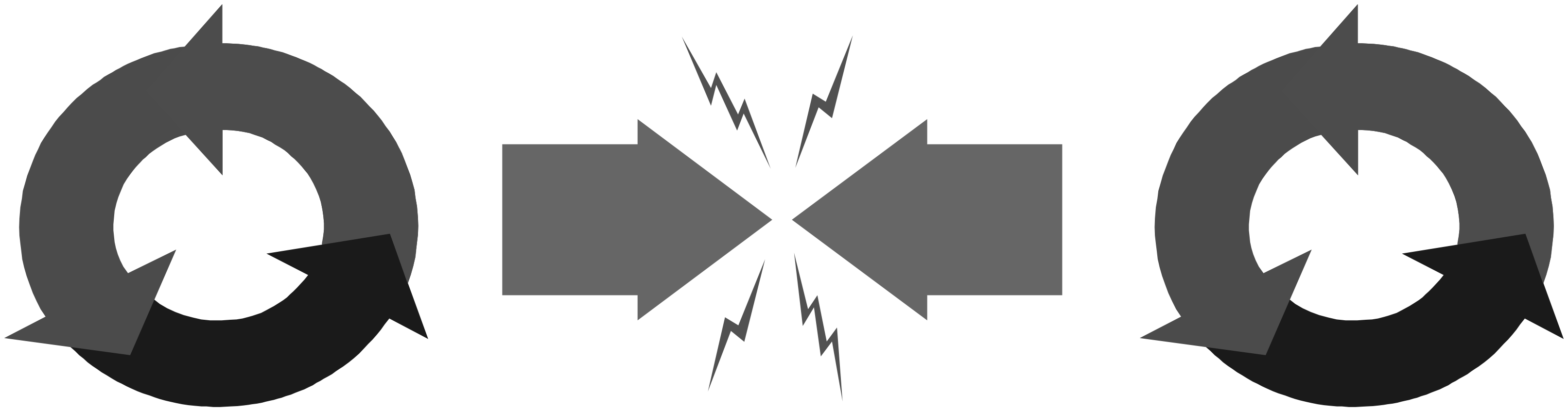
4 - Shared Objects & Mutual Exclusion



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Repetition – “Concurrent Execution”

Concepts: pseudo- vs. real concurrent execution
concurrent execution and **interleaving**
process interaction

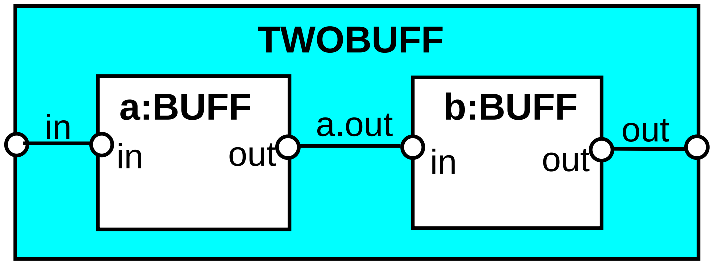
Models: **parallel composition** of asynchronous processes
- interleaving
interaction - ***shared actions***
process labeling, action relabeling, and hiding
structure diagrams

Practice: Multithreaded Java programs

Repetition (week 06) - Specifically

- FSP:
  - P || Q — // parallel composition
  - a:P — // action prefixing
  - {...}::P — // set prefixing
  - P / {x/y} — // action relabling
  - P \ {...} — // hiding
  - P @ {...} — // keeping (hide complement)

- Structure Diagrams:



