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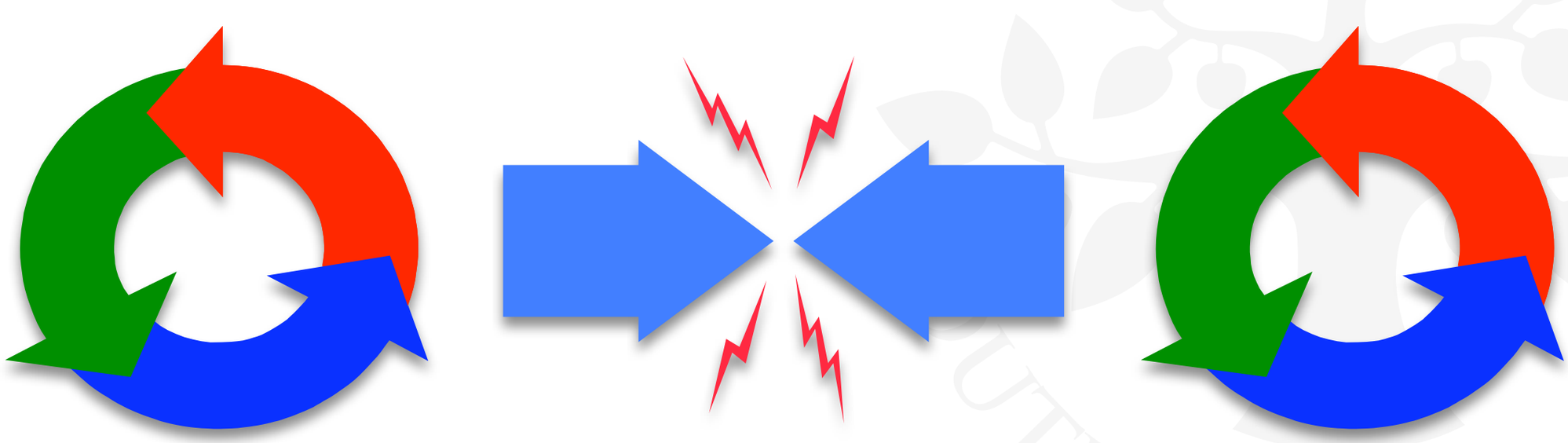
Shared Objects & Mutual Exclusion



Repetition (Finite State Processes; FSP)

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Finite State Processes (FSP) can be defined using:

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- X[i:0..N] =x[N-i] -> P // process & action index
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UNIVERSITY OF SOUTHERN DENMARK

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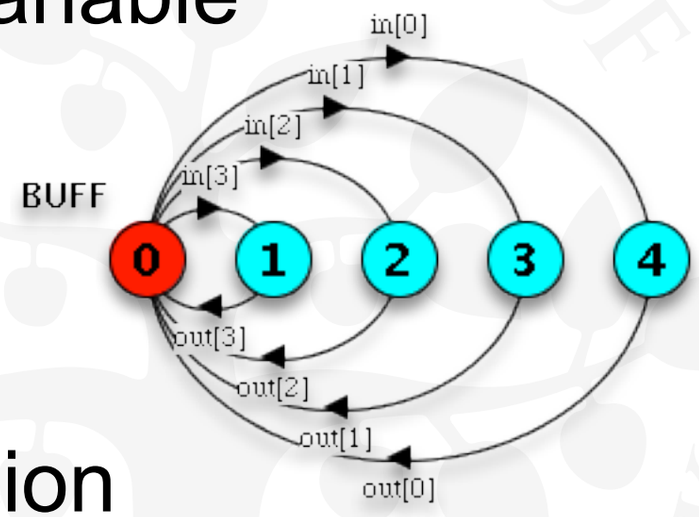


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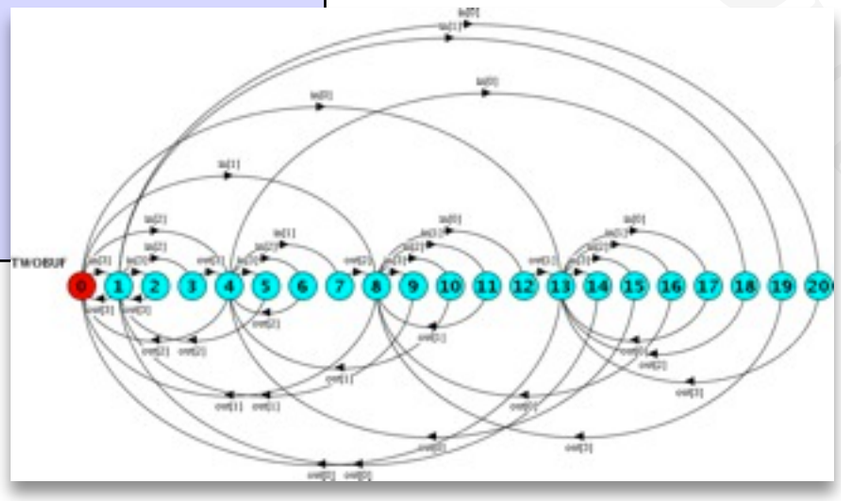

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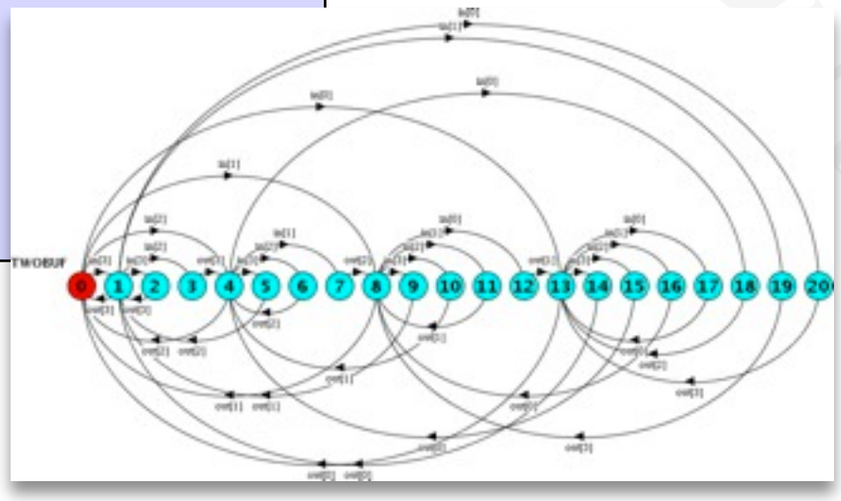
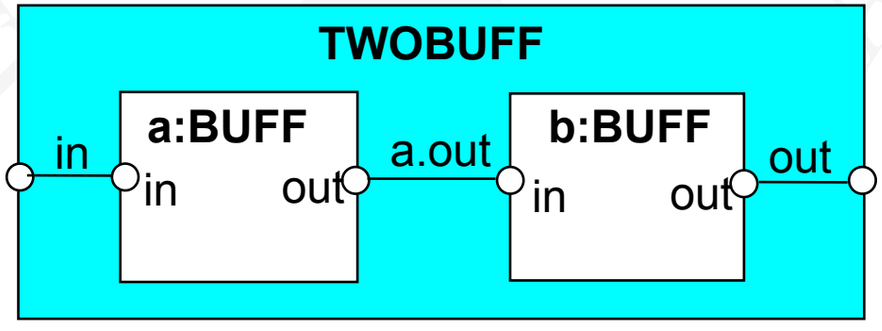


Structure Diagrams:



Structure Diagrams - Resource Sharing

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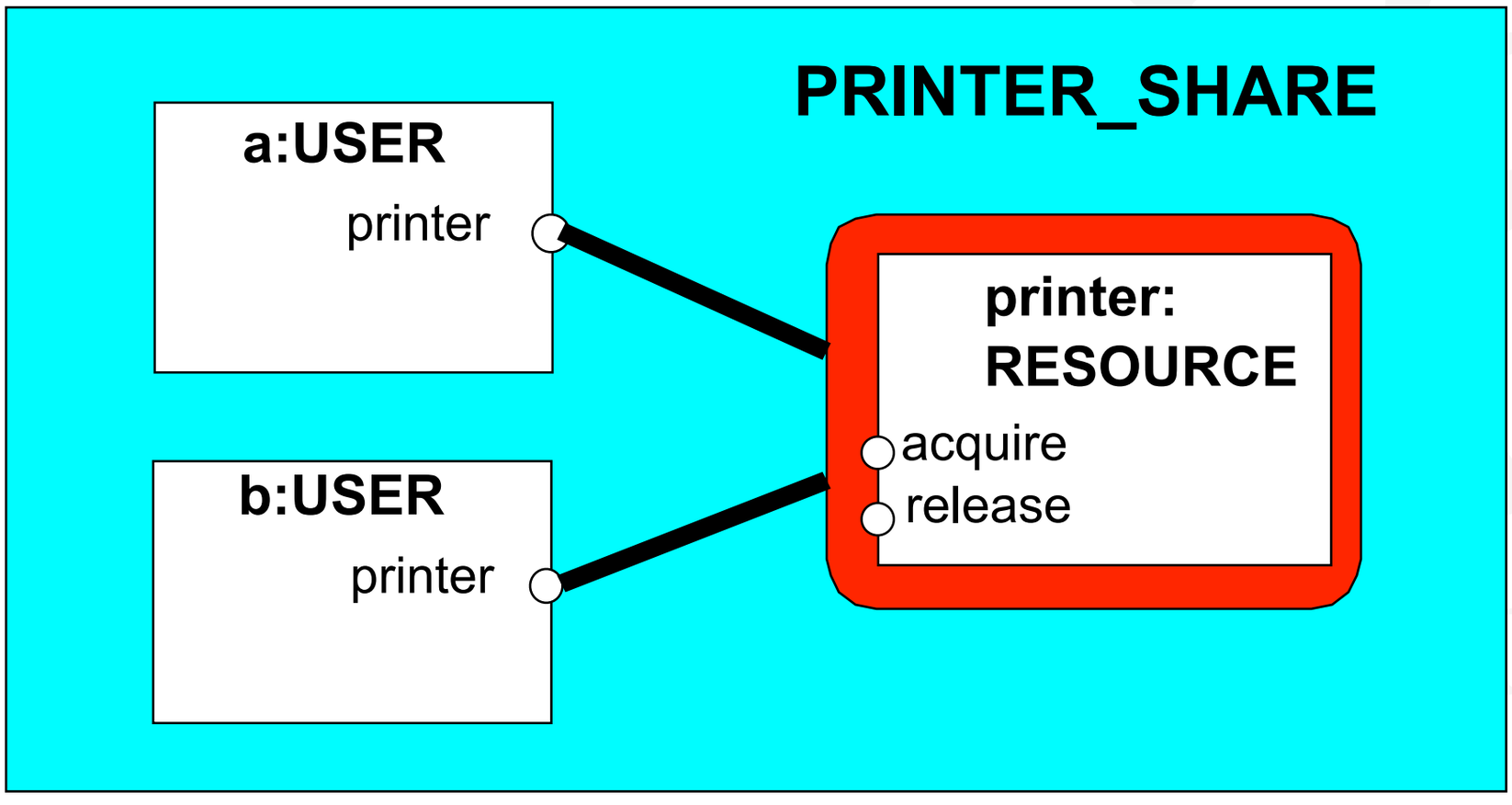

How To Create The Parallel Composed LTS


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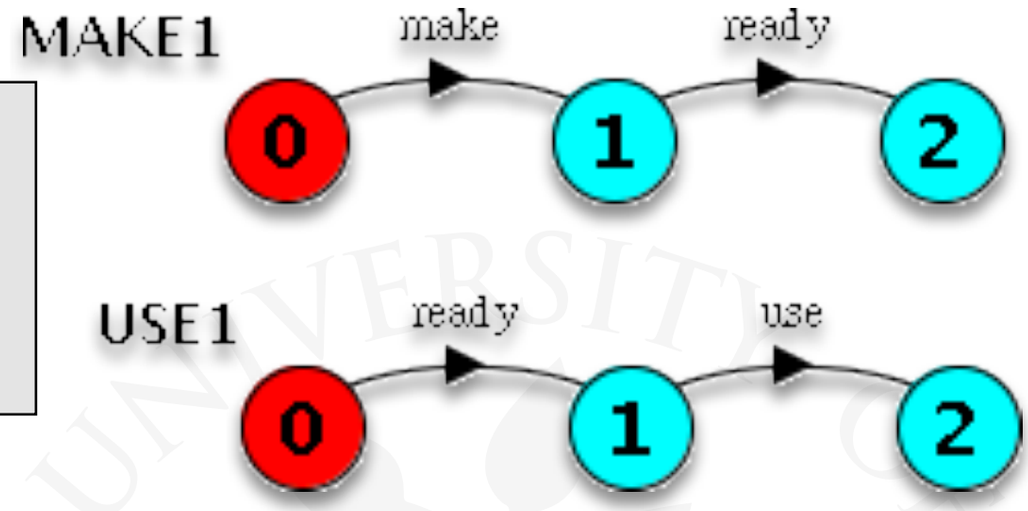

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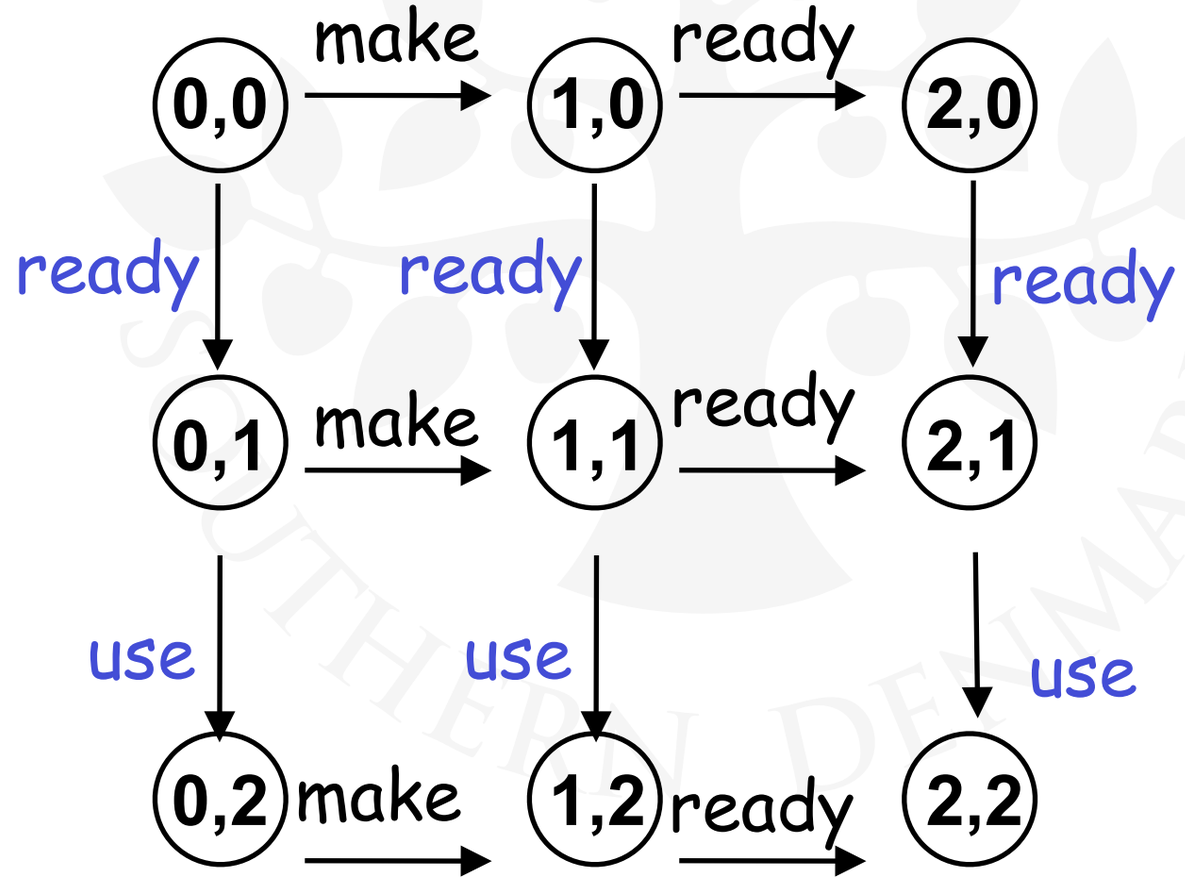

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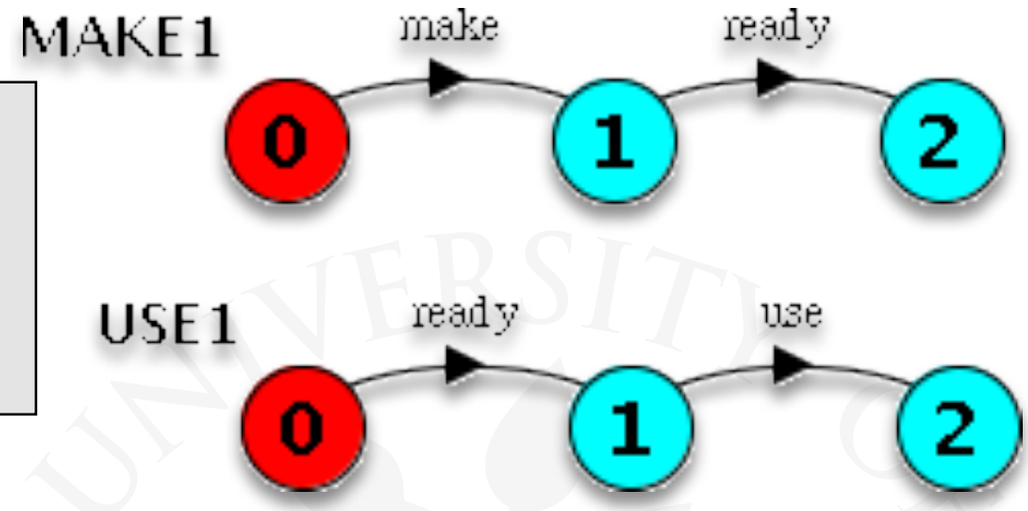

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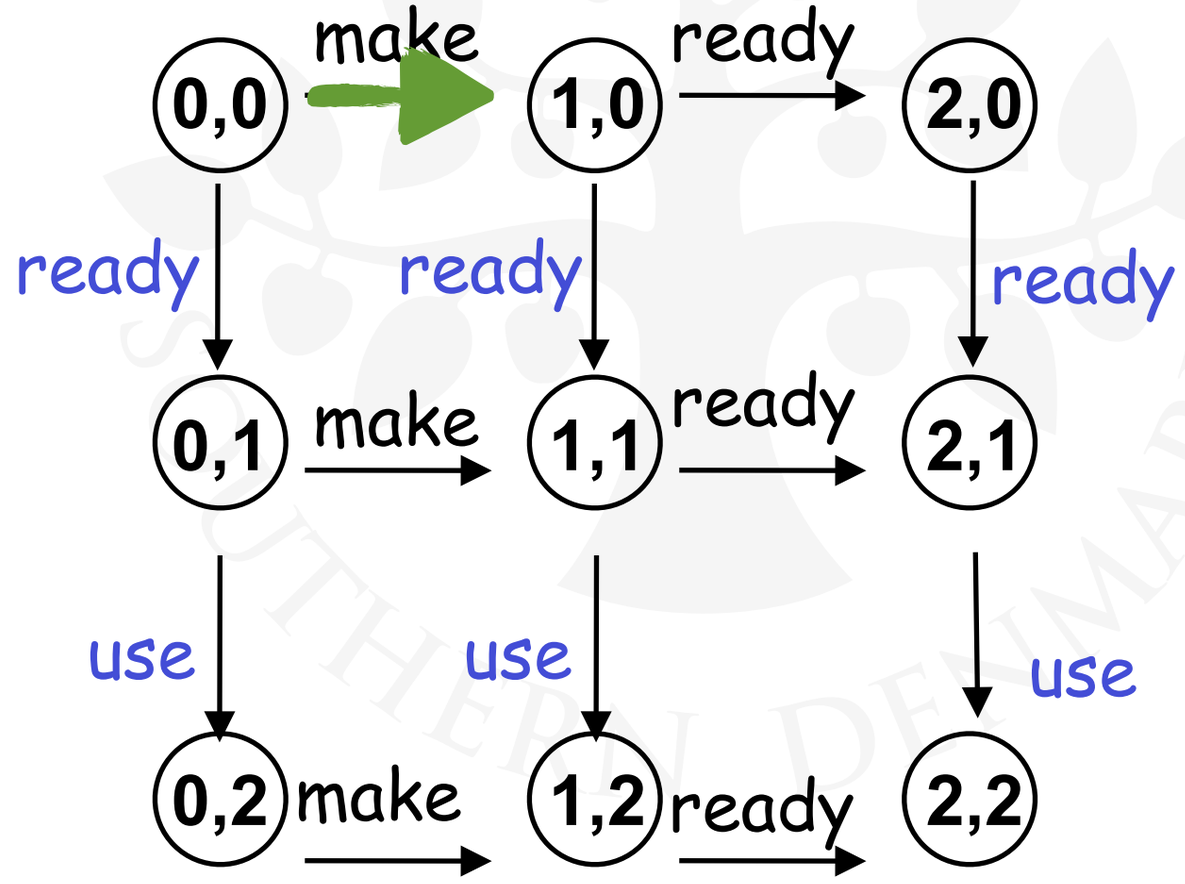

