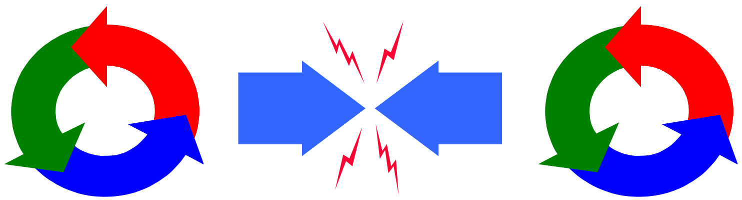
Chapter 4

Shared Objects & Mutual Exclusion



Shared Objects & Mutual Exclusion

Concepts: process interference.
mutual exclusion and locks.

Models: model checking for interference
modelling mutual exclusion

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

A Concert Hall Booking System

A central computer connected to remote terminals via communication links is used to automate seat reservations for a concert hall.

To book a seat, a client chooses a free seat and the clerk enters the number of the chosen seat at the terminal and issues a ticket, if it is free.

A system is required which avoids double bookings of the same seat whilst allowing clients free choice of the available seats.

Construct an abstract model of the system and demonstrate that your model does not permit double bookings.

Concert Hall Booking System

```
const False = 0
const True  = 1
range Bool =  False..True

SEAT = SEAT[False],
SEAT[reserved:Bool]
     = ( when (!reserved) reserve -> SEAT[True]
       | query[reserved] -> SEAT[reserved]
       | when (reserved) reserve -> ERROR
                           //error of reserved twice
       ).

range Seats = 1..2
||SEATS = (seat[Seats]:SEAT).
```

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

Concert Hall Booking System

```
TERMINAL = (choose[s:Seats]
           -> seat[s].query[reserved:Bool]
           -> if (!reserved) then
                (seat[s].reserve -> TERMINAL)
              else
                TERMINAL
           ).

set Terminals = {a,b}

||CONCERT = ( Terminals:TERMINAL || Terminals::SEATS ).
```

Does this system allow double booking of a seat?

Concert Hall Booking System – no interference?

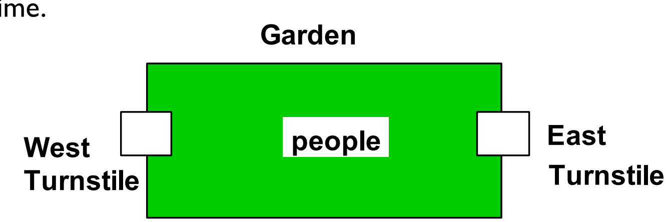
```
LOCK = (acquire -> release -> LOCK).
               //lock for the booking system

TERMINAL = (choose[s:Seats] -> acquire
           -> seat[s].query[reserved:Bool]
           -> if (!reserved) then
                (seat[s].reserve -> release-> TERMINAL)
              else
                (release -> TERMINAL)
           ).

set Terminals = {a,b}

||CONCERT = (Terminals:TERMINAL || Terminals::SEATS
            || Terminals::LOCK).
```

Would locking at the seat level permit more concurrency?

4.1 Interference

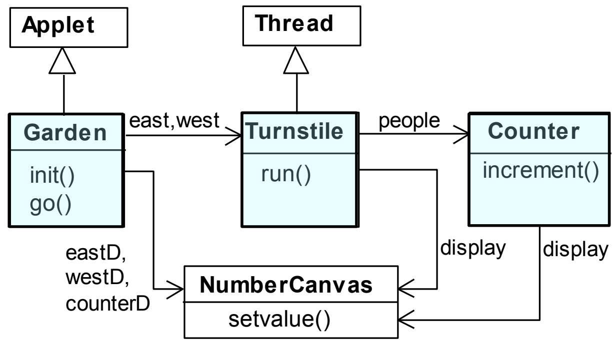
Ornamental garden problem:

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.

