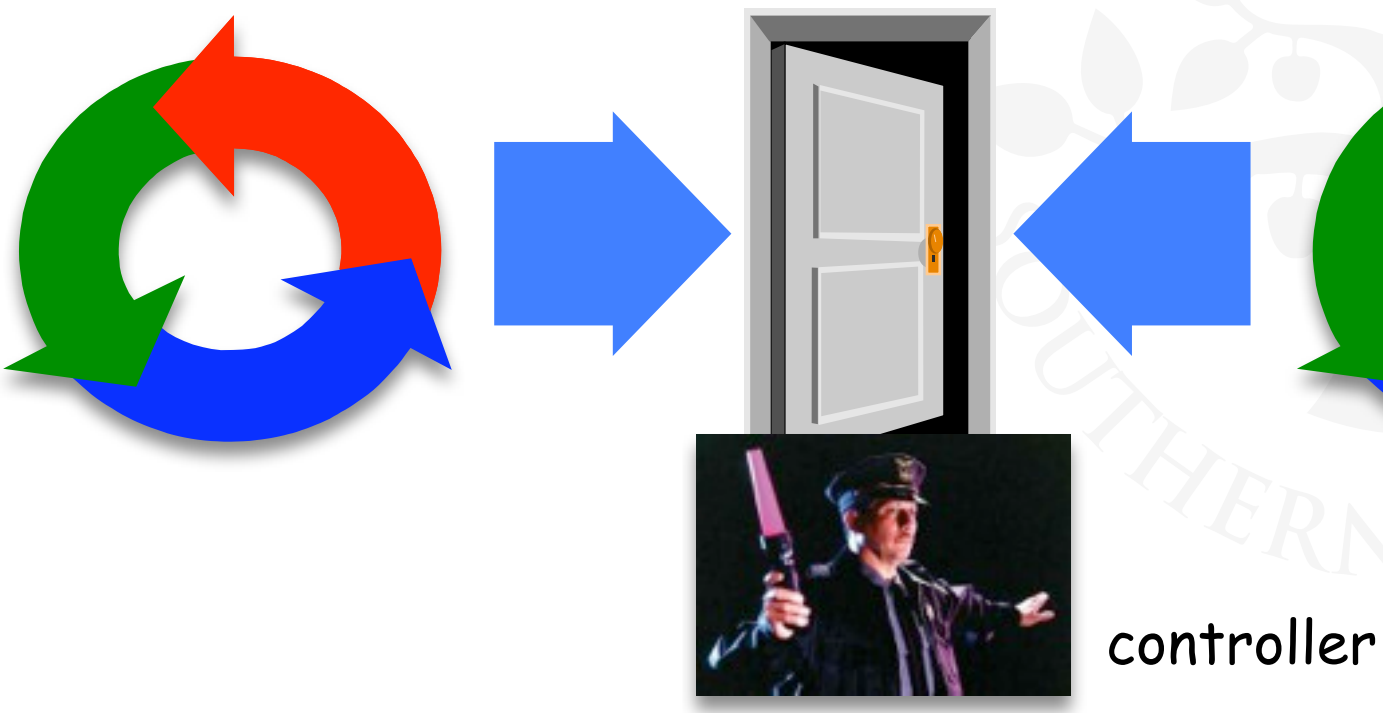
Chapter 5

University of Southern Denmark

Monitors & Condition Synchronisation



Monitors & Condition Synchronisation

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Concepts: monitors (and controllers):

Monitors & Condition Synchronisation

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encapsulated data + access procedures +