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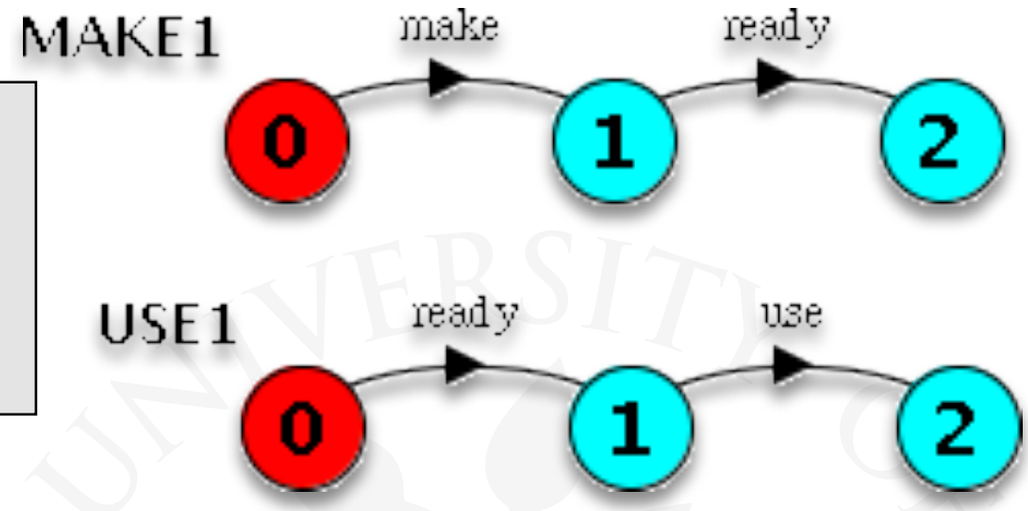

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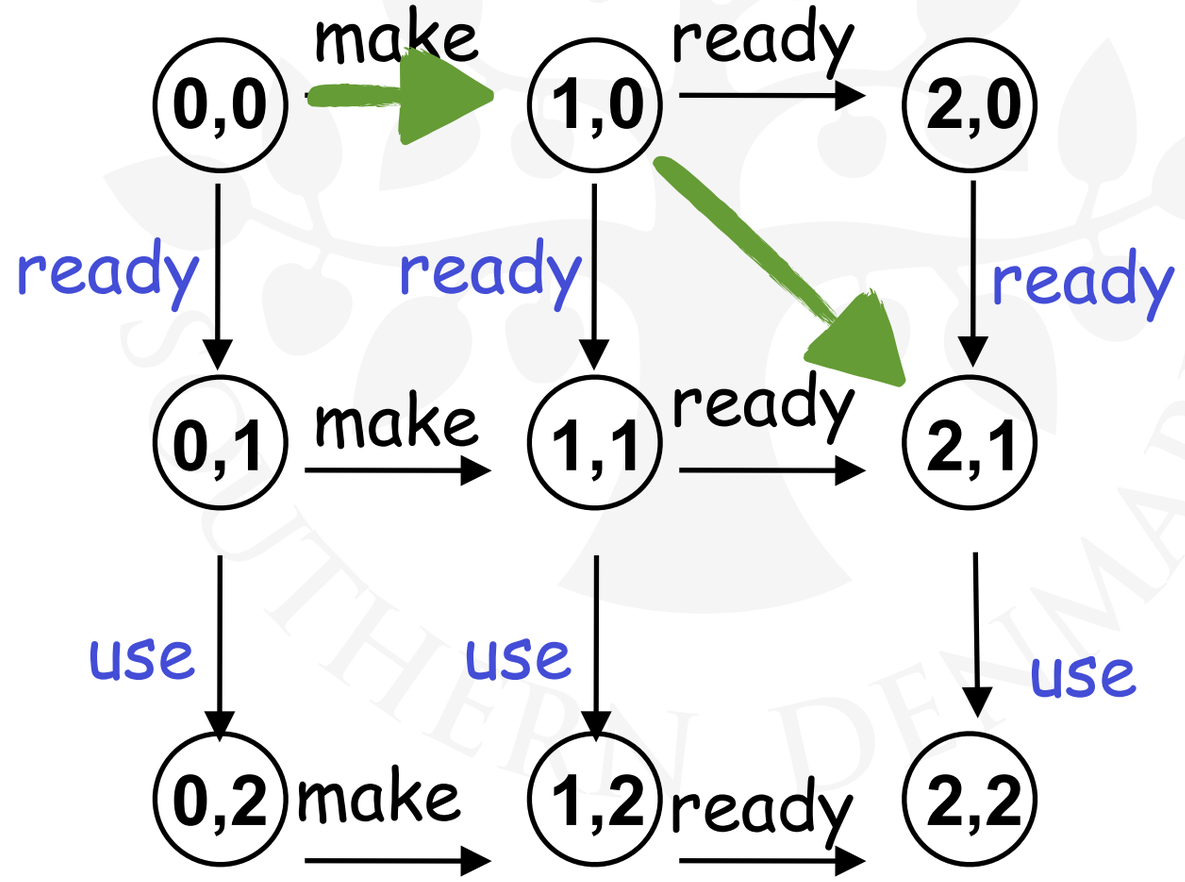

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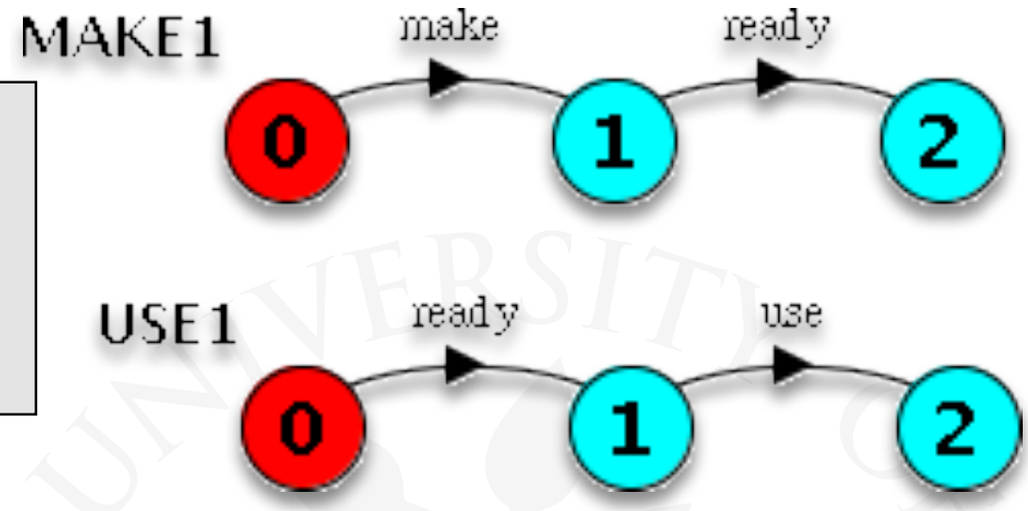

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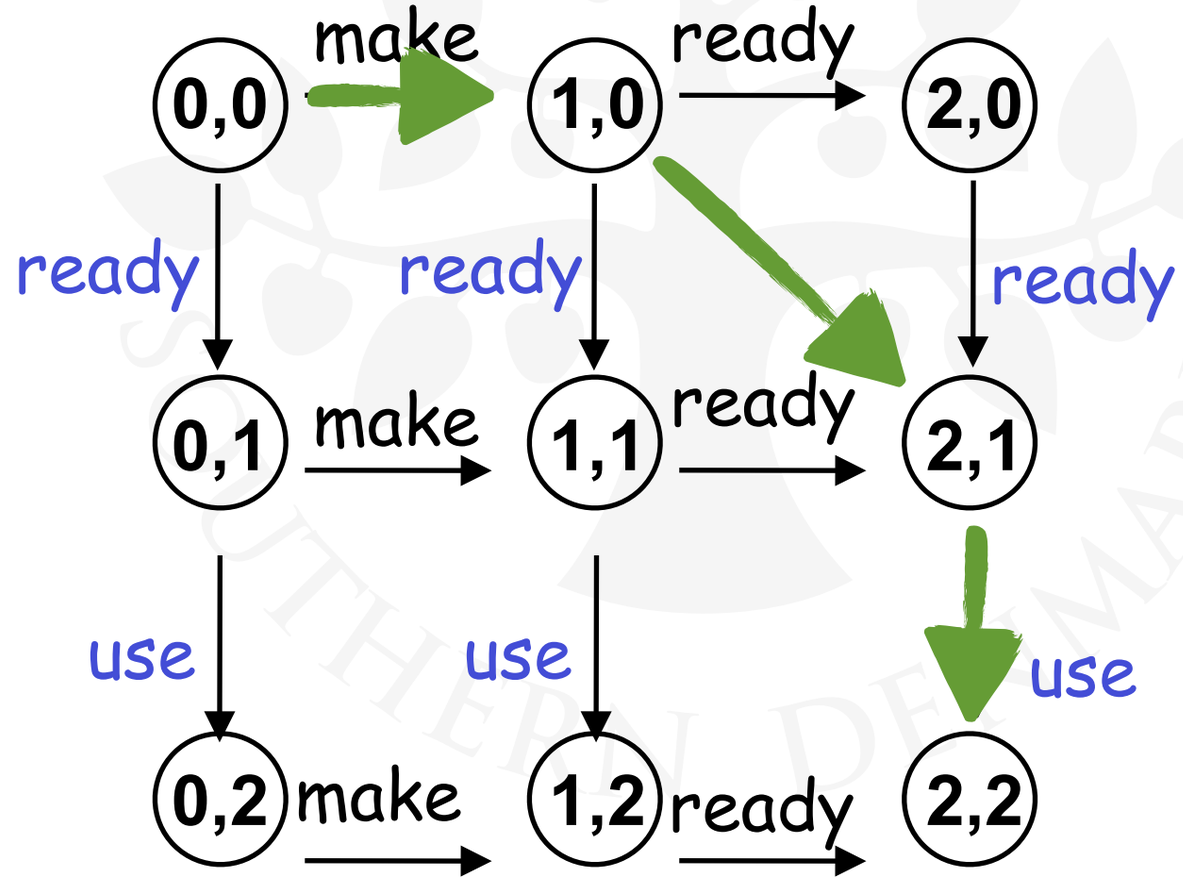

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University of Southern Denmark

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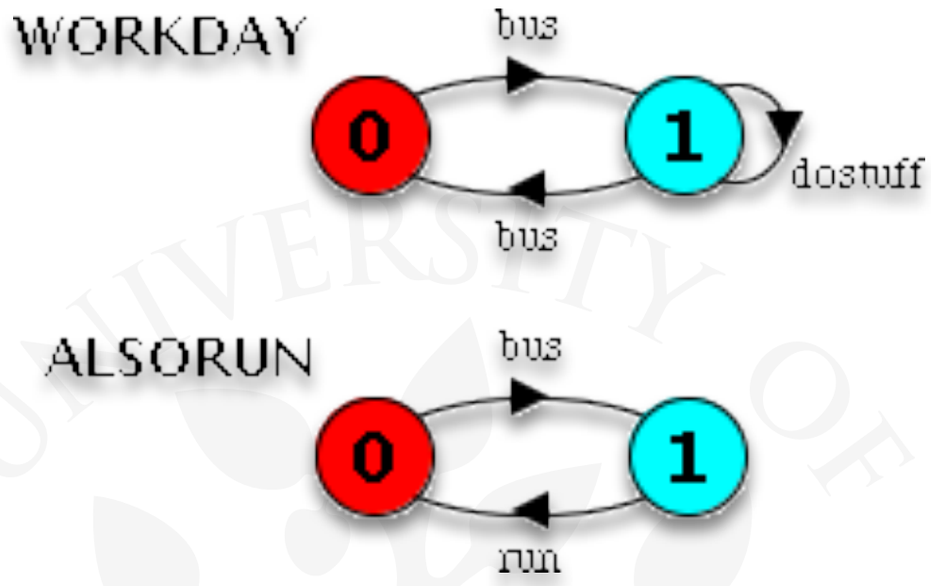

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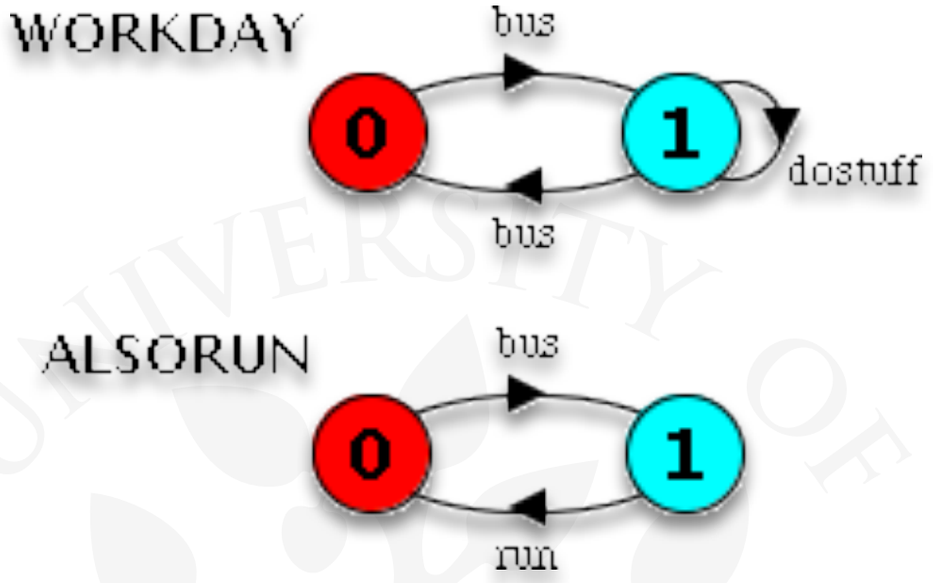

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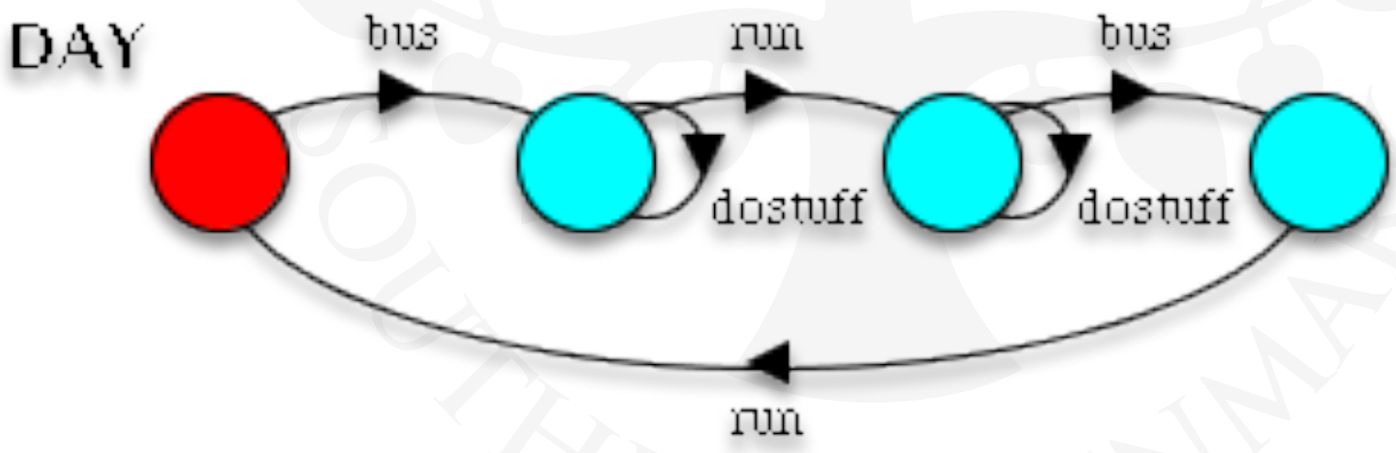

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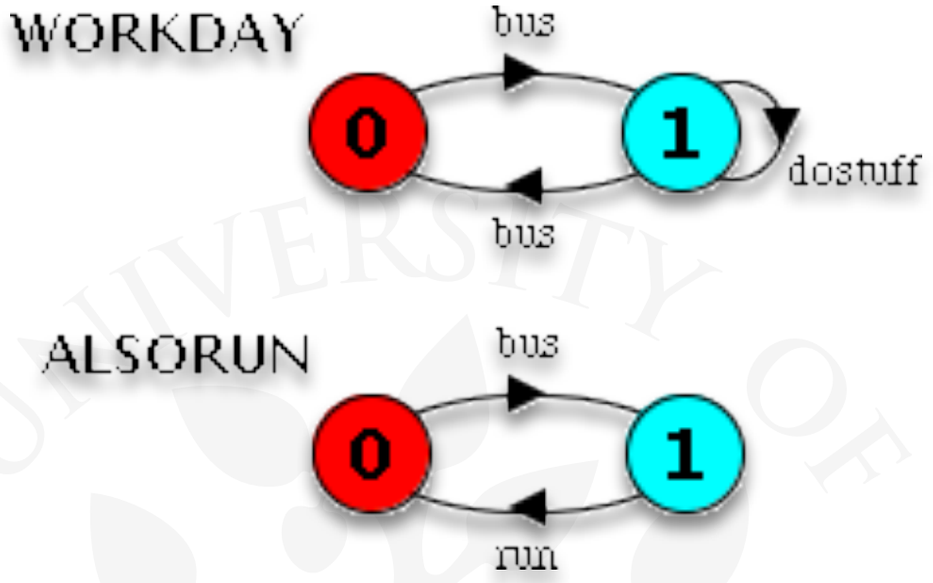

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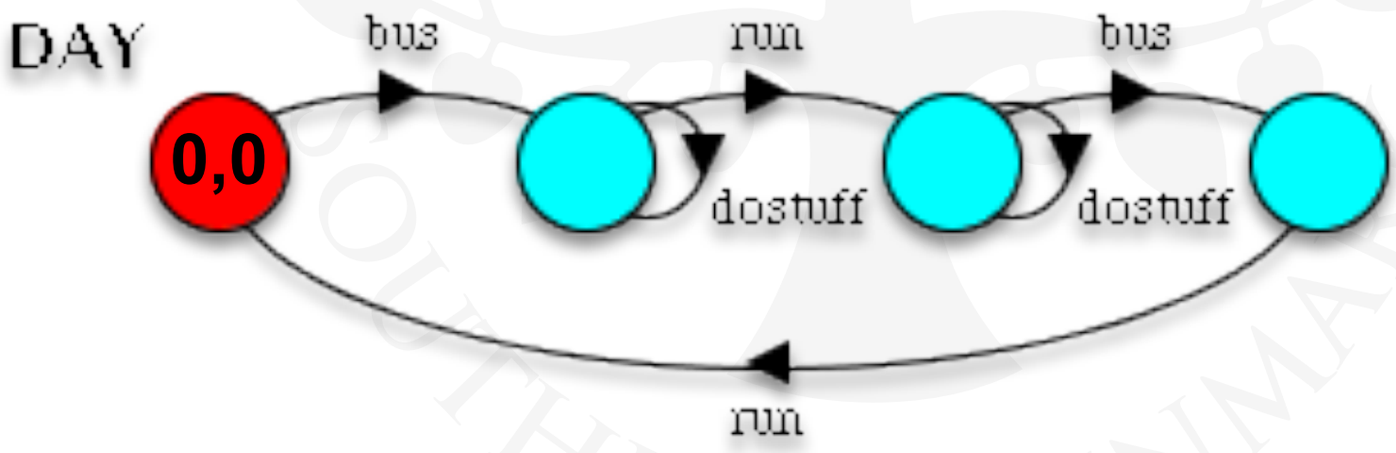

