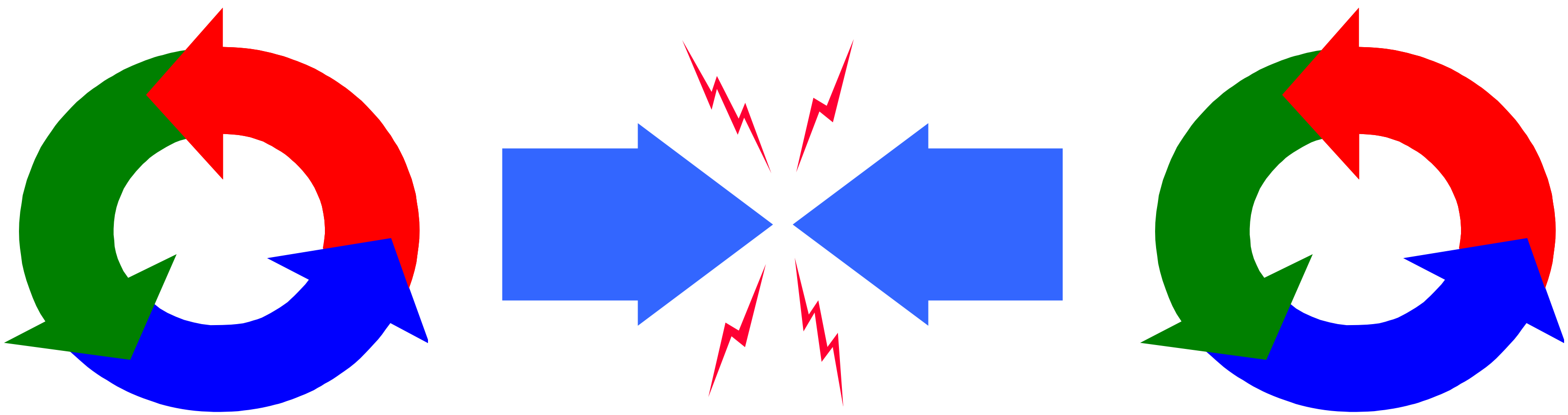
Chapter 4

Shared Objects & Mutual Exclusion



Shared Objects & Mutual Exclusion

Concepts: process interference.
mutual exclusion.

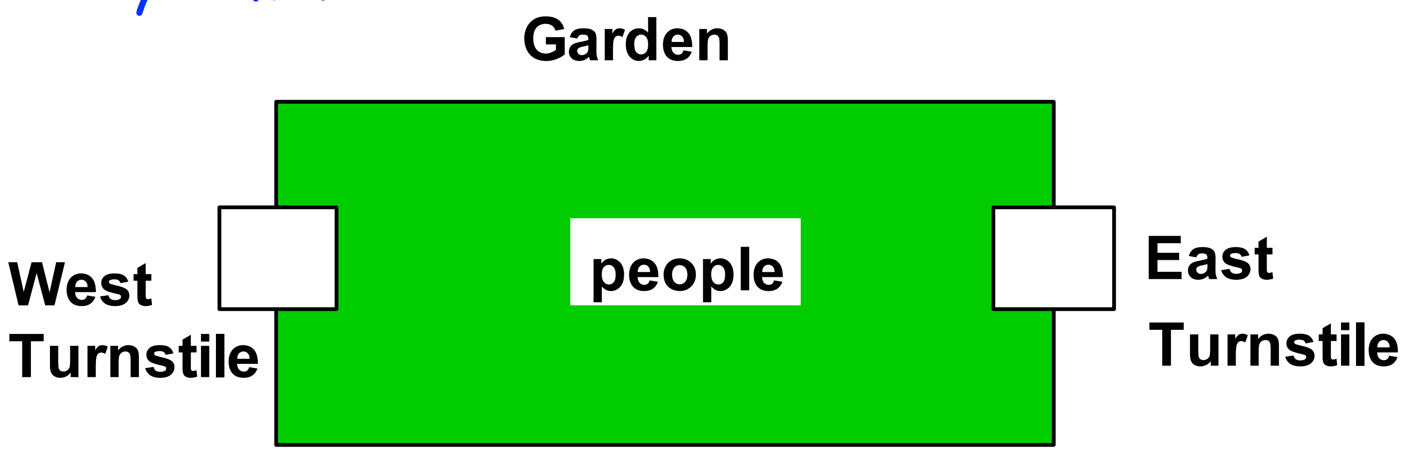
Models: model checking for interference
model mutual exclusion