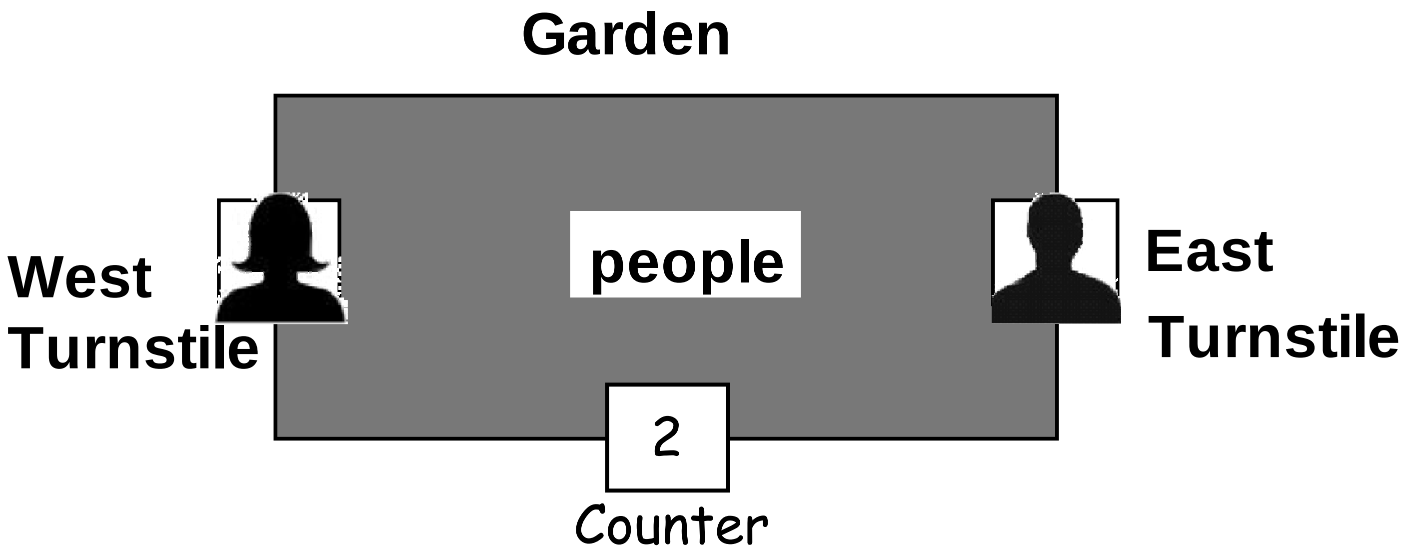
Shared Objects & Mutual Exclusion

- Concepts:
  - Process interference
  - Mutual exclusion
- Models:
  - Model-checking for interference
  - Modelling mutual exclusion
- Practice:
  - Thread interference in shared objects in Java
  - Mutual exclusion in Java
  - synchronized objects, methods, and statements

4.1 Interference

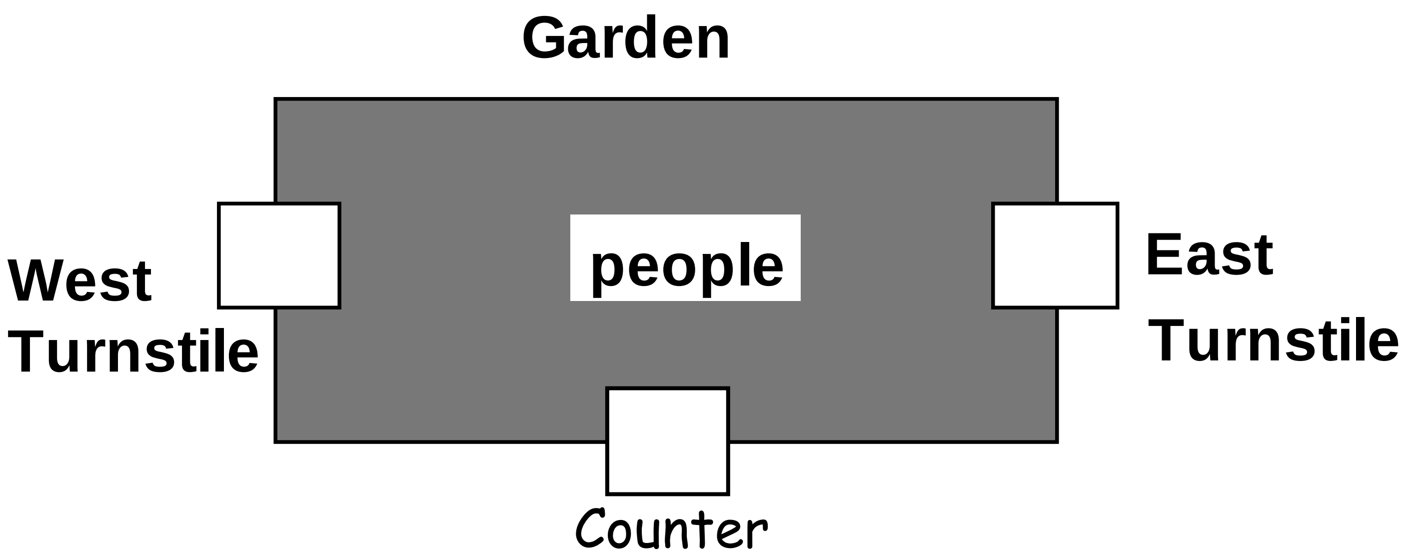
The "*Ornamental Garden Problem*":