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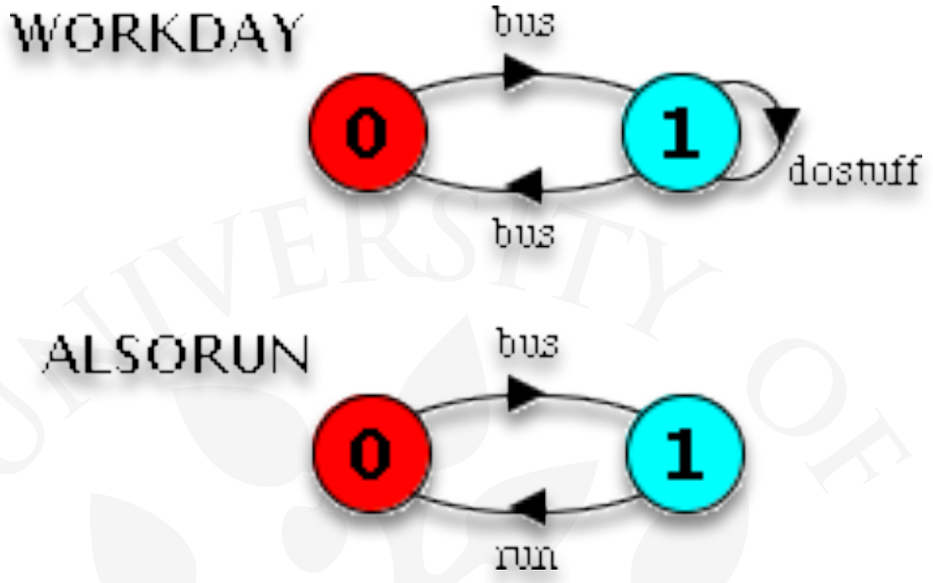

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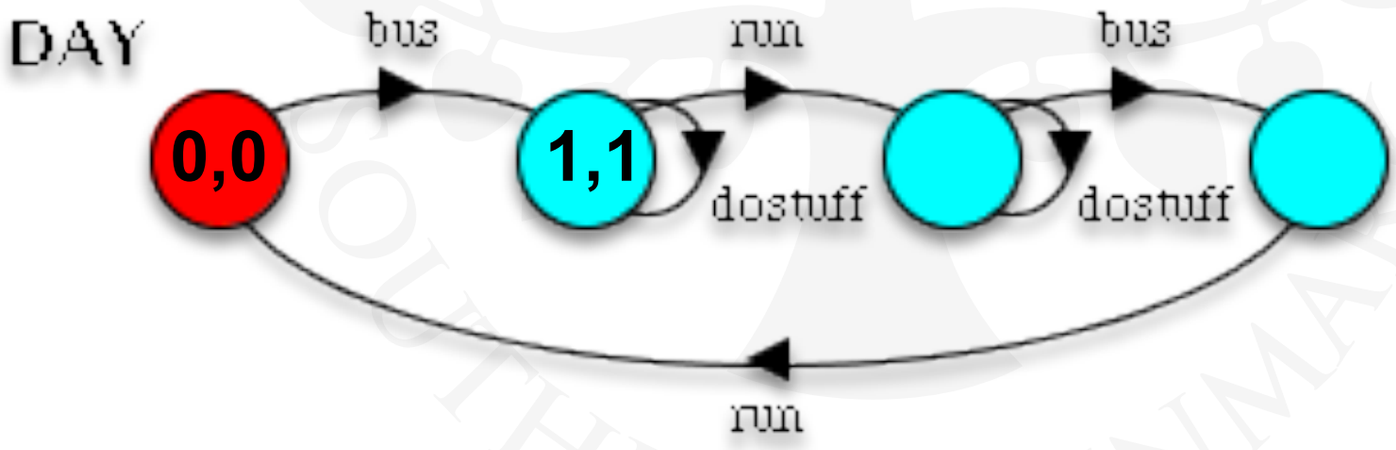

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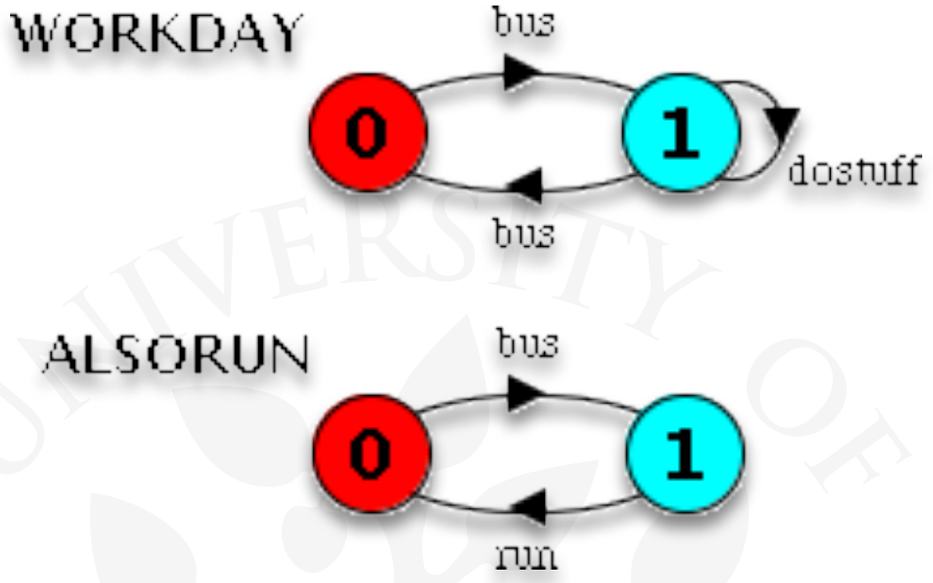

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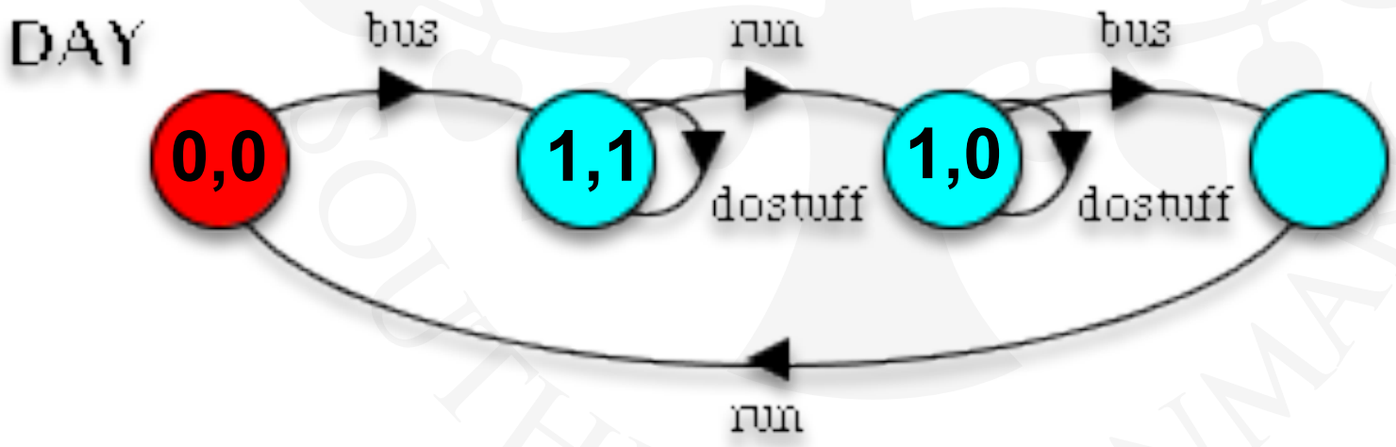

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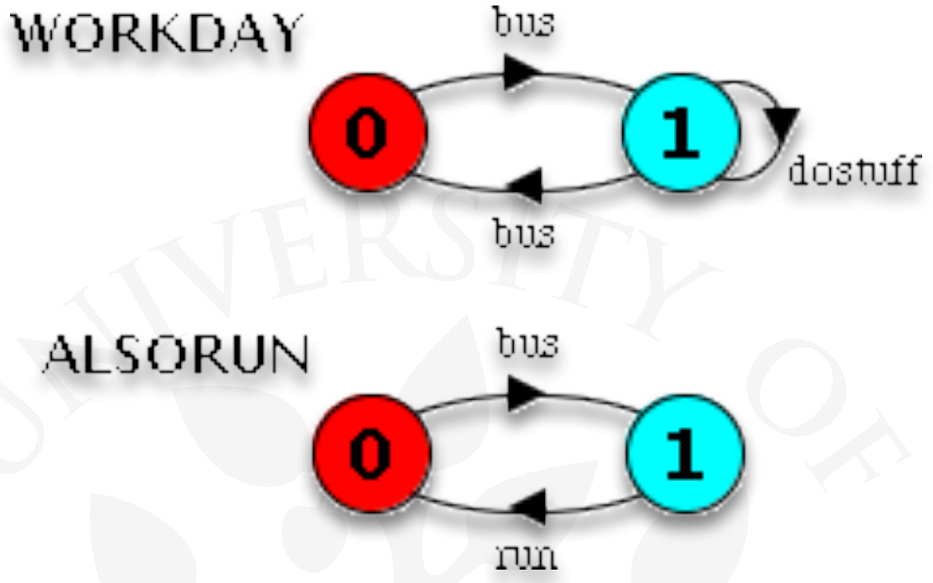

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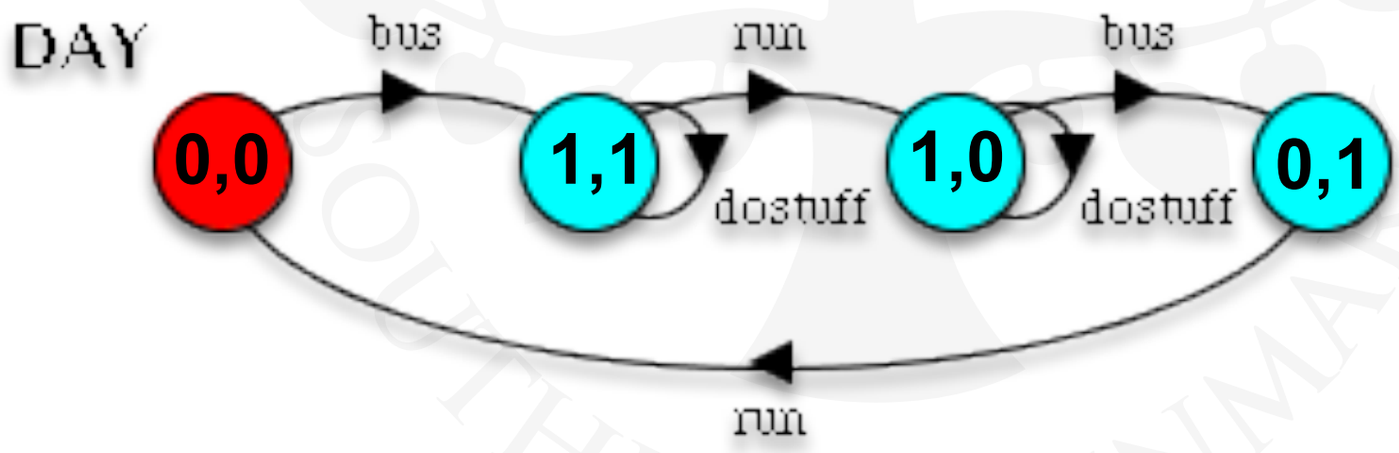

Chapter 4:
Shared Objects & Mutual Exclusion

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  - Mutual exclusion in Java
  - Synchronised objects, methods, and statements

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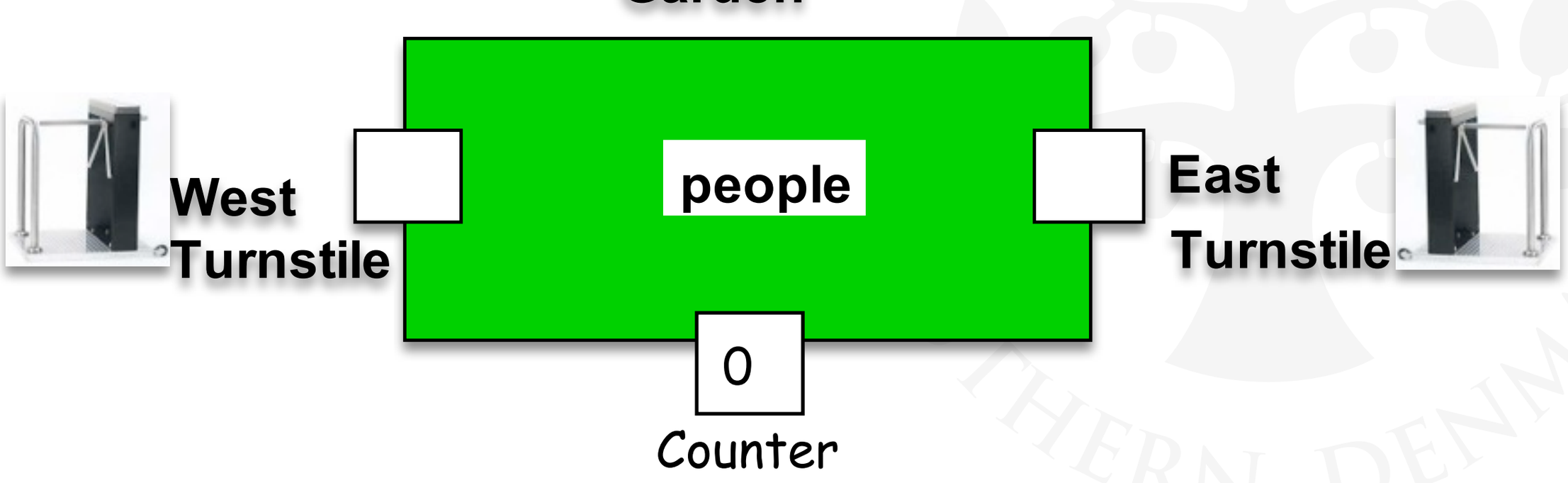
People enter an ornamental garden through either of two turnstiles. Management wishes to know how many are in the garden at any time. (Nobody can exit).



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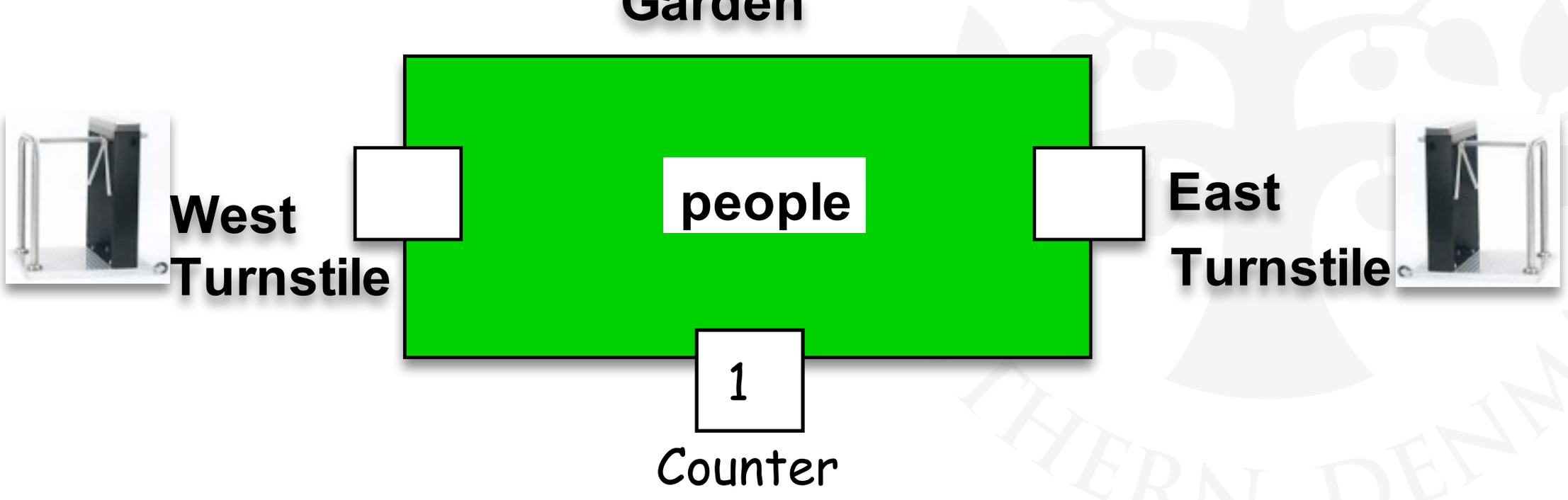

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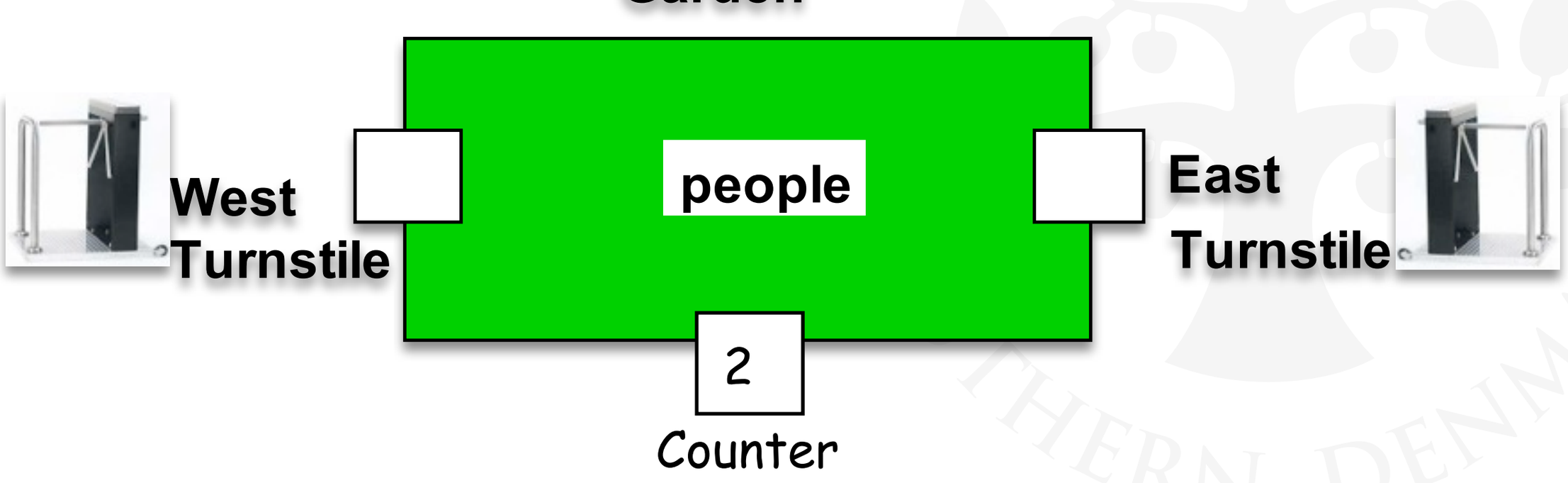

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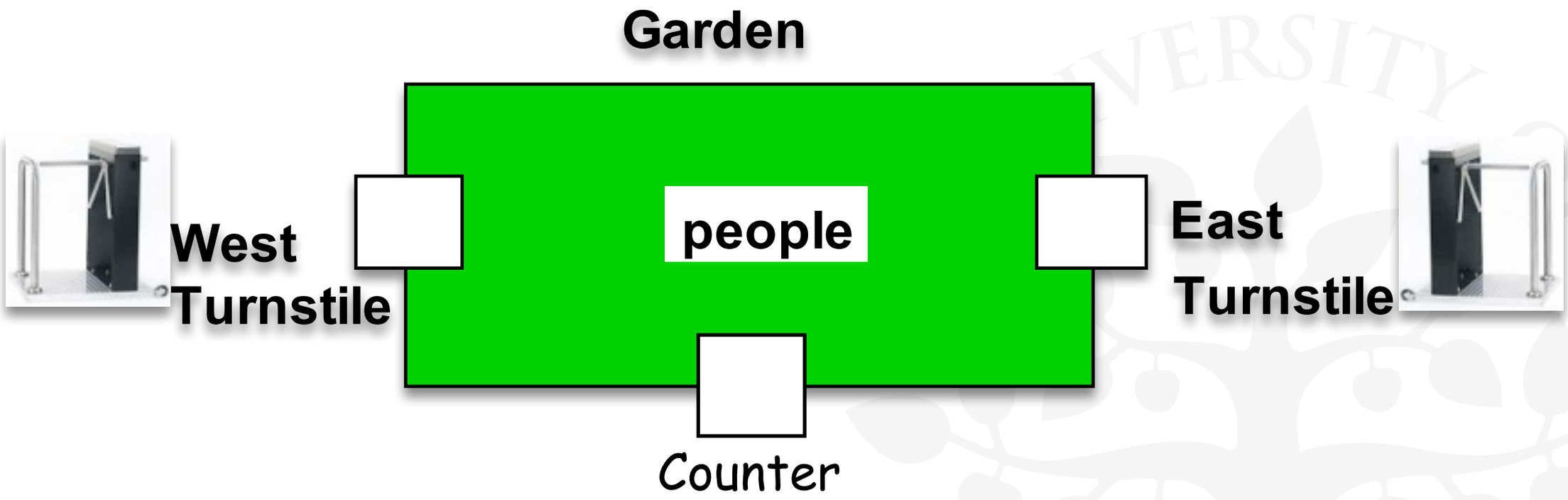