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

4.1 Interference

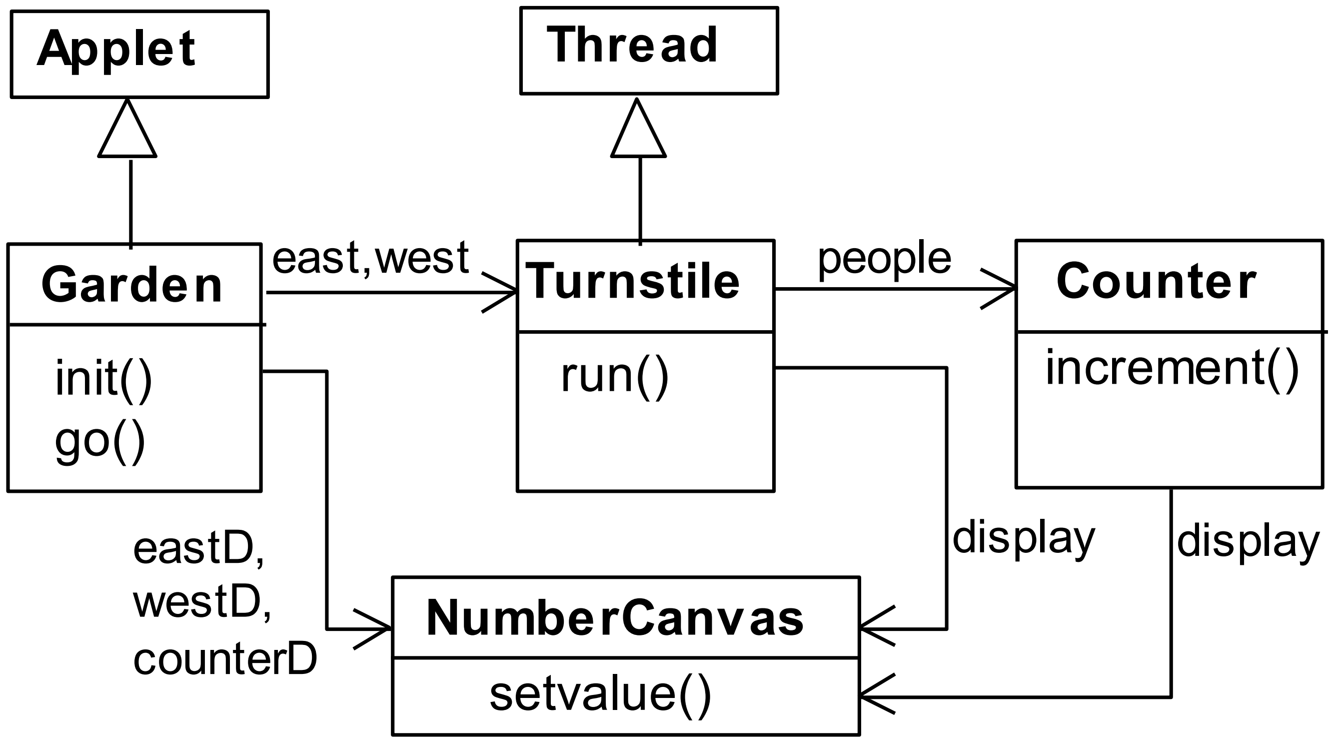
Ornamental garden problem:

People enter an ornamental garden through either of two turnstiles. Management wants 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();
}
```

counter: shared object by **`west`** and **`east`**.

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(); // sleep 200 ms
    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.

Simulate Class

```
class Simulate {

    public static void HWinterrupt() {
        if (Math.random() < 0.5)
          try{
                  Thread.sleep(200);
          } catch(InterruptedException e){

          };
    }
}
```

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

```
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.