People enter an ornamental garden through either of two turnstiles. Management wishes to know how many are in the garden at any time. (Nobody can exit).



Exercise: variant with Entrance/Exit instead of West/East...

4.1 Ornamental Garden Problem (cont'd)

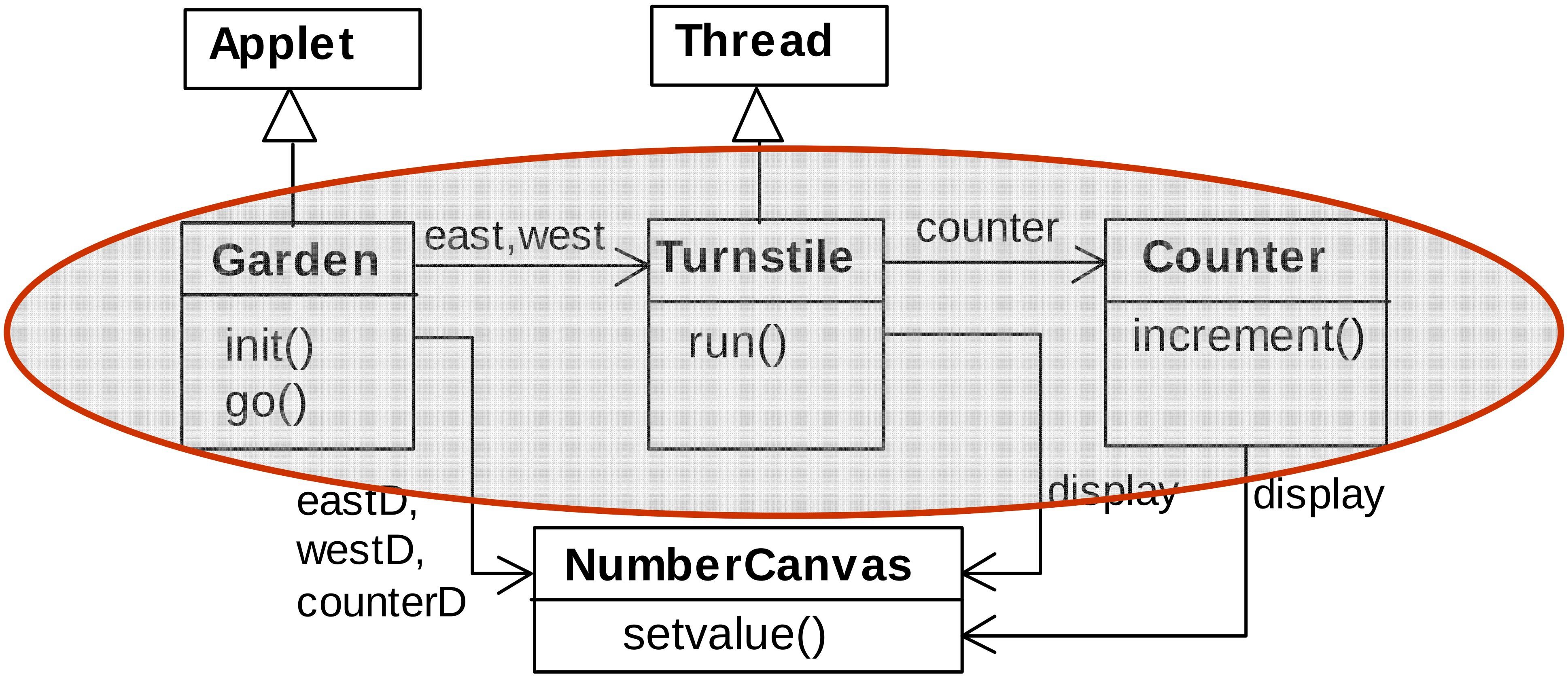


Java implementation:

The concurrent program consists of:

- two concurrent threads (west & east); and
- a shared counter object

Class Diagram



Ornamental Garden Program

The **go()** method of the Garden applet…

```
class Garden extends Applet {
    NumberCanvas counterD, westD, eastD;
    …
    private void go() {
        counter = new Counter(counterD);
        west = new Turnstile(westD,counter);
        east = new Turnstile(eastD,counter);
        west.start();
        east.start();
    }
}
```

…creates the shared **Counter** object & the **Turnstile** threads.

The Turnstile Class

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

    public void run() {
        try {
            display.setvalue(0);
            for (int i=1; i<=Garden.MAX; i++) {
                Thread.sleep(1000);
                display.setvalue(i);
                counter.increment();
            }
        } catch (InterruptedException _) {}
    }
}
```

The **Turnstile** thread simulates periodic arrival of visitors by invoking the counter object's **increment()** method every second

The *Shared* Counter Class

The **increment()** method of the Counter class increments its internal value and updates the display.

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

    void increment() {
        value = value + 1;
        display.setvalue(value);
    }
}
```

Counter class – Well, Actually…

```
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.

Running the Applet

After the East and West turnstile threads each have incremented the counter **20 times**, the garden people counter is **not the sum of the counts** displayed.

Why?

The *Shared* Counter Class (cont'd)

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

    void increment() {
        value = value + 1;
        display.setvalue(value);
    }
}
```

Thread switch!