Monitors & Condition Synchronisation

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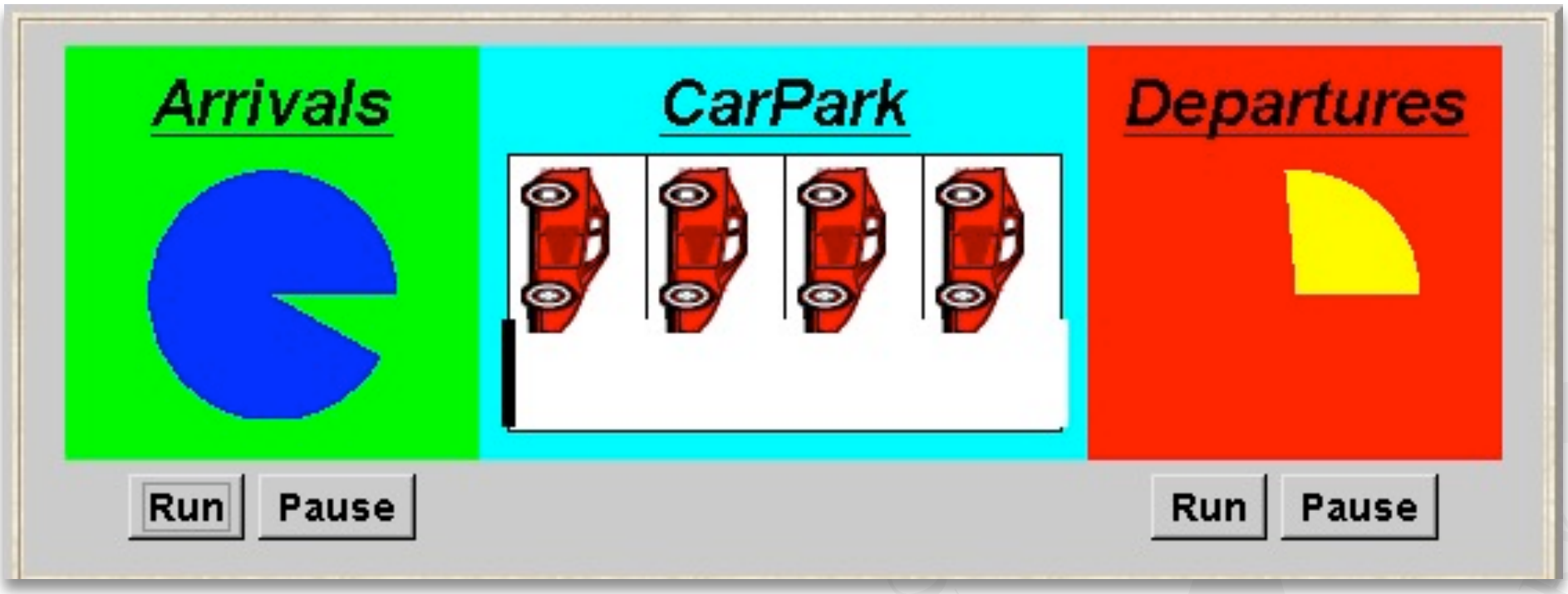
wait(), notify() and notifyAll() for condition synchronisation
single thread active in the monitor at a time