DISPLAY =(value.read[T]->DISPLAY)+{value.write[T]}

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

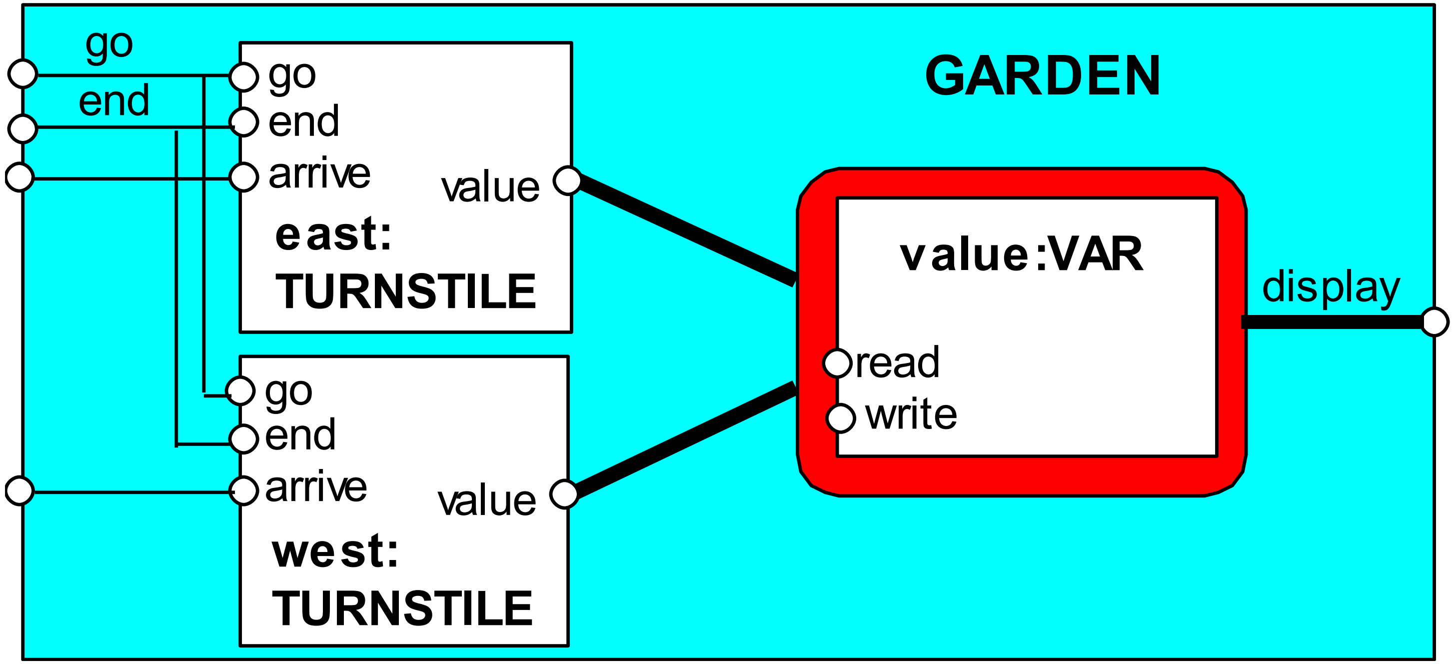
The alphabet of shared process **VAR** is declared explicitly as a **set** constant, **VarAlpha**.

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 process **VAR** must be controlled (shared) by a **TURNSTILE**.