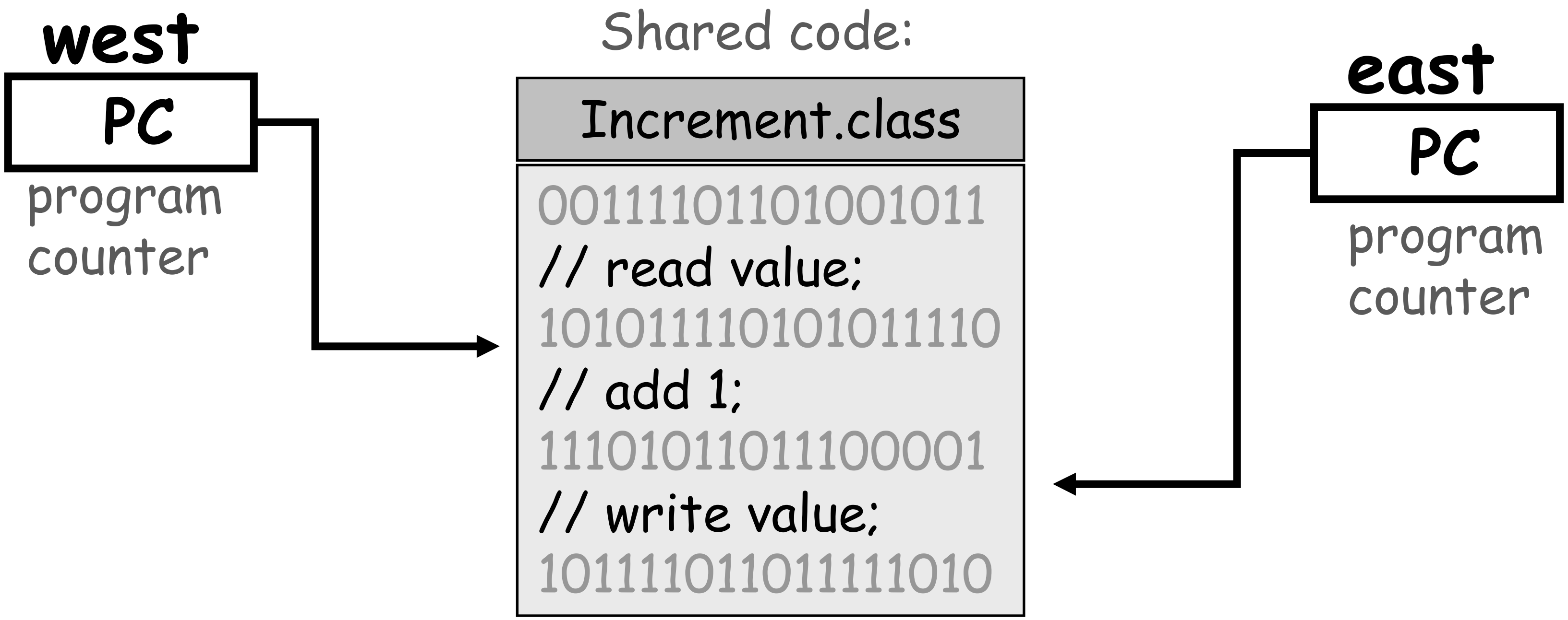
```
value = value + 1;      // 1) read value
value = value + 1;      // 2) add one
value = value + 1;      // 3) write result
```

Recall: *thread switching* (or hardware interrupts) can occur at **any** time

Concurrent Method Activation

Java method activation is **not atomic**!

Thus, threads **east** and **west** may be executing the code for the increment method at the same time.



Counter Class: How to Exhibit this Behaviour?

```
class Counter {
    void increment() {

        value = value + 1;

        display.setvalue(value);
    }
}
```

Counter Class: How to Exhibit this Behaviour?