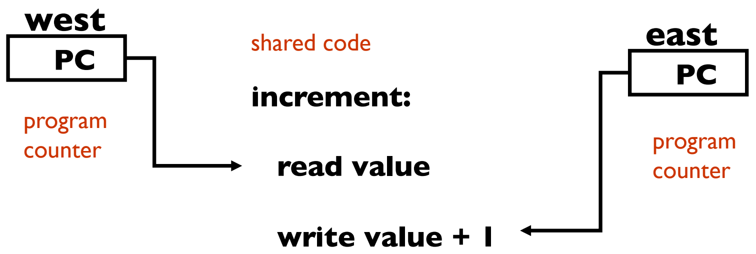
The **counter** simulates a hardware interrupt during an **increment()**, between reading and writing to the shared counter **value**. Interrupt randomly calls **Thread.sleep()** to force a thread switch.

ornamental garden program - display

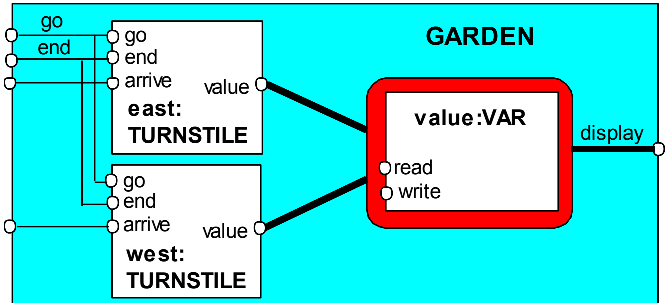
After the East and West turnstile threads have each incremented its counter 20 times, the garden people counter is not the sum of the counts displayed. Counter increments have been lost. ***Why?***

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

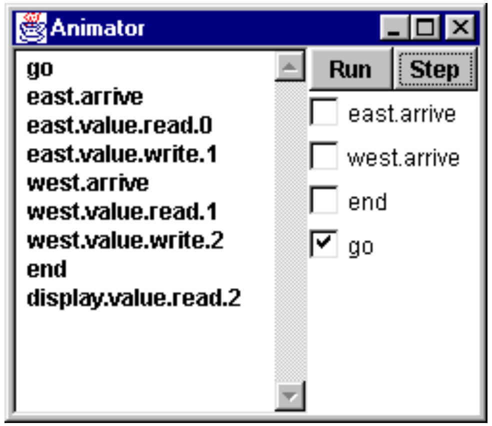
```
const N = 4
range T = 0..N
set VarAlpha = { value.{read[T],write[T]} }

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** such as **value.write[0]**.

All actions in the shared **VAR** must be controlled (shared) by a **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}.
```

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 (mutex)

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 (often referred to as "mutex")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.

Is TEST satisfied?

COUNTER: Abstraction using action hiding

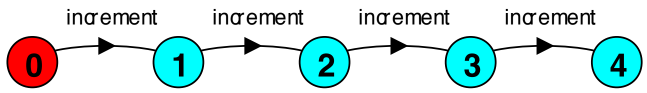
```
const N = 4
range T = 0..N

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.

4.4 Java Concurrency Utilities Package

Java SE 5 intriduced a package of advanced concurrency utilities in *java.util.concurrent*, later extended in JSE8.

This includes many additional, explicit mechanisms such as atomic variables, a task scheduling framework (for thread and thread pool instantiation and control), and synchronizers such as **semaphores** (later), mutexes, barriers and **explicit locks with timeout.**

***synchronized*:**	implicit lock associated with each object, block structured and recursive (reentrant) *(Java mutex and POSIX pthread mutexes are not reentrant)*
***Lock interface*:**	explicit lock objects, with methods *lock(), unlock(), tryLock()* with optional timeout.
***ReentrantLock*:**	implements Lock (optionally *fair*), reentrant with methods *lock(), unlock(), tryLock()* with optional timeout, …

Counter – with an explicit lock

```
class LockedCounter extends Counter {

   final ReentrantLock inclock = new ReentrantLock();

   LockedCounter(NumberCanvas n)
     {super(n);}

   public void increment()throws InterruptedException {
     inclock.lock();
     try {
        super.increment();
     } finally {inclock.unlock();}
   }
}
```

Explicit locks are more dangerous and less efficient than ***synchronized****. Use only if required for non-block structured situations requiring flexibility (such as chain locking: acquire lock on A, then on B, then release A and acquire C, …) or for other advanced features such as timed or polled lock acquisition. (At the memory level,* ***volatile*** *can be used to force reads/writes on a shared variable to main memory rather than cached thread-locally).*

Summary

- Concepts
  - **process interference**
  - **mutual exclusion and locks**
- Models
  - **model checking for interference**
  - **modelling mutual exclusion**
- Practice
  - **thread interference in shared Java objects**
  - **mutual exclusion in Java (synchronized objects/methods).**