instances: east, west, display

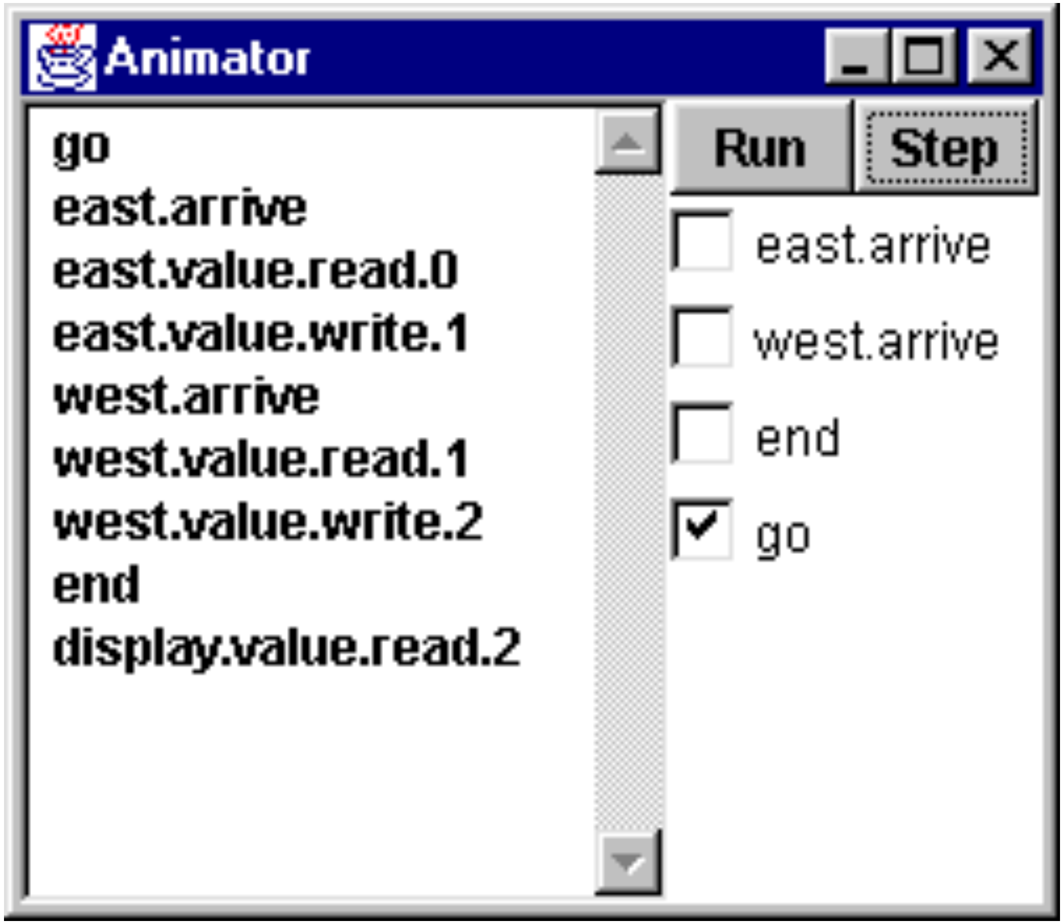
Ornamental Garden Model



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

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

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 modelled 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.

Ref: http://java.sun.com/docs/books/tutorial/essential/concurrency/syncrgb.html

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 :

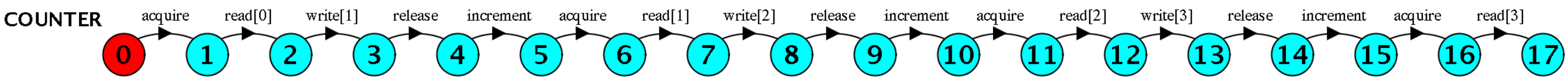
```
LOCK = (acquire->release->LOCK).
||LOCKVAR = (LOCK || VAR).

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.
```

```
// previous version

INCREMENT = (
      value.read[x:T]
   -> value.write[x+1]
   -> RUN
)+VarAlpha.
```

Modeling Mutual Exclusion



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

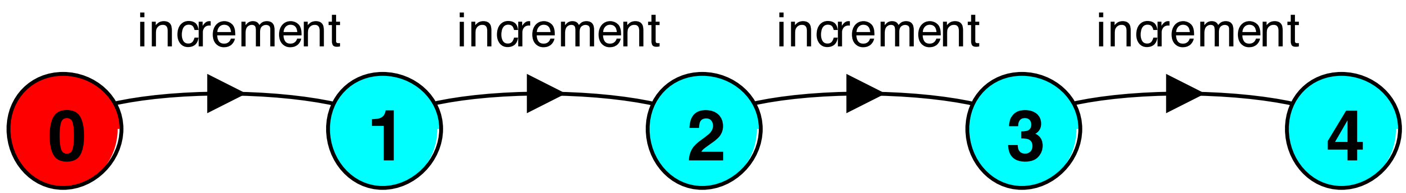
To model shared objects directly in terms of their synchronized methods, we can abstract the details by hiding.

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

```
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}.
```

COUNTER: Abstraction using Action Hiding

Minimized LTS:



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

```
const N = 4
range T = 0..N
COUNTER = COUNTER[0],
COUNTER[v:T] = (when (v<N) increment -> COUNTER[v+1]).
```

This exhibits "equivalent" behavior i.e. has the same observable behavior.

Summary

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