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

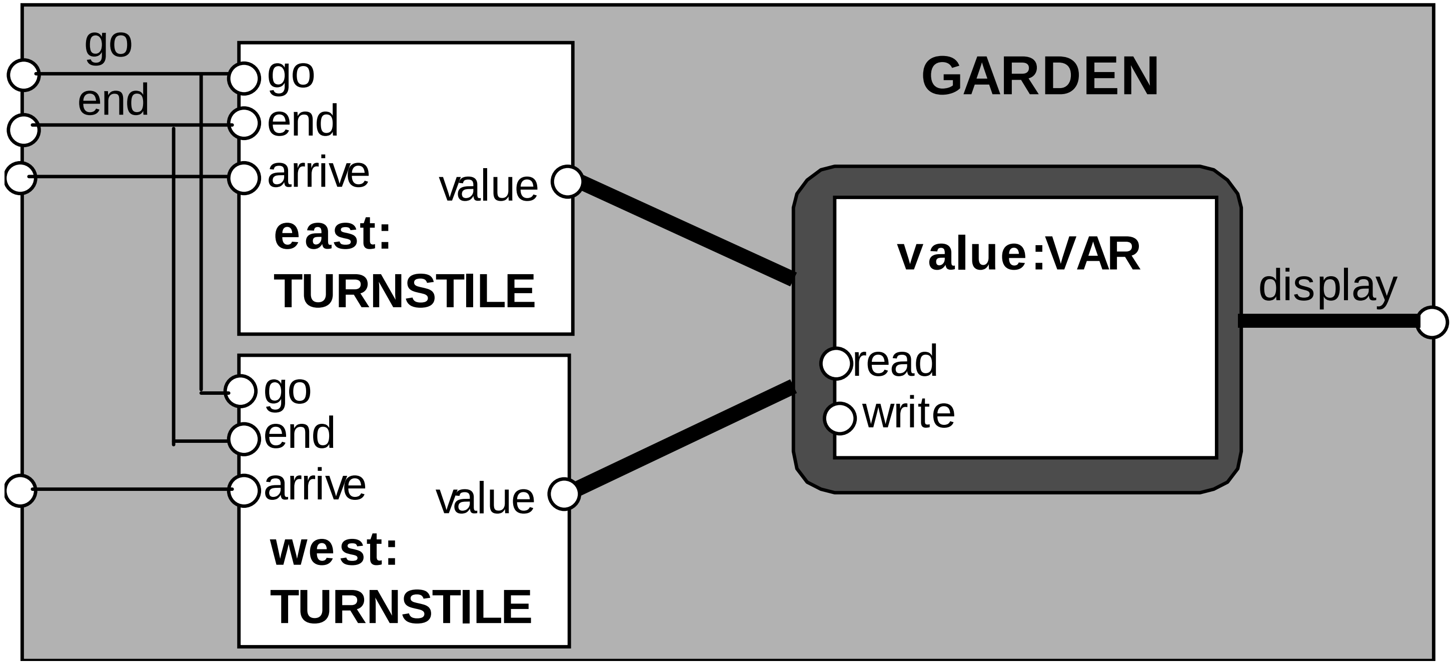
The **counter** simulates a *hardware interrupt* during an **increment()**, between reading and writing to the shared counter **value**.

```
class Simulate {    // randomly force thread switch!
    public static void HWinterrupt() {
        if (random()<0.5) Thread.yield();
    }
}
```

Running the Applet

The erroneous behaviour occurs all the time!

Ornamental Garden Model (Structure Diagram)



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

TURNSTILE:
Increment is modelled inside TURNSTILE since Java method activation is not atomic (*i.e.*, thread objects **east** and **west** may interleave their **read** and **write** actions).

Ornamental Garden Model (FSP)