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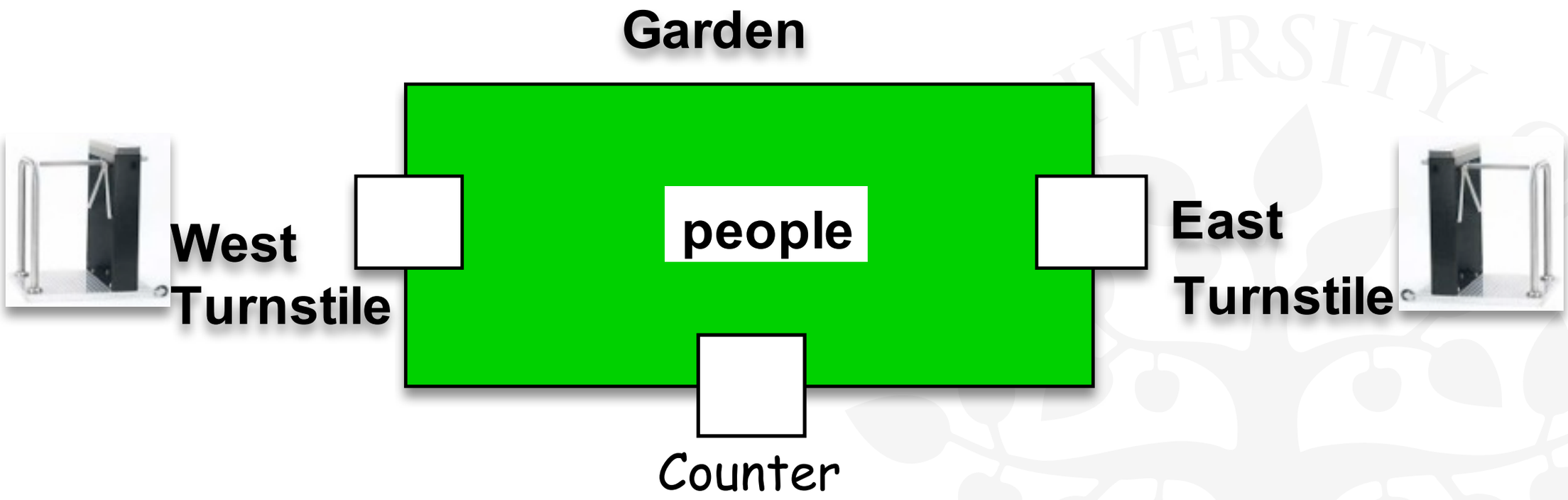

Java implementation:

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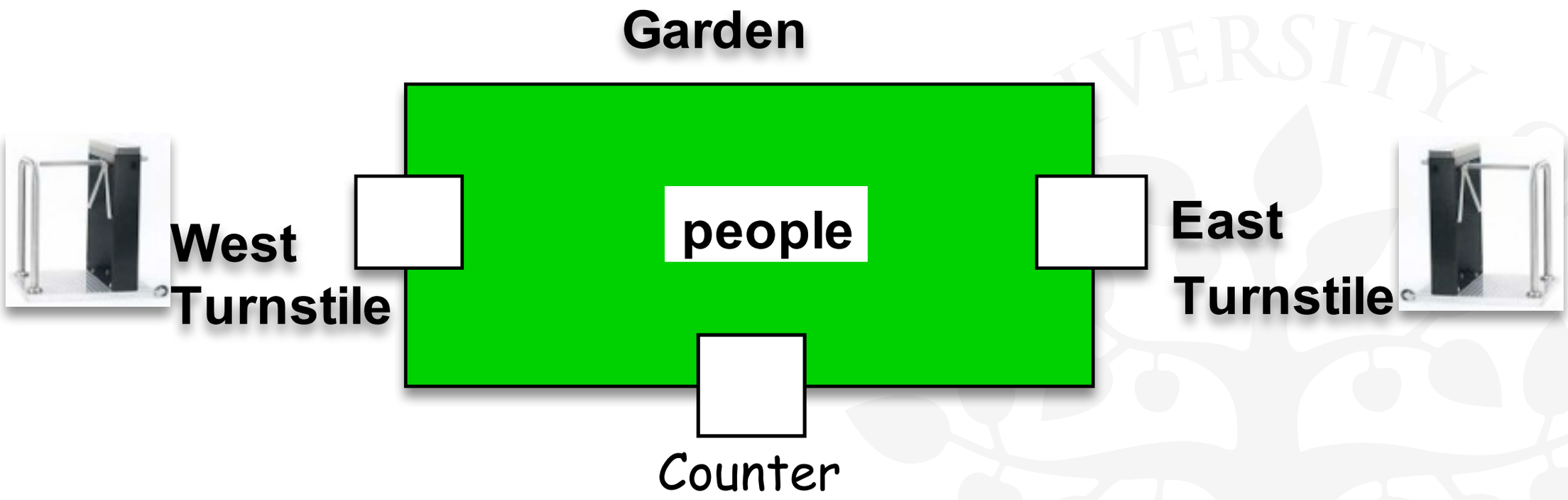

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The concurrent program consists of:

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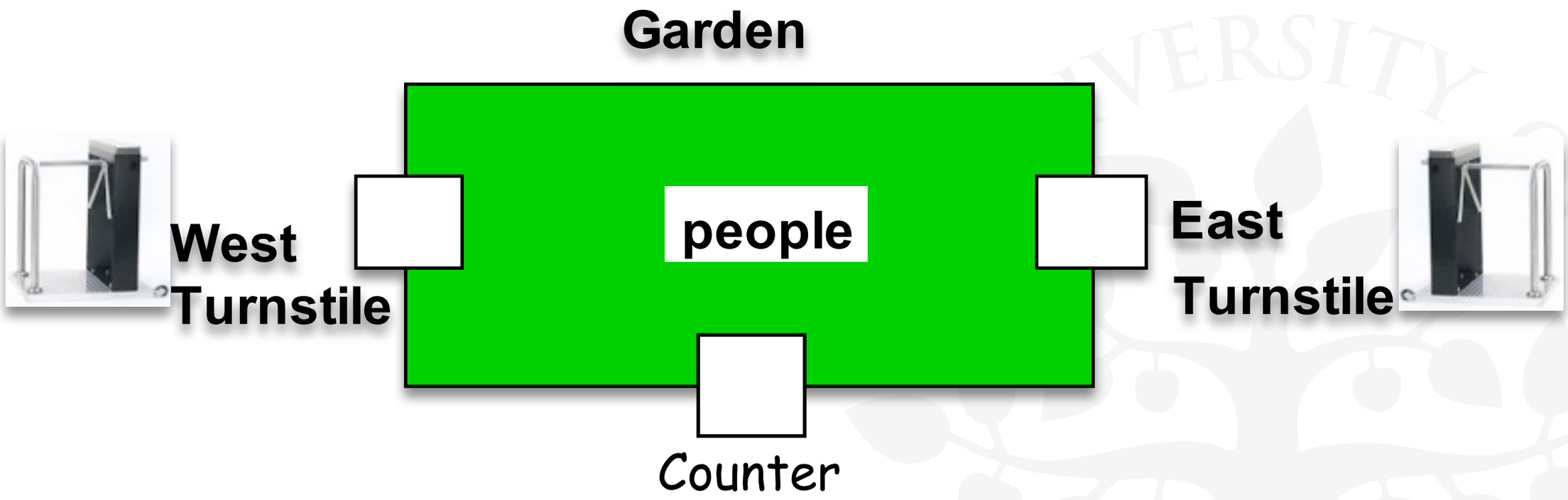

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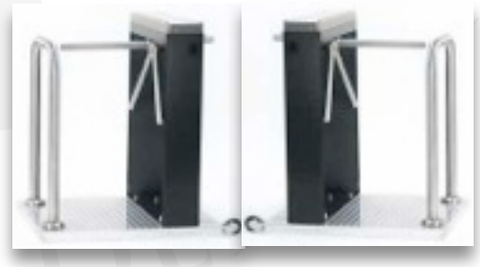

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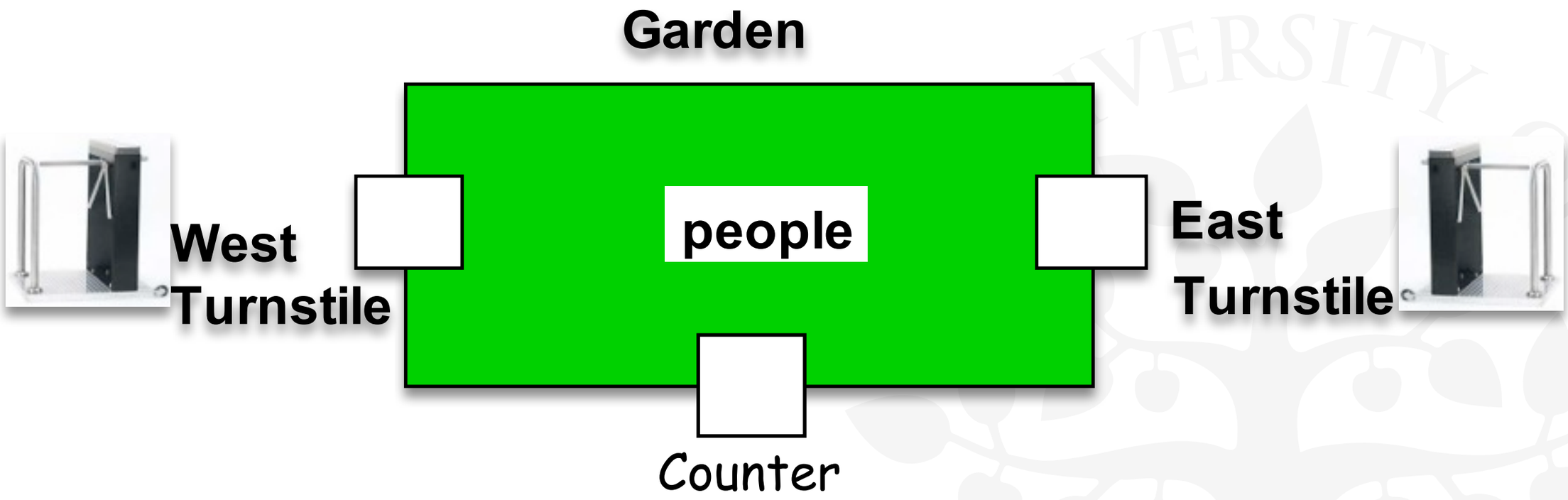
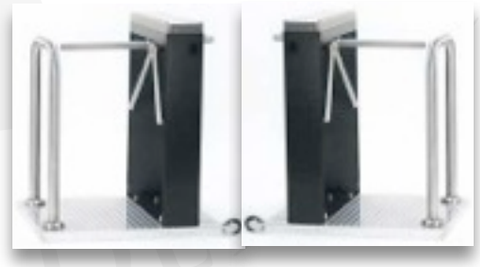


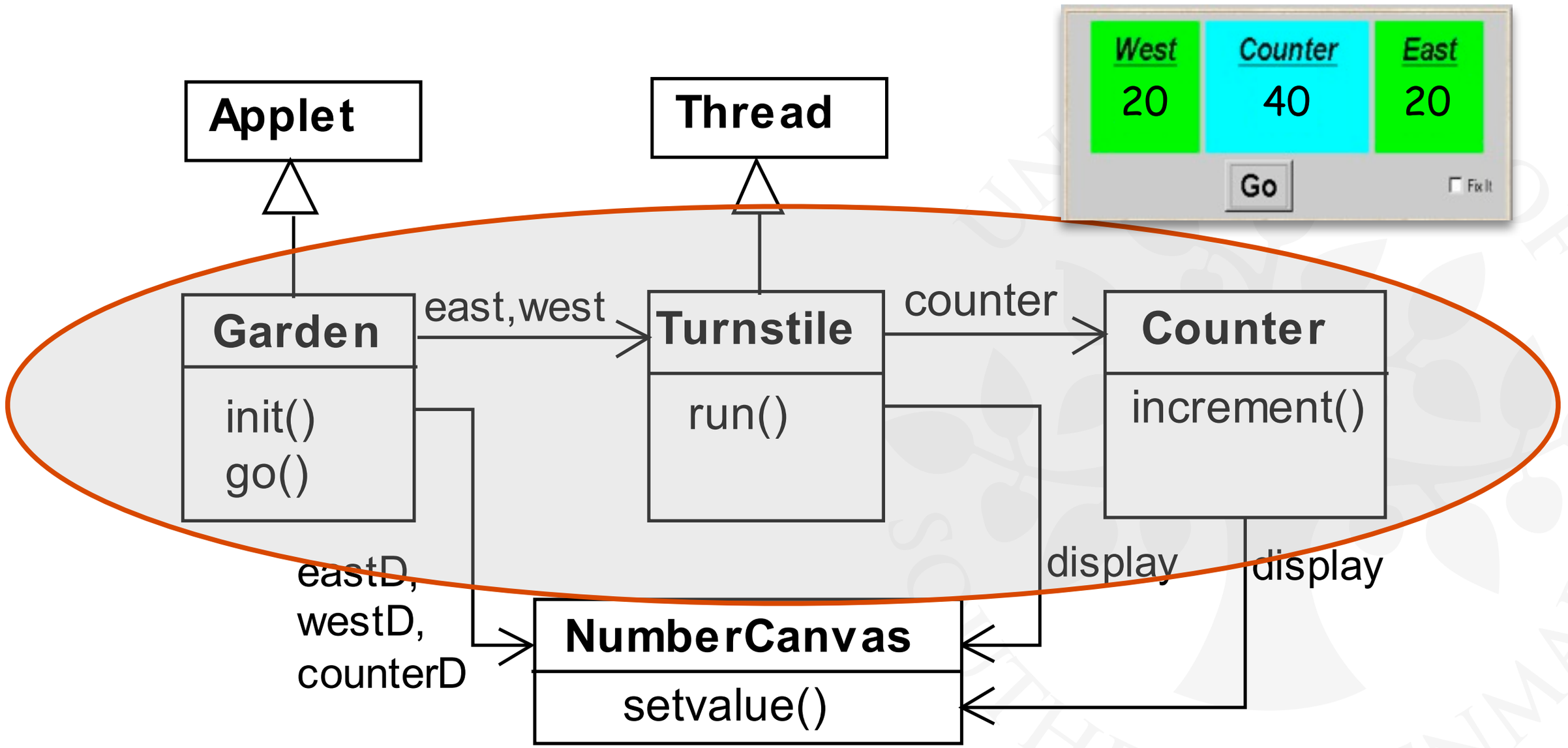
Java implementation:

The concurrent program consists of:

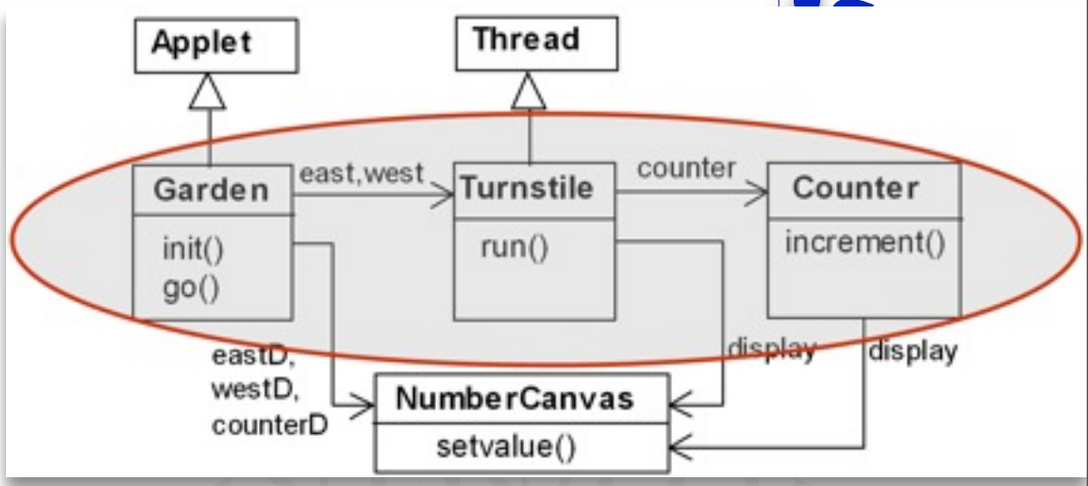
- two concurrent threads (west & east); and
- a shared counter object



Class Diagram



Ornamental Garden Program

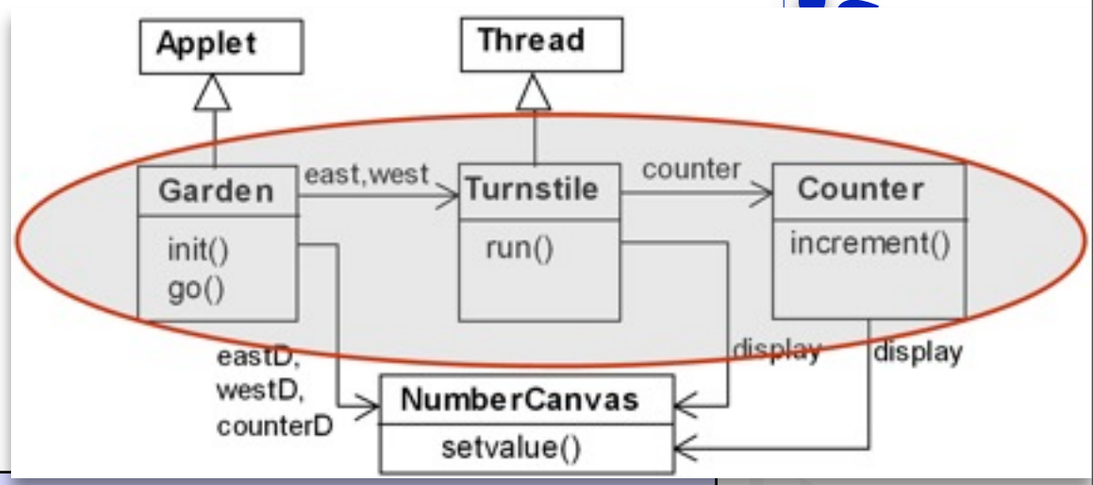


The **go()** method of the Garden applet…

```
class Garden extends Applet {
    NumberCanvas counterD, westD, eastD;
    Turnstile east, west;
    ...
    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.

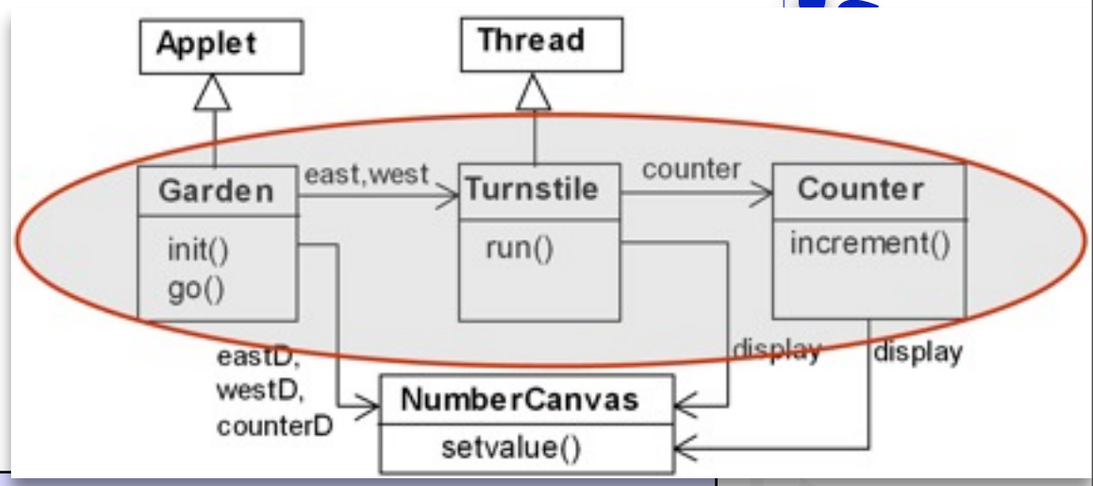
The Turnstile Class