Condition Synchronisation

5.1 Condition Synchronisation (Car Park)



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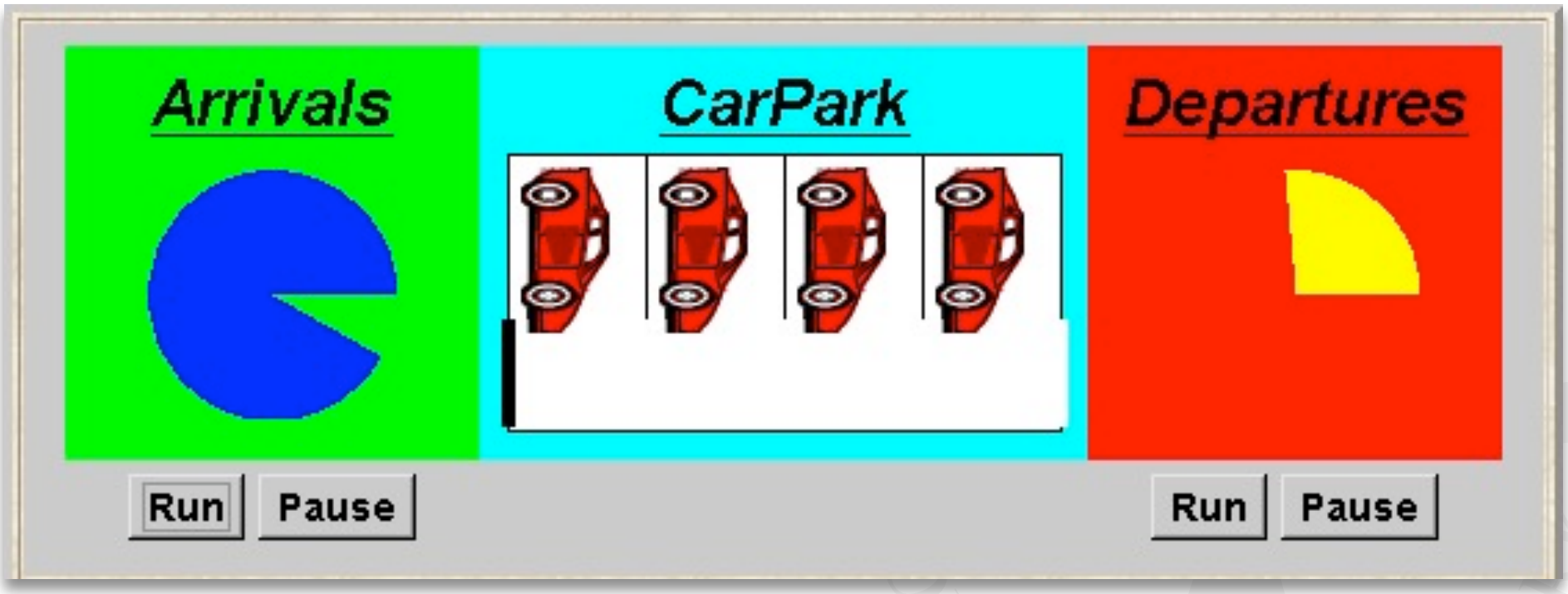

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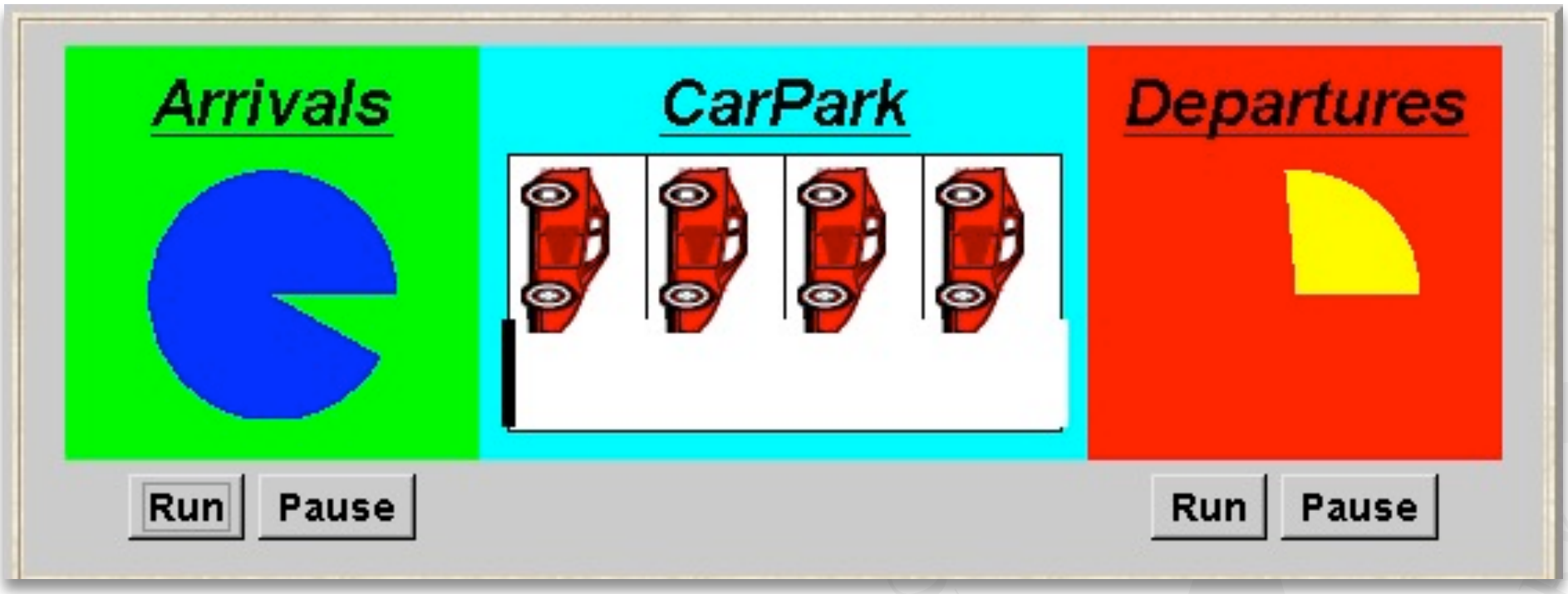