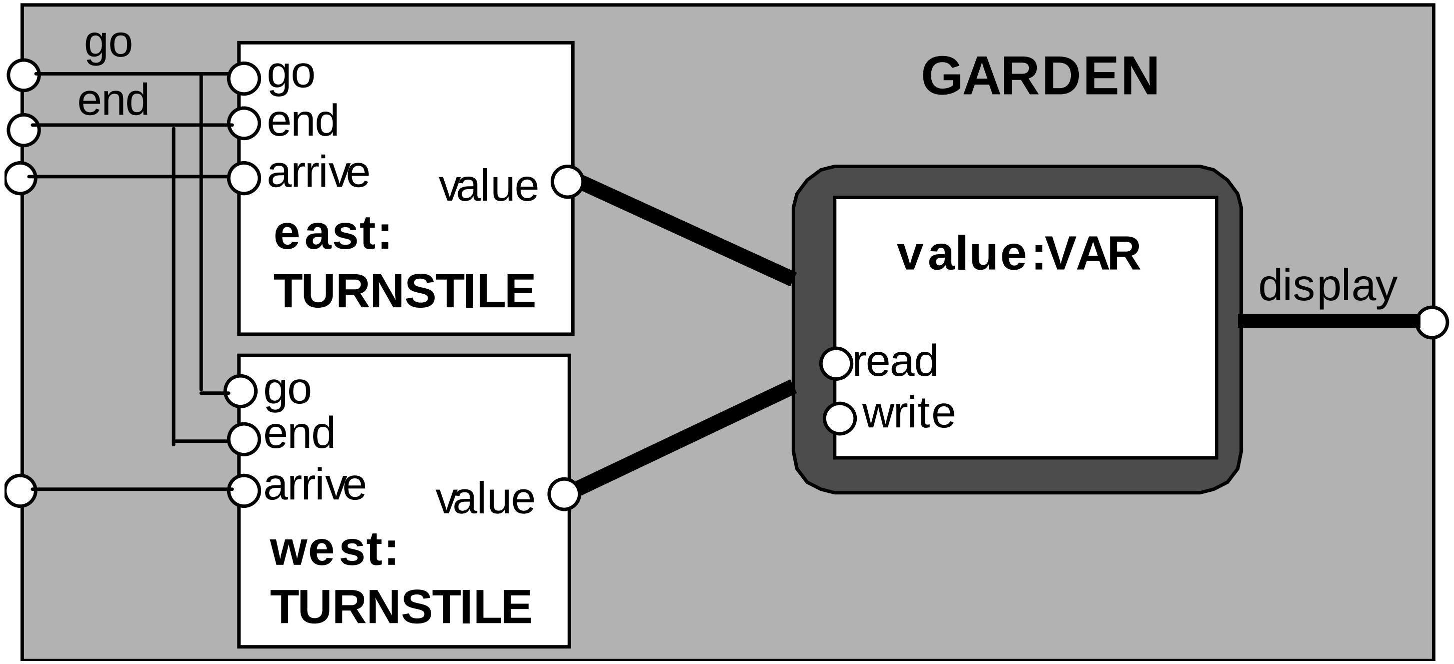
```
const N = 4
range T = 0..N
set VarAlpha = { value.{read[T],write[T]} }

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**.

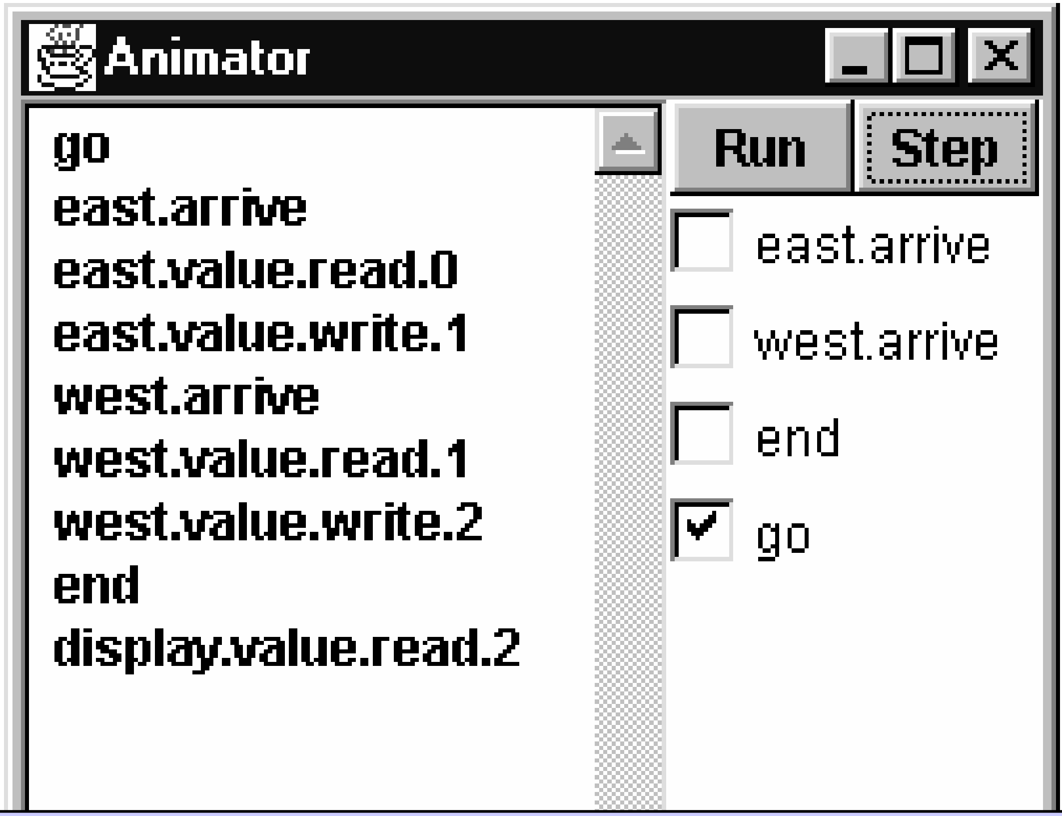
The alphabet of **TURNSTILE** is extended with **VarAlpha** to ensure no unintended free actions in **VAR** ie. all actions in **VAR** must be controlled by a **TURNSTILE**.

Ornamental Garden Model (Structure Diagram)

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



Checking for Errors - Animation



Scenario checking - use animation to produce a trace.

Is the model correct?

"Never send a human to do a machine's job"

- Agent Smith (1999)

Checking for Errors - Compose with Error Detector

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.

Checking for Errors - Exhaustive Analysis