```
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 Class

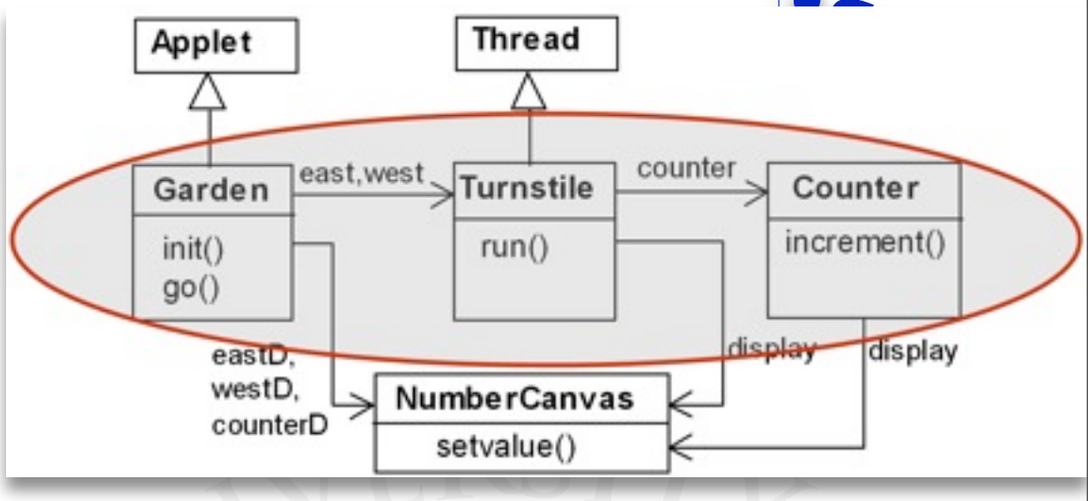



```
class Turnstile extends Thread {
    NumberCanvas display;
    Counter counter;

    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);
    }
}
```

Running The Applet

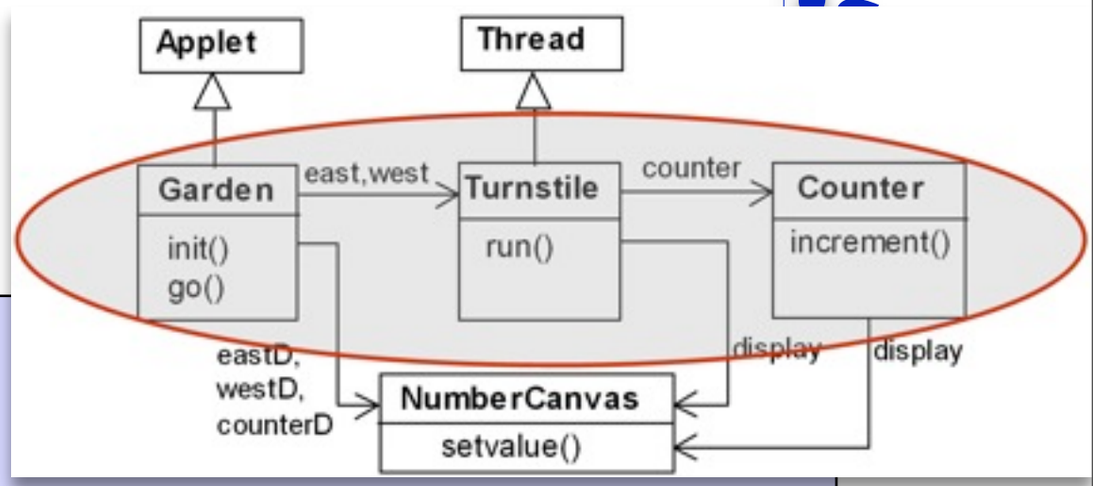
After the East and West turnstile threads each have incremented the counter **20 times**, the garden people counter is **not always the sum of the counts** displayed.

Running The Applet

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

Why?

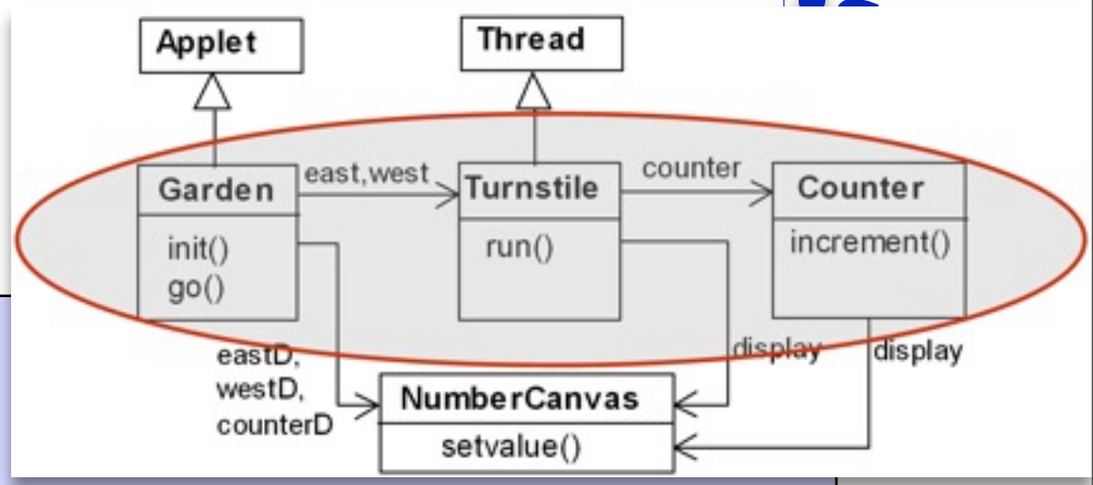
The *Shared* Counter Class (cont'd)




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

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

The *Shared* Counter Class (cont'd)

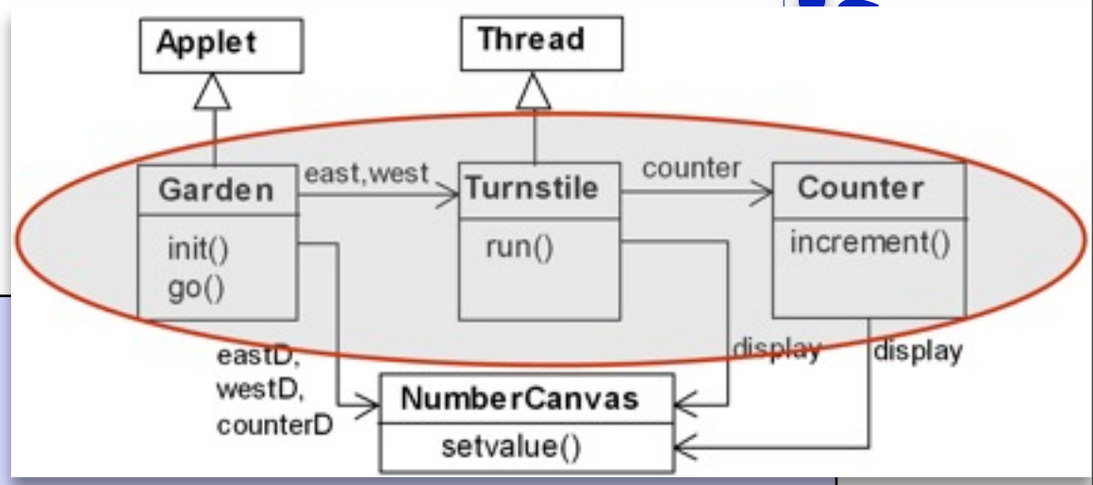



```
class Counter {
    int value;
    NumberCanvas display;

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

```
javac Counter.java
javap -c Counter > Counter.bc
```

The *Shared* Counter Class (cont'd)

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class Counter {
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}
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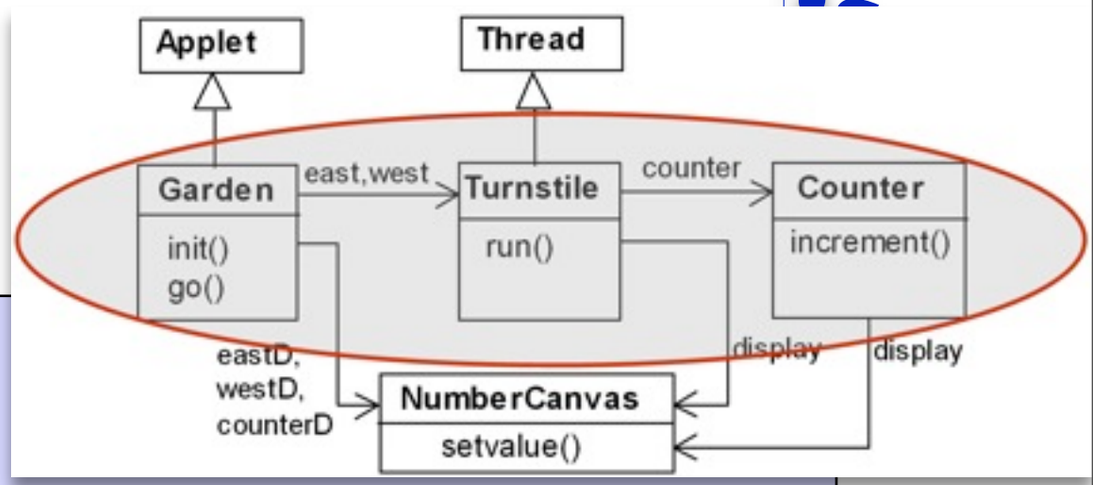
javap -c Counter > Counter.bc
```

The *Shared* Counter Class (cont'd)




```
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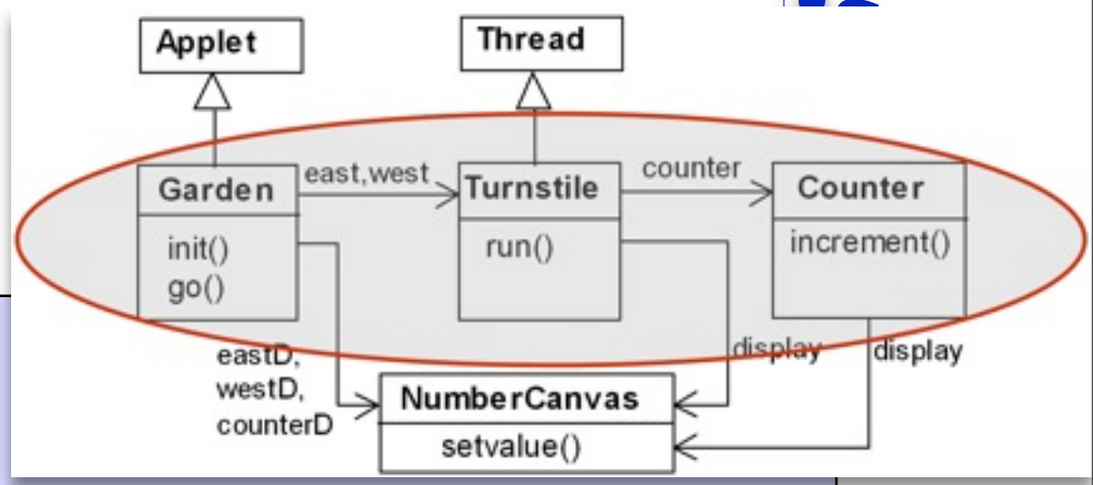
    NumberCanvas display;

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

javac Counter.java
javap -c Counter > Counter.bc

```
aload_0          // push "this" onto stack
getfield #2      // get value of "this.value"
iconst_1         // push 1 onto stack
iadd             // add two top stack elements
putfield #2      // put result into "this.value"
```

The *Shared* Counter Class (cont'd)




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

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

javac Counter.java
javap -c Counter > Counter.bc

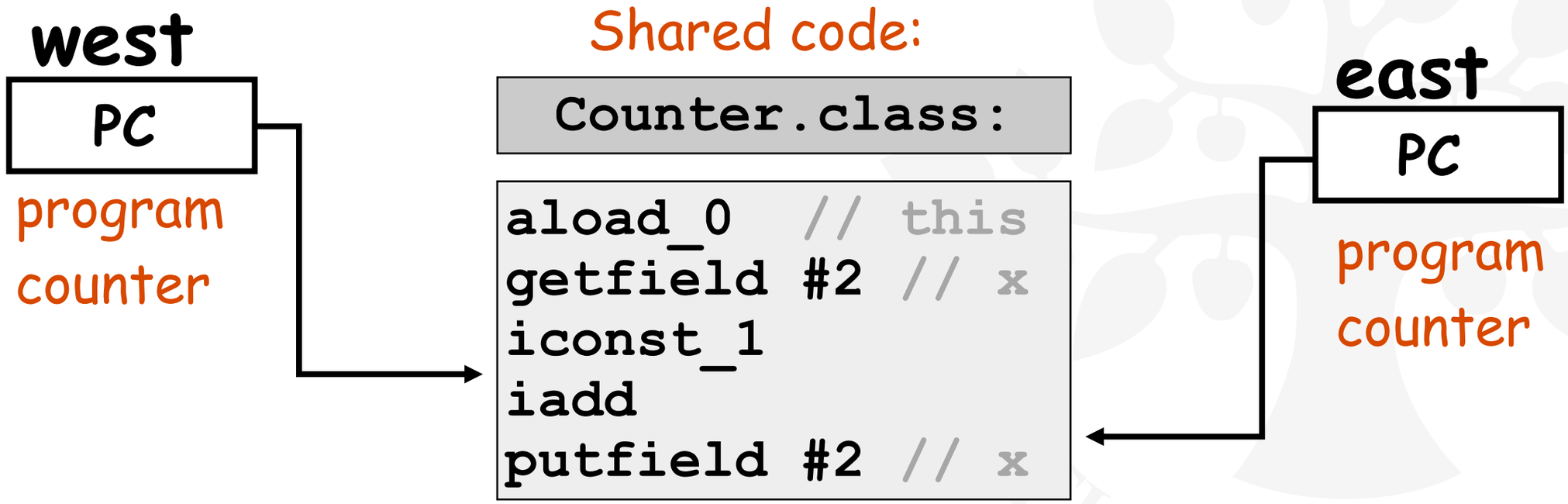
Thread switch?

```
aload_0          // push "this" onto stack
getfield #2      // get value of "this.value"
iconst_1         // push 1 onto stack
iadd             // add two top stack elements
putfield #2      // put result into "this.value"
```

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.



Pedagogification; The Counter Class (cont'd)


```
class Counter {
    void increment() {

        value = value + 1;

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

Pedagogification; The Counter Class (cont'd)