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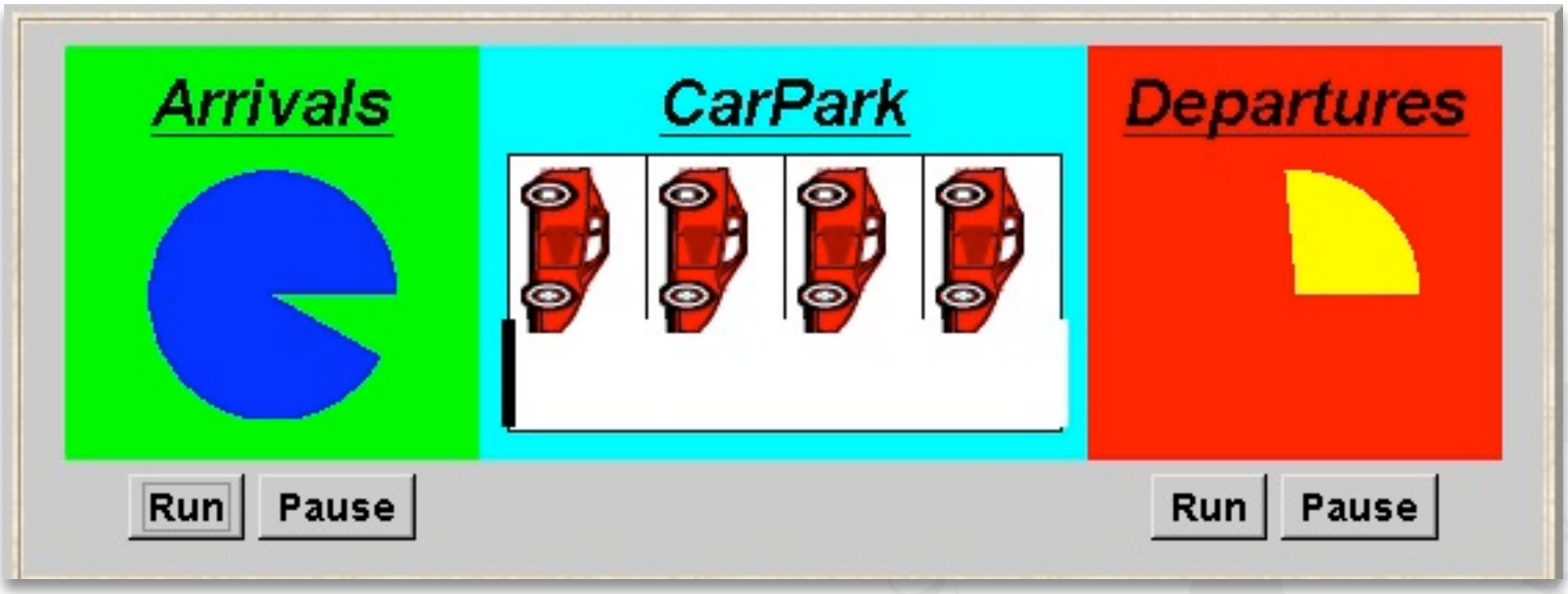

A controller is required to ensure:

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Car Park Model (Actions and Processes)

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