```
||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 the **ERROR** state.

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:

- 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**.

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

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

The Garden Class (revisited)

If the **fixit** checkbox is ticked, the **go()** method creates a **SynchronizedCounter**:

```
class Garden extends Applet {
    private void go() {
        if (!fixit.getState())
            counter = new Counter(counterD);
        else
            counter = new SynchCounter(counterD);
        west = new Turnstile(westD,counter);
        east = new Turnstile(eastD,counter);
        west.start();
        east.start();
    }
}
```

Mutual Exclusion - The Ornamental Garden

Java associates a *lock* with every object.

The Java compiler inserts code to:

- acquire the lock before executing a synchronized method
- 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(counter) {counter.increment();}
```

Why is this "less elegant"?

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

Java synchronized Statement

Synchronized methods:

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

Variant - the synchronized *statement* :

object reference

```
void increment() {
    synchronized(semaphore_object) {
        value = value + 1;
    }
    display.setvalue(value);
}
```

Use synch *methods* whenever possible.

4.3 Modeling Mutual Exclusion

Define a mutual exclusion LOCK process:

```
LOCK = (acq -> rel -> LOCK).
```

...and compose it with the shared VAR in the Garden:

```
||LOCKVAR = (LOCK || VAR).
```

Update the alphabet set:

```
set VarAlpha = {value.{read[T],write[T], acq, rel}}.
```

Modify **TURNSTILE** to *acquire* and *release* the lock:

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

Revised Ornamental Garden Model - Checking for Errors

A sample trace:

```
go
east.arrive
east.value.acq
east.value.read.0
east.value.write.1
east.value.rel
west.arrive
west.value.acq
west.value.read.1
west.value.write.2
west.value.rel
end
display.value.read.2
right
```

Use **LTSA** to perform an exhaustive check:
"is TEST satisfied"?

Yes! No error found!

COUNTER: Abstraction Using Action Hiding

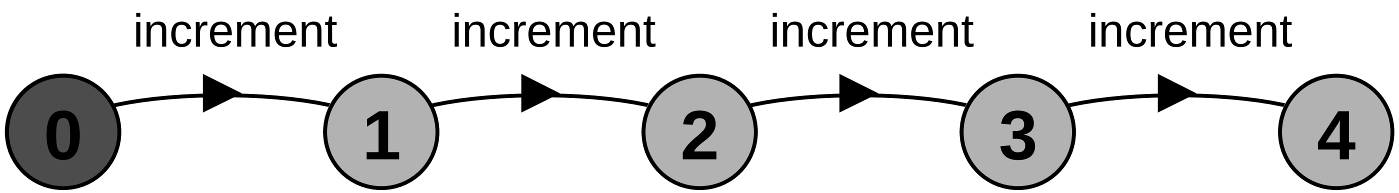
```
const N = 4
range T = 0..N

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).