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

Pedagogification; The Counter Class (cont'd)


```
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**.

Pedagogification; The Counter Class (cont'd)

University of Southern Denmark

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

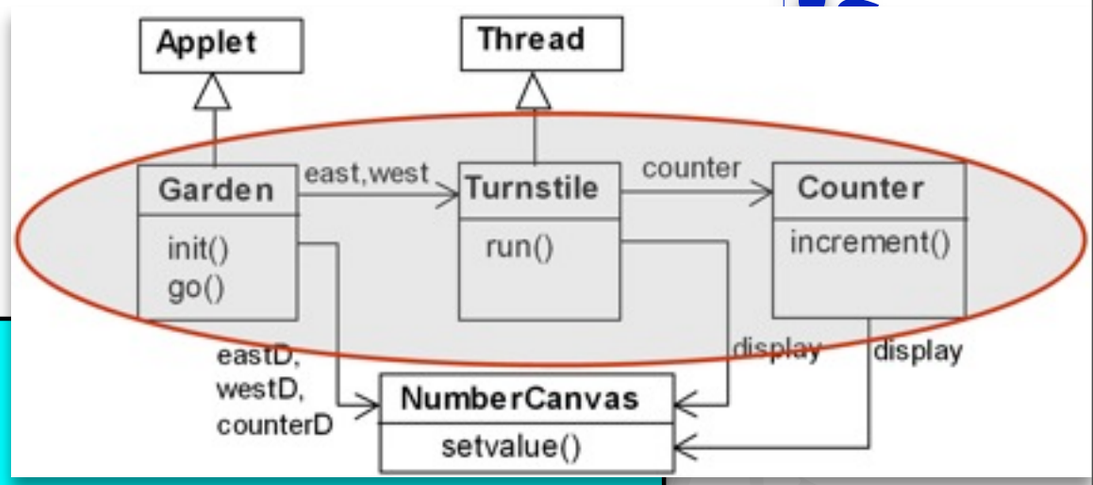
The **counter** simulates a hardware interrupt during an **increment()**, between reading and writing to the shared counter **value**.

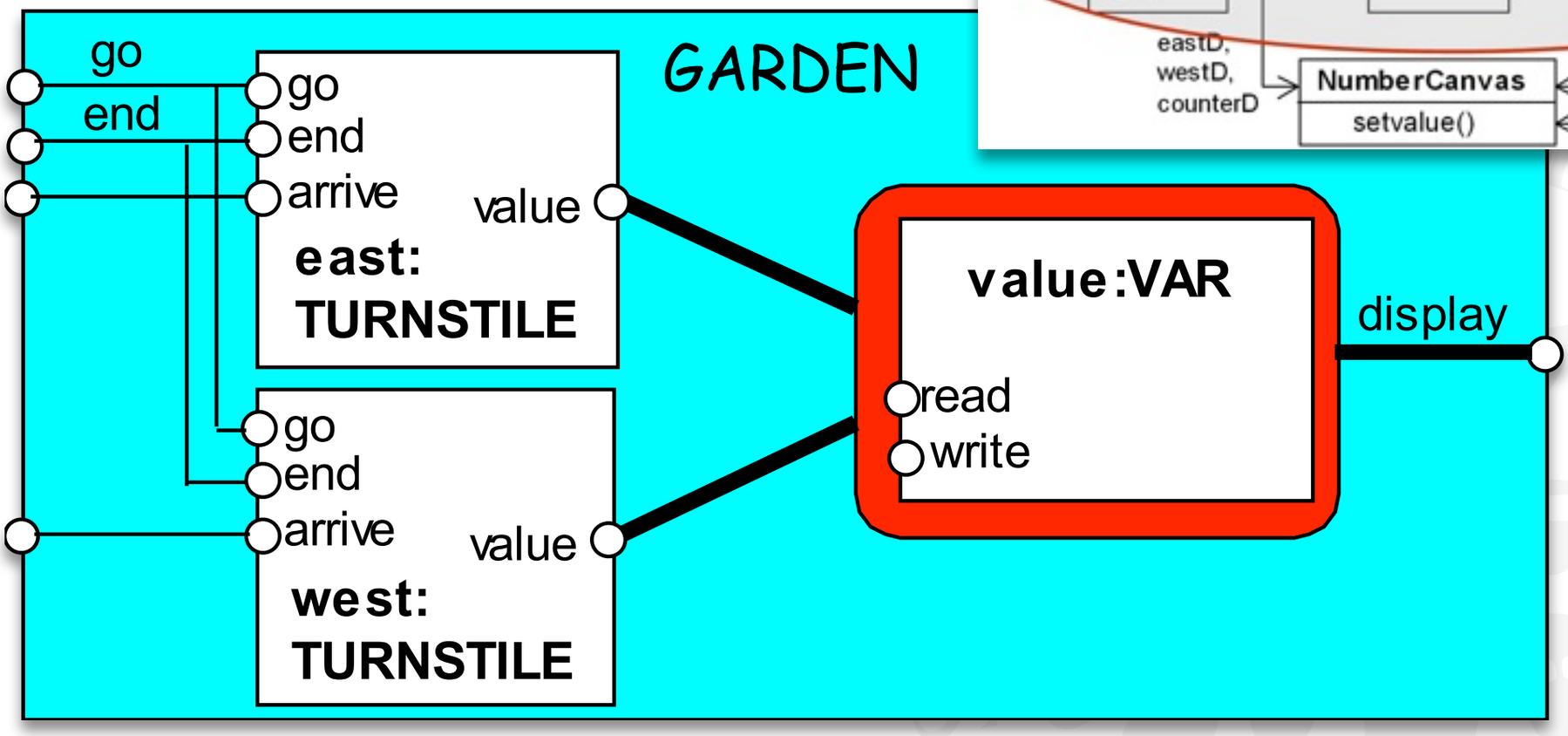
```
class Simulate {     // randomly force thread switch!
    public static void HWinterrupt() {
        if (random()<0.5) Thread.yield();
    }
}
```

Running The Applet

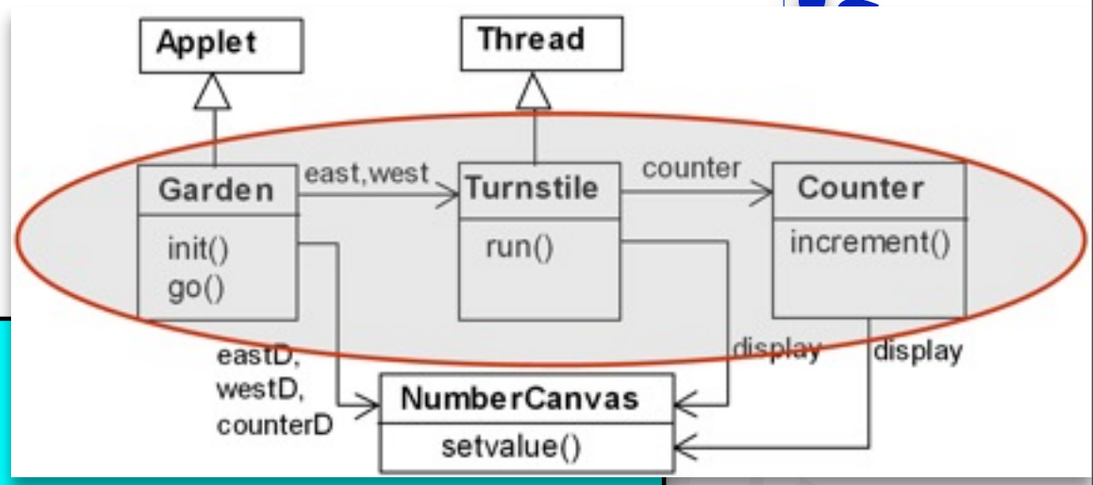
Now the erroneous behaviour occurs almost all the time!

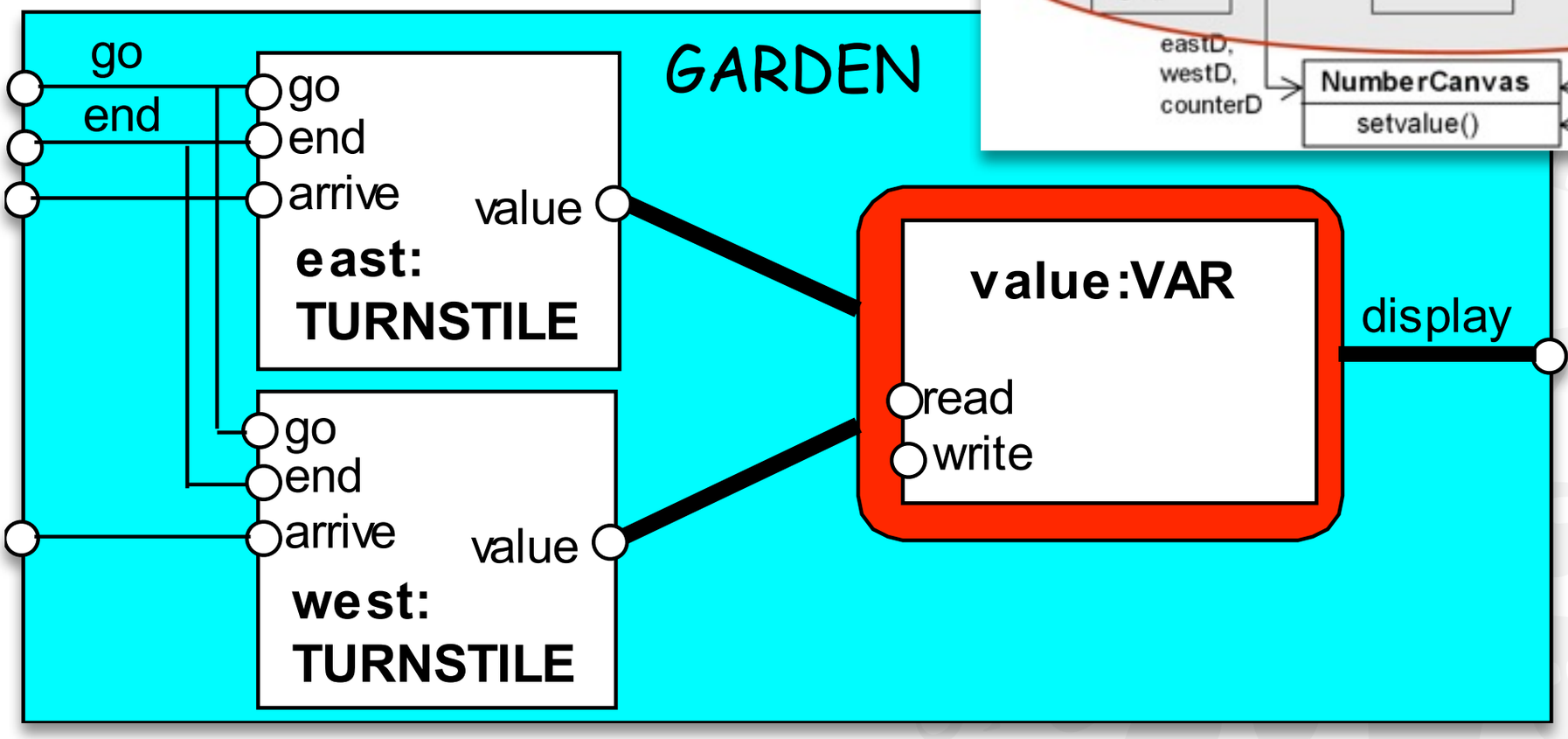
Garden Model (Structure Diagram)





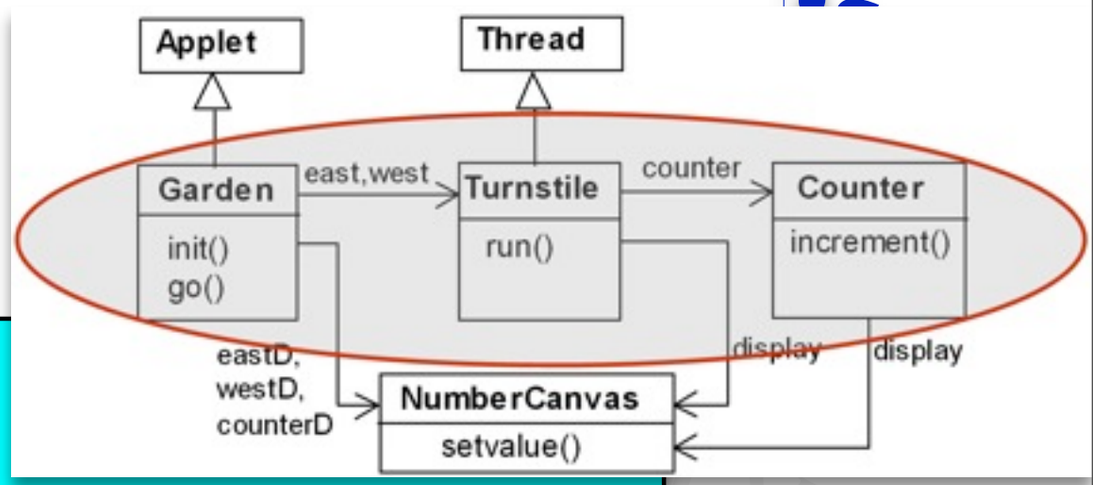
Garden Model (Structure Diagram)

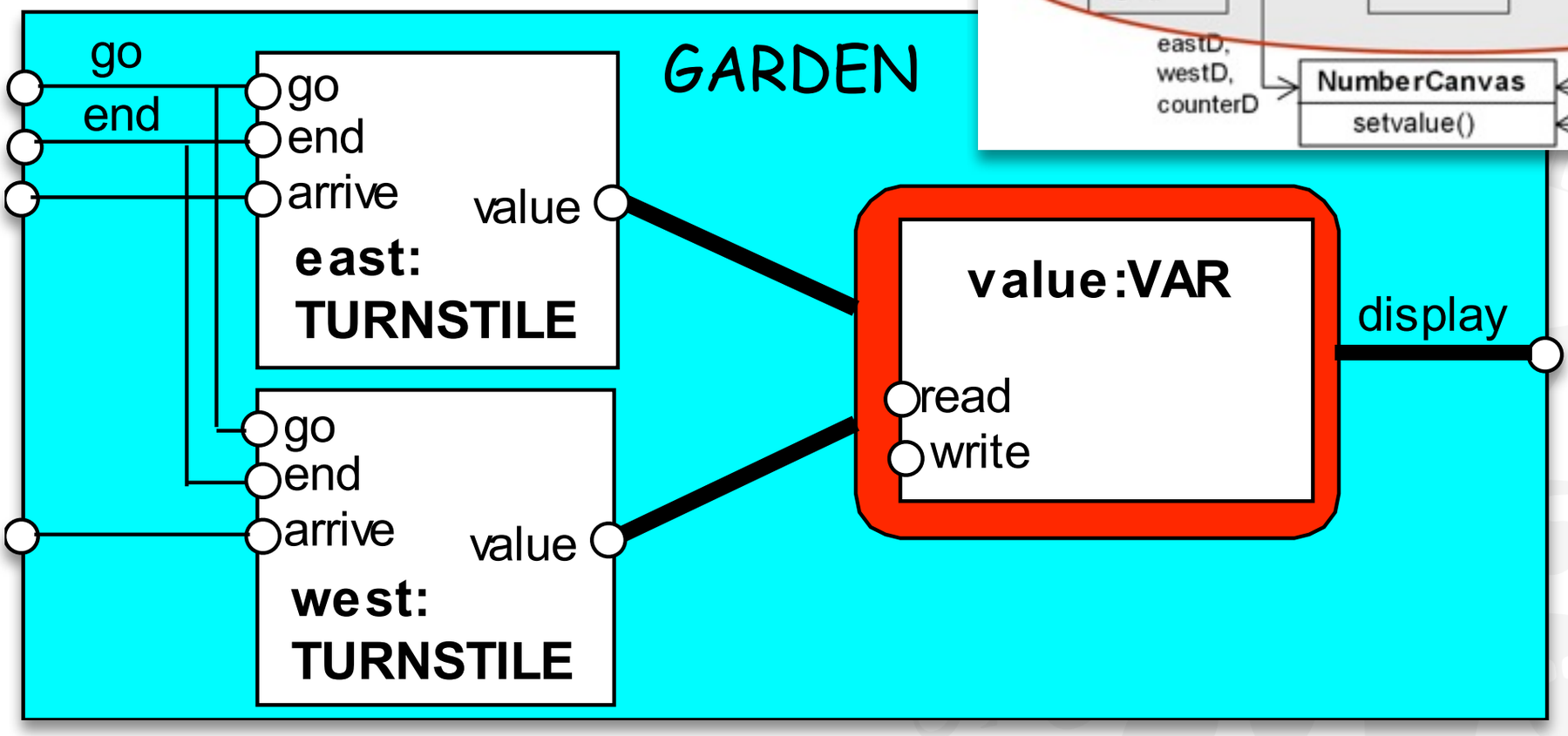




VAR:
models read and write access to the shared counter **`value`**.

Garden Model (Structure Diagram)

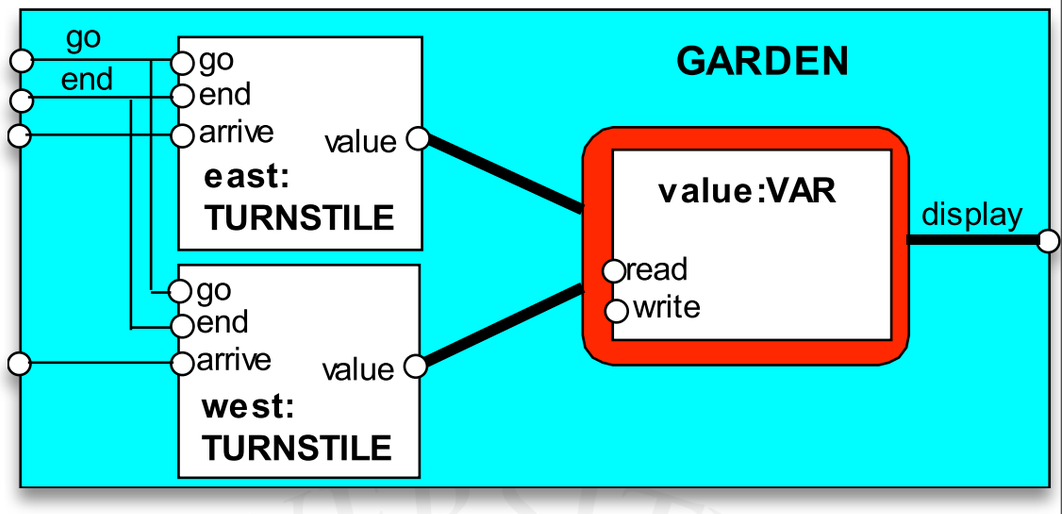




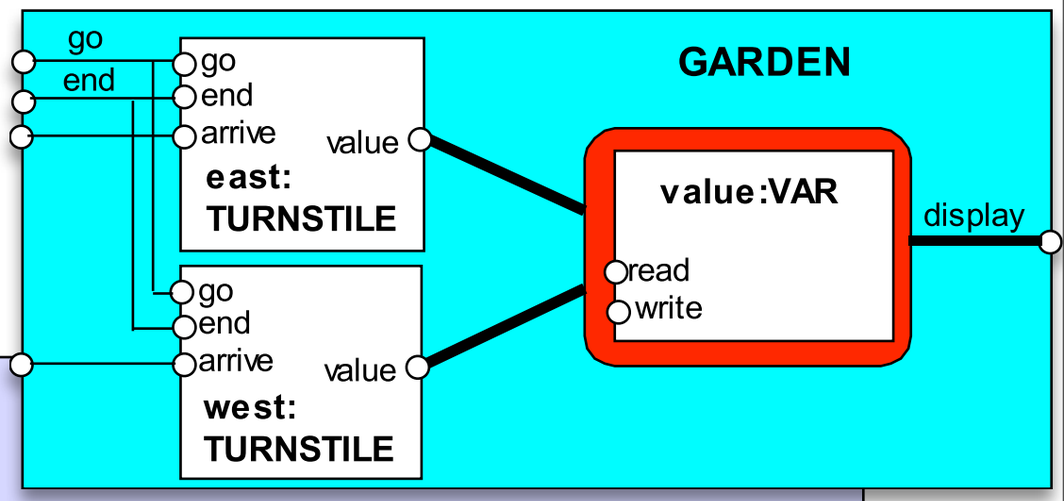
VAR:
models read and write access to the shared counter **`value`**.

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)

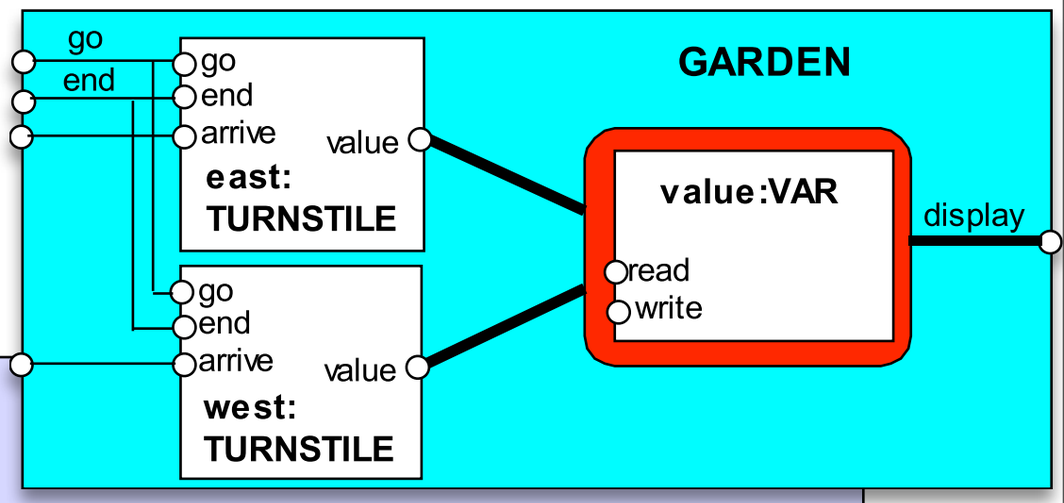


Ornamental Garden Model (FSP)




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

Ornamental Garden Model (FSP)




```
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VAR       = VAR[0],
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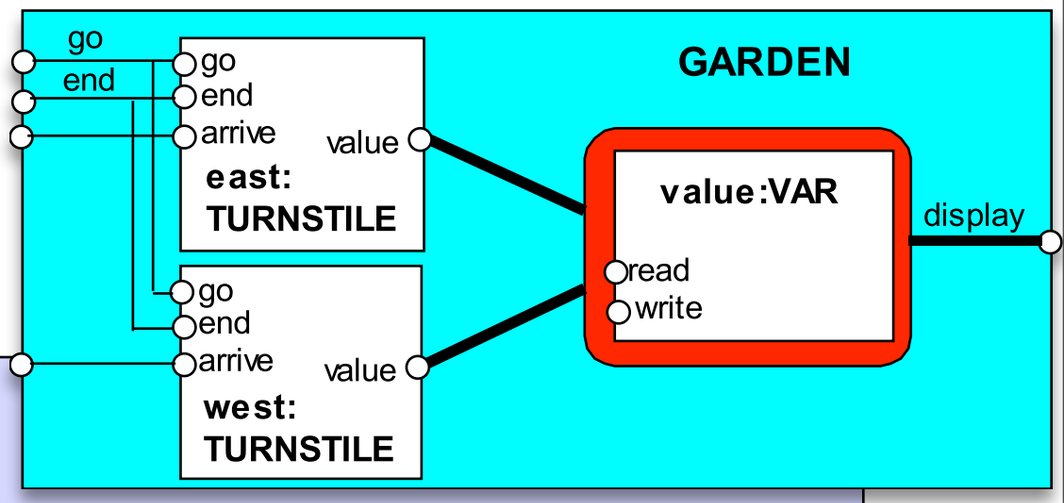
```

Ornamental Garden Model (FSP)

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TURNSTILE = (go -> RUN),
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INCREMENT = (value.read[x:T] -> value.write[x+1] -> RUN)
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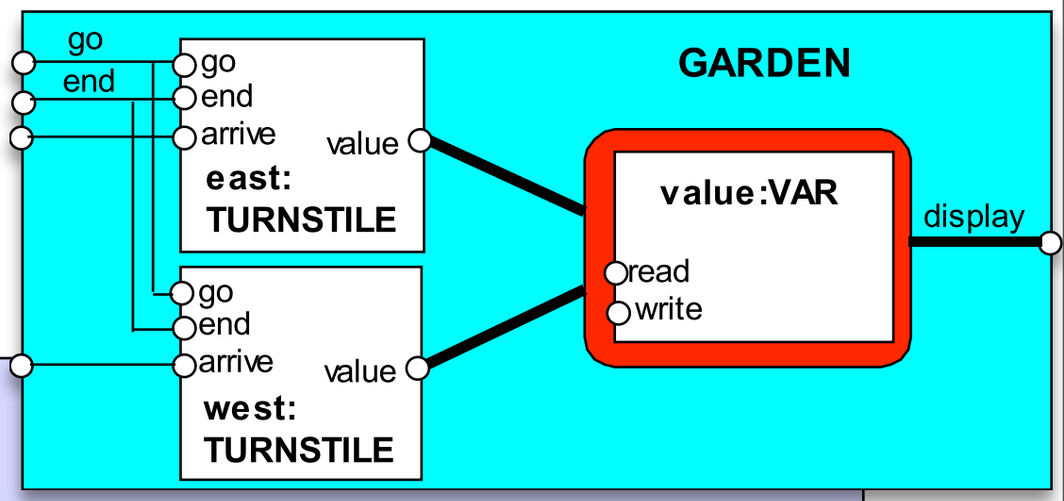
Ornamental Garden Model (FSP)

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                                        +{value.write[0]}.
```

