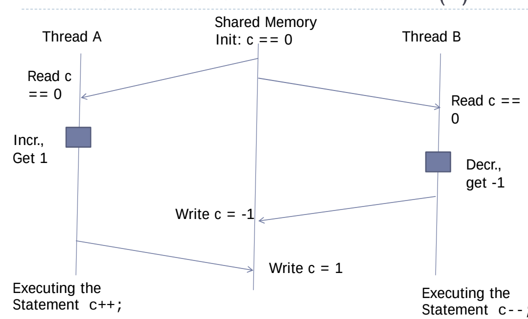
```
class Counter {
        private int c = 0;
        public void increment() {
                        c++;
        }
        public void decrement() {
                        c--;
        }
        public int value() {
                        return c;
        }
}
```

"Correct" operation: One execution of increment adds 1
One execution of decrement subtracts 1

Inter-thread interference from prevent the result from being so. Why?

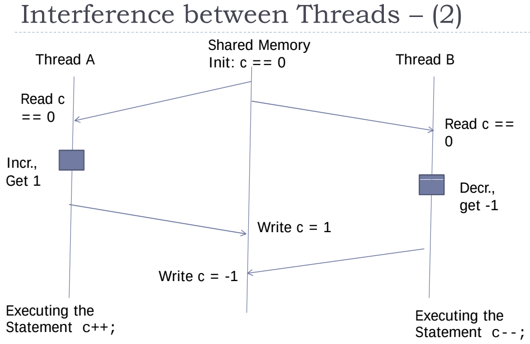


## Interference between Threads – (1)






## Interference between Threads – (2)






## What do we need?

- Mutually exclusive access to the counter
- How to do that?
  - Language level construct – Lock.
  - Acquire lock prior to any access of counter.
  - Release lock after any access of counter.
- Does it require locking discipline then?
  - Well, accesses happen through methods of the shared object
    - In this case, objects of the Counter class
    - Mark these methods as "synchronized"
    - Avoid managing locks for each call of these methods !!

## Synchronized Methods

Java programming provides two basic synchronization idioms: *synchronized methods* and *synchronized statements*

```
public class SynchronizedCounter {
      private int c = 0;
      public synchronized void increment() {
                        c++;
      }
      public synchronized void decrement() {
                        c--;
     }
     public synchronized int value() {
                        return c;
     }
}
```



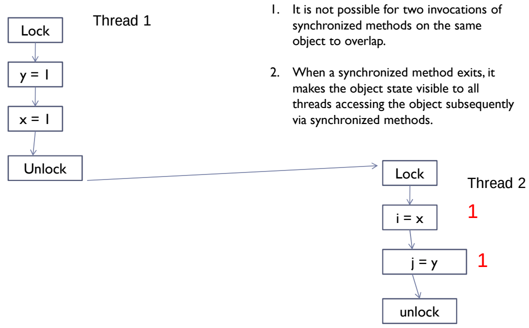
## Shared Objects & Mutual Exclusion

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).

## Why synchronized methods?



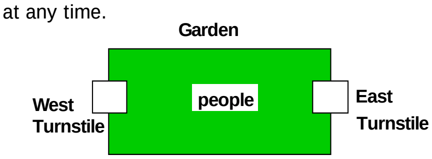

1. It is not possible for two invocations of synchronized methods on the same object to overlap.
2. When a synchronized method exits, it makes the object state visible to all threads accessing the object subsequently via synchronized methods.



## 4.1 Interference

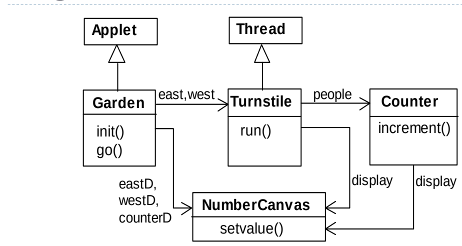
**Ornamental garden problem:**

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 0.5 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

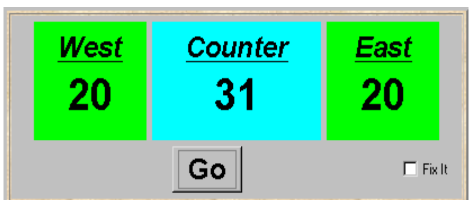
```
class Counter {
  int value=0;
  NumberCanvas display;

  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);
  }
}
```

```
class Simulate {
    public static void HWinterrupt(){
        if (Math.random() < 0.5) Thread.yield();
}
```

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.