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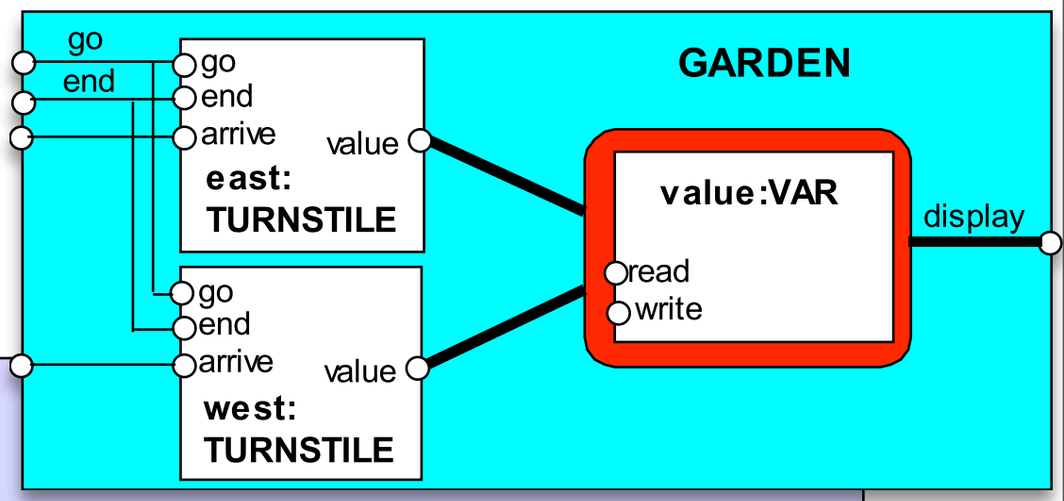


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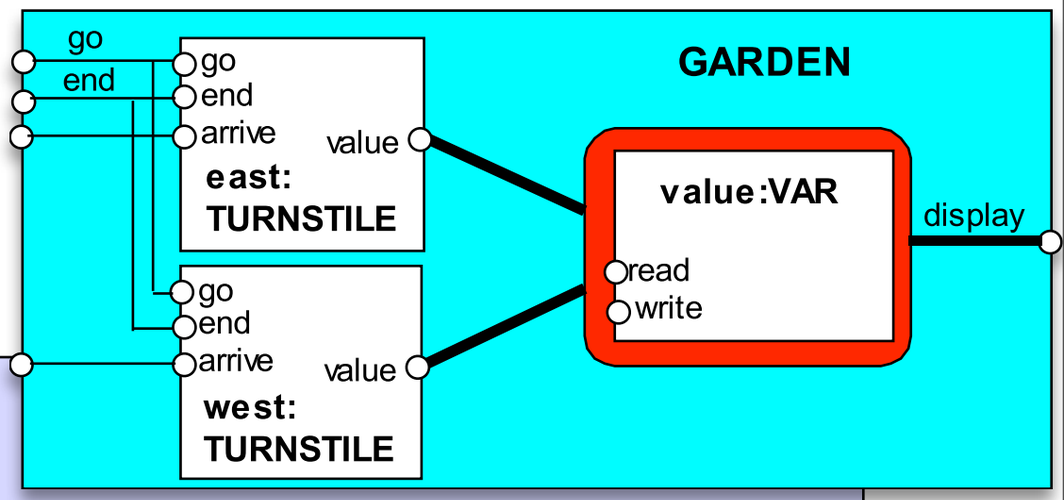
                                        +{value.write[0]}.

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

Ornamental Garden Model (FSP)

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

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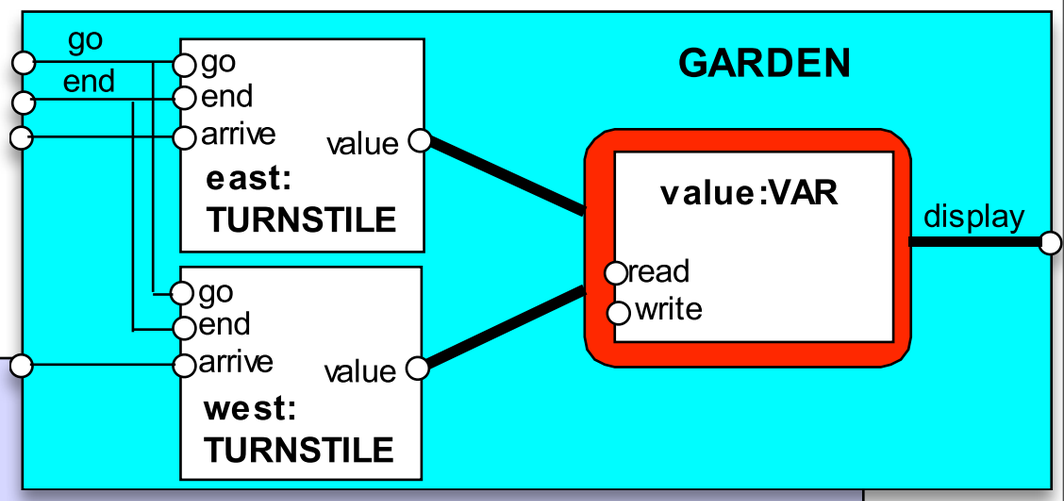

Ornamental Garden Model (FSP)

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

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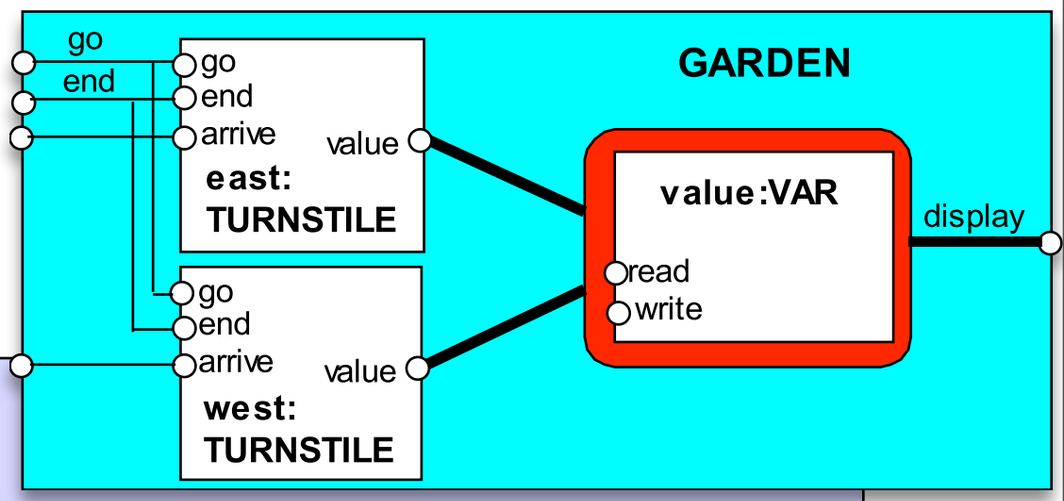
```

Ornamental Garden Model (FSP)

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      /{ go / {east,west}.go , end / {east,west}.end}.
```
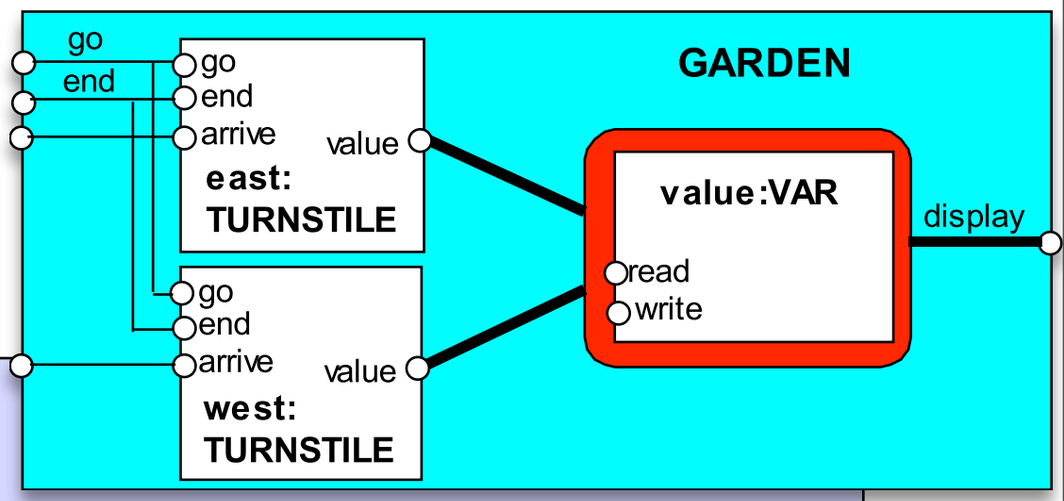

α(VAR) ?

Ornamental Garden Model (FSP)

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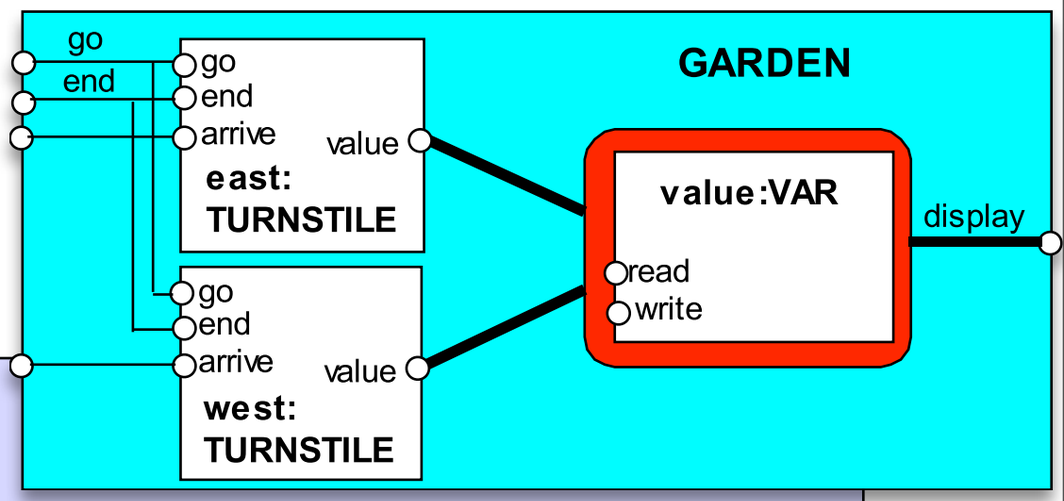
```

α(VAR) ?

α(value:VAR) ?

Ornamental Garden Model (FSP)

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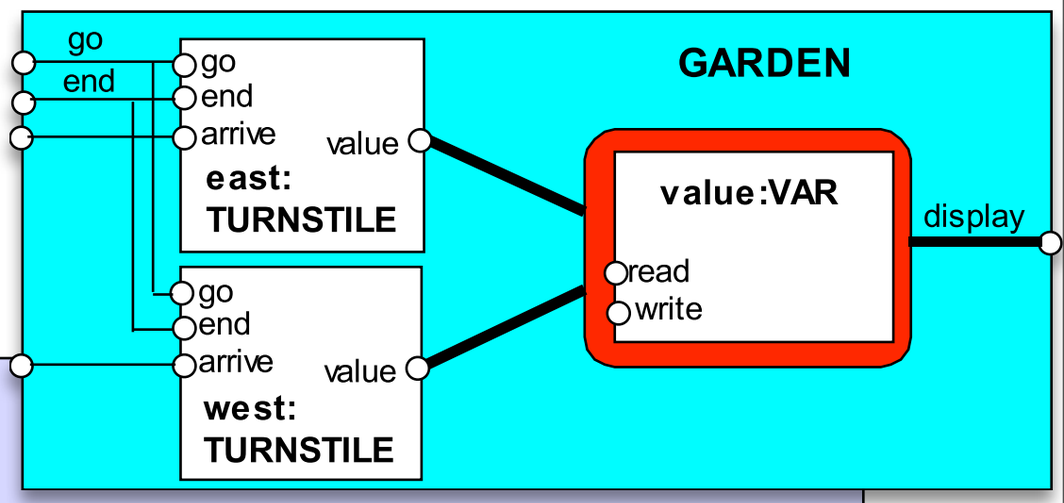
α(VAR) ?

α(value:VAR) ?

α({east,west,display}::value:VAR) ?

Ornamental Garden Model (FSP)

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```

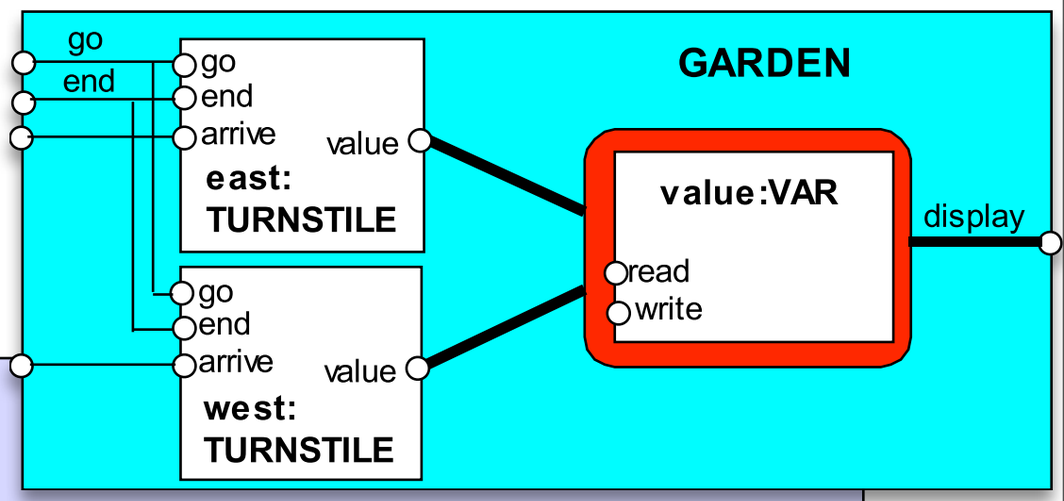
α(VAR) ?

α(value:VAR) ?

α({east,west,display}::value:VAR) ?

α(TURNSTILE) ?

Ornamental Garden Model (FSP)

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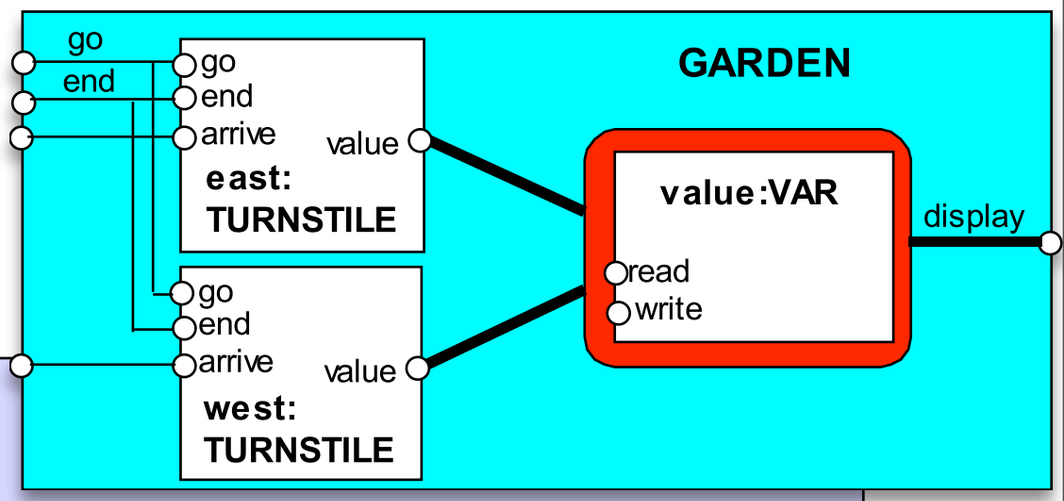
α(VAR) ? α(value:VAR) ? α({east,west,display}::value:VAR) ?

α(TURNSTILE) ? α(east:TURNSTILE) ?

Ornamental Garden Model (FSP)

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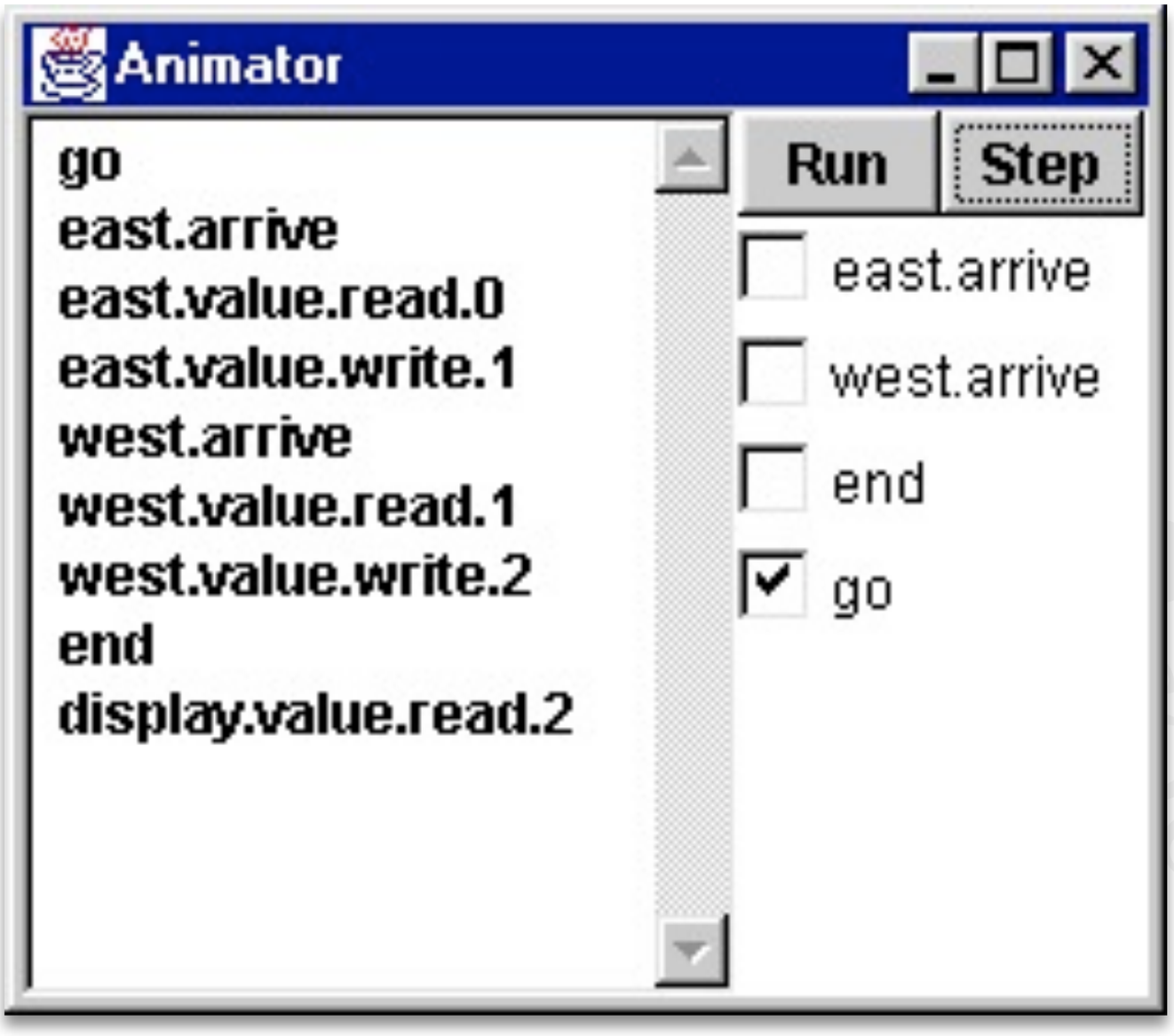
```

α(VAR) ? α(value:VAR) ? α({east,west,display}::value:VAR) ?

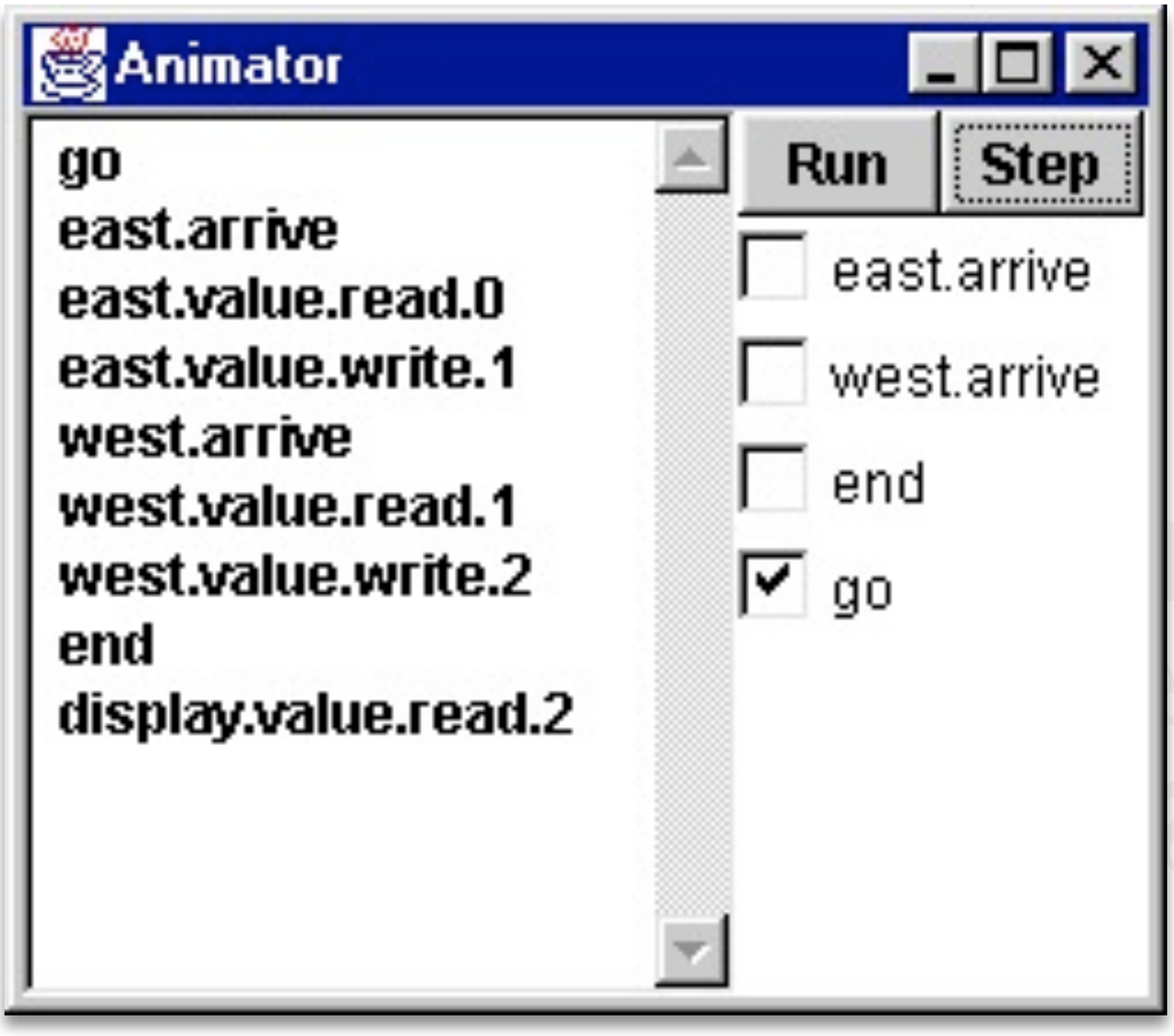
α(TURNSTILE) ? α(east:TURNSTILE) ? α(display:DISPLAY) ?

Checking For Errors - Animation



Scenario checking - use animation to produce a trace.

Checking For Errors - Animation



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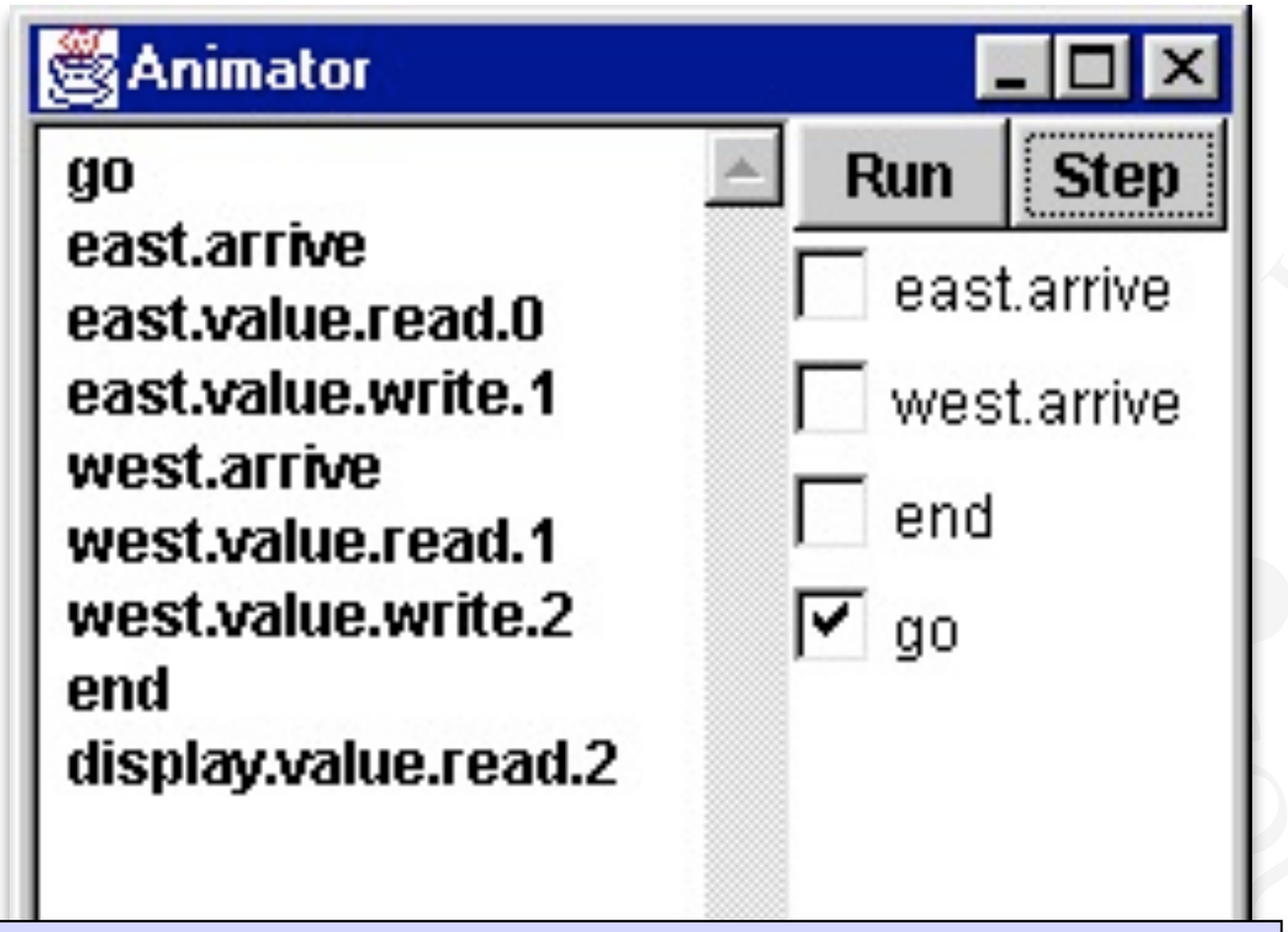
Checking For Errors - Animation



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:

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```
TEST          = TEST[0],

TEST[v:T]     = (when (v<N) west.arrive->TEST[v+1]
                |when (v<N) east.arrive->TEST[v+1]
                |end -> CHECK[v]),
```

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:

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TEST[v:T]     = (when (v<N) west.arrive->TEST[v+1]
                |when (v<N) east.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)).
```

Checking For Errors - Exhaustive Analysis

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

Use **LTSA** to perform an exhaustive search for **ERROR**:

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
```

Checking For Errors - Exhaustive Analysis


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

Use **LTSA** to perform an exhaustive search for **ERROR**:

```
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    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**.

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Interference And Mutual Exclusion

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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`**.

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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 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

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The Java compiler inserts code to:

- acquire the lock before executing a synchronized method
- release the lock after the synchronized method returns.

Concurrent threads are blocked until the lock is released.

Java `Synchronized` Statement

Synchronized methods:

```
synchronized void increment() {
    super.increment();
}
synchronized void decrement() {
    super.decrement();
}
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synchronized void increment() {
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Variant - the synchronized statement :

```
class Turnstile{
    ...
    public void run() {
    ...
        synchronized(counter) {
            counter.increment();
        }
    ...
```

Java `Synchronized` Statement

Synchronized methods:

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synchronized void increment() {
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object reference

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synchronized void increment() {
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Variant - the synchronized statement :

```
class Turnstile{
    ...
    public void run() {
    ...
        synchronized(counter) {
            counter.increment();
        }
    ...
```

object reference

Use synch methods whenever possible.

Java -> Java Bytecode

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```
1  class X {
2    int x;
3    void m() {
4      synchronized(this) {
5        x++;
6      }
7    }
8  }
```

Java -> Java Bytecode

```
1  class X {
2    int x;
3    void m() {
4      synchronized(this) {
5        x++;
6      }
7    }
8  }
```

compile

```
Method void m()
>> max_stack=3, max_locals=3 <<

    0 aload_0
    1 dup
    2 astore_1
    3 monitorenter
    4 aload_0
    5 dup
    6 getfield #2 <Field X.x:int>
    9 iconst_1
   10 iadd
   11 putfield #2 <Field X.x:int>
   14 aload_1
   15 monitorexit
   16 goto 24
   19 astore_2
   20 aload_1
   21 monitorexit
   22 aload_2
   23 athrow
   24 return


Exception table:
   from    to  target type
      4    16    19   any
     19    22    19   any
```

4.3 Modelling Mutual Exclusion

```
||GARDEN = (east:TURNSTILE || west:TURNSTILE || {east,west,display}::value:LOCKVAR)
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||GARDEN = (east:TURNSTILE || west:TURNSTILE || {east,west,display}::value:LOCKVAR)
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Define a mutual exclusion LOCK process:

```
LOCK = (acq -> rel -> LOCK).
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4.3 Modelling Mutual Exclusion

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||GARDEN = (east:TURNSTILE || west:TURNSTILE || {east,west,display}::value:LOCKVAR)
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LOCK = (acq -> rel -> LOCK).
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...and compose it with the shared VAR in the Garden:

```
||LOCKVAR = (LOCK || VAR).
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Define a mutual exclusion LOCK process:

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

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

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

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 )+{value.write[0]}.
```

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
```

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"?

COUNTER: Abstraction Using Action Hiding

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```
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]
                -> write[x+1]
                -> release->increment->INCREMENT)
                    +{read[T],write[T]}.

||COUNTER = (INCREMENT||LOCK||VAR)@{increment}.
```

COUNTER: Abstraction Using Action Hiding

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]
                -> write[x+1]
                -> release->increment->INCREMENT)
                    +{read[T],write[T]}.

||COUNTER = (INCREMENT||LOCK||VAR)@{increment}.
```

COUNTER: Abstraction Using Action Hiding

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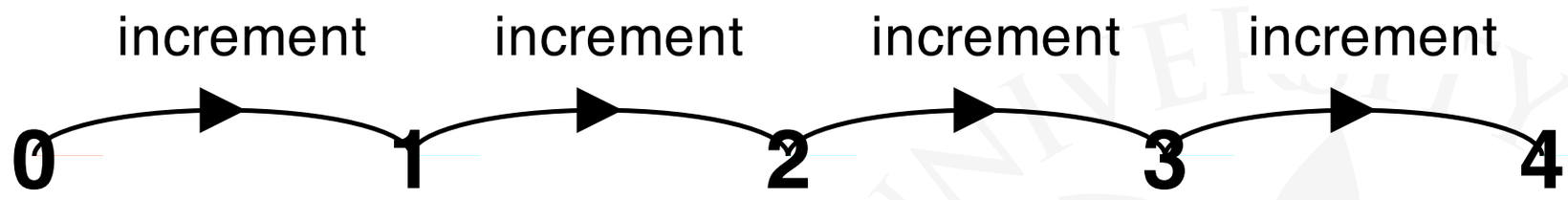
```
COUNTER = COUNTER[0]
COUNTER[v:T] = (when (v<N) increment -> COUNTER[v+1]).
```

COUNTER: Abstraction Using Action Hiding

Minimised LTS:

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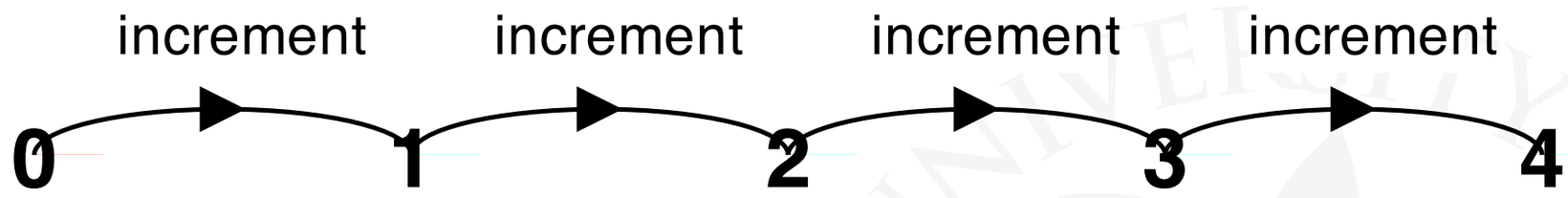

We can give a more abstract, simpler description of a **COUNTER** which generates the same LTS:

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COUNTER = COUNTER[0]
COUNTER[v:T] = (when (v<N) increment -> COUNTER[v+1]).
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COUNTER: Abstraction Using Action Hiding

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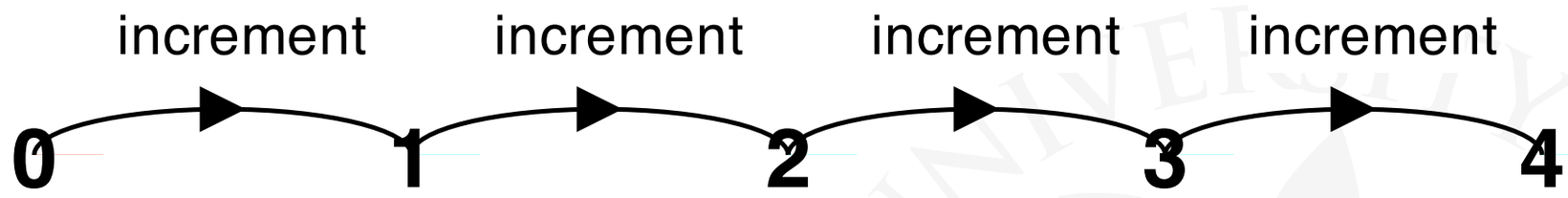

We can give a more abstract, simpler description of a **COUNTER** which generates the same LTS:

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

This therefore exhibits "equivalent" behaviour, i.e., has the same observable behaviour.

Active & Passive Processes

Active & Passive Processes

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Comparing FSP and Java

- active processes : threads, e.g., TURNSTILE
- passive processes: shared objects, e.g., COUNTER

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

VAR = VAR[0], VAR[u:T] = (read[u]->VAR[u] | write[v:T]->VAR[v]).
LOCK = (acquire->release->LOCK).
||LOCKVAR = (LOCK || VAR).

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

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

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

Java Memory Model


```
public class NoVisibility {
    private static boolean ready;
    private static int number;

    private static class ReaderThread extends Thread {
        public void run() {
            while (!ready) {
                yield();
            }
            System.out.println(number);
        }
    }

    public static void main(String[] args) {
        new ReaderThread().start();
        number = 42;
        ready = true;
    }
}
```

Synchronisation In Java Is Not Just Mutual Exclusion; It's Also About Memory Visibility

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Thread A

```
y=1
lock M
x=1
unlock M
```

Everything before the unlock on M

Without synchronisation, there is no such guarantee.

Synchronisation In Java Is Not Just Mutual Exclusion; It's Also About Memory Visibility

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Thread A

y=1
lock M
x=1
unlock M

Everything before the unlock on M

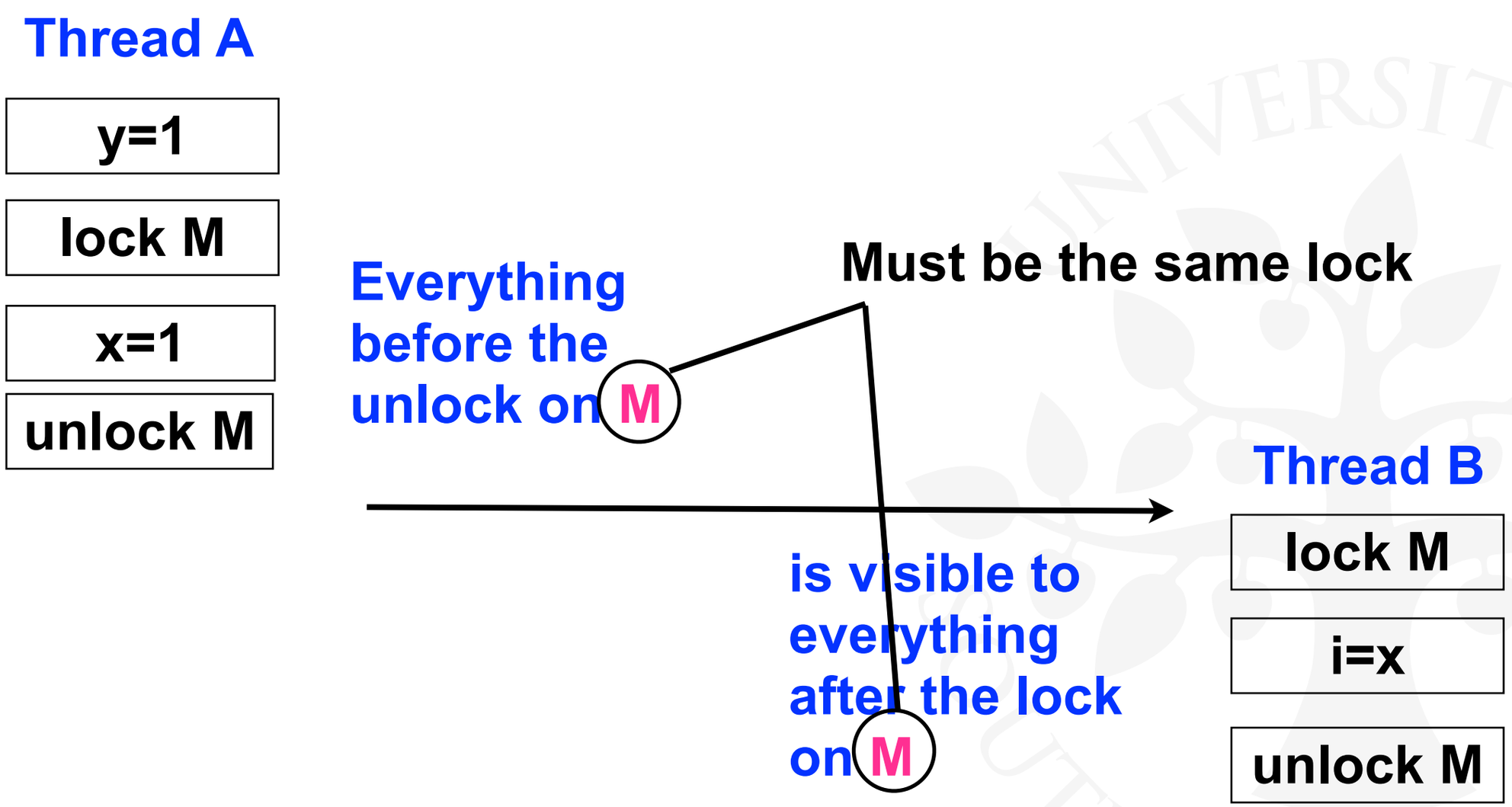
is visible to everything after the lock on M

Thread B

lock M
i=x
unlock M
j=y

Without synchronisation, there is no such guarantee.

Synchronisation In Java Is Not Just Mutual Exclusion; It's Also About Memory Visibility



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