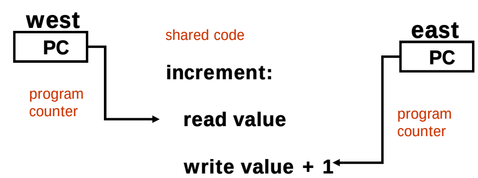
## ornamental garden program - display



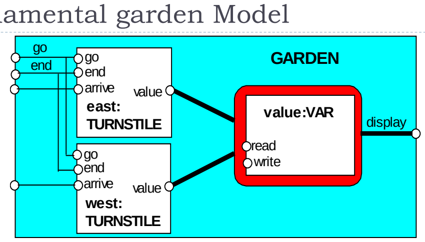

After the East and West turnstile threads have each incremented its counter 20 times, the garden people counter is not the sum of the counts displayed. Counter increments have been lost. ***Why?***

## 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**.

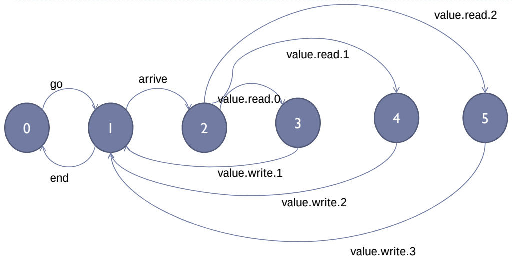
## ornamental garden model

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

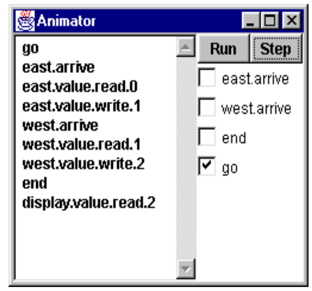
The alphabet of **TURNSTILE** is extended with **VarAlpha** to ensure no unintended free actions in **VAR** ie. all actions in **VAR** must be controlled by a **TURNSTILE**.

## State Model for Turnstile






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

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.

Methods with mutually exclusive access 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**.

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

```
class SynchronizedCounter extends Counter {

  SynchronizedCounter(NumberCanvas n)
     {Counter(n);}

   synchronized void increment() {
        Counter.increment();
   }
}
```

## 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 safe way to correct the example would be to modify the **`Turnstile.run()`** method:

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

***Why is this "less safe"?***

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

## A "less safe" way

```
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);
        synchronized(people){ people.increment();}
      }
    } catch (InterruptedException e) {}
  }
}
```



## Why is it less safe?

The lock is not embedded in the counter object itself.

Every "user" of the counter object (in this case the turnstile threads) will have to take the responsibility of imposing the lock, prior to manipulating the shared counter object.

This is an issue we will always face while programming mutually exclusive access to shared objects in Java.



## Recursive locking in Java

If a thread t acquires a lock on an object o, t can repeatedly lock o.

The lock counts how many times it has been acquired by the same thread, and does not allow another thread to access object o.

This allows the synchronized methods to be recursive, e.g. consider

```
public synchronized void increment(int n){
      if (n>0){
            ++value;
             increment(n-1);
      } else return;
}
```

What would happen on a call to increment(5) if recursive locking was not allowed in Java?



## 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
correct
```

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

***Is TEST satisfied?***

## COUNTER: Abstraction using action hiding

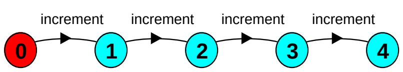
```
const N = 4
range T = 0..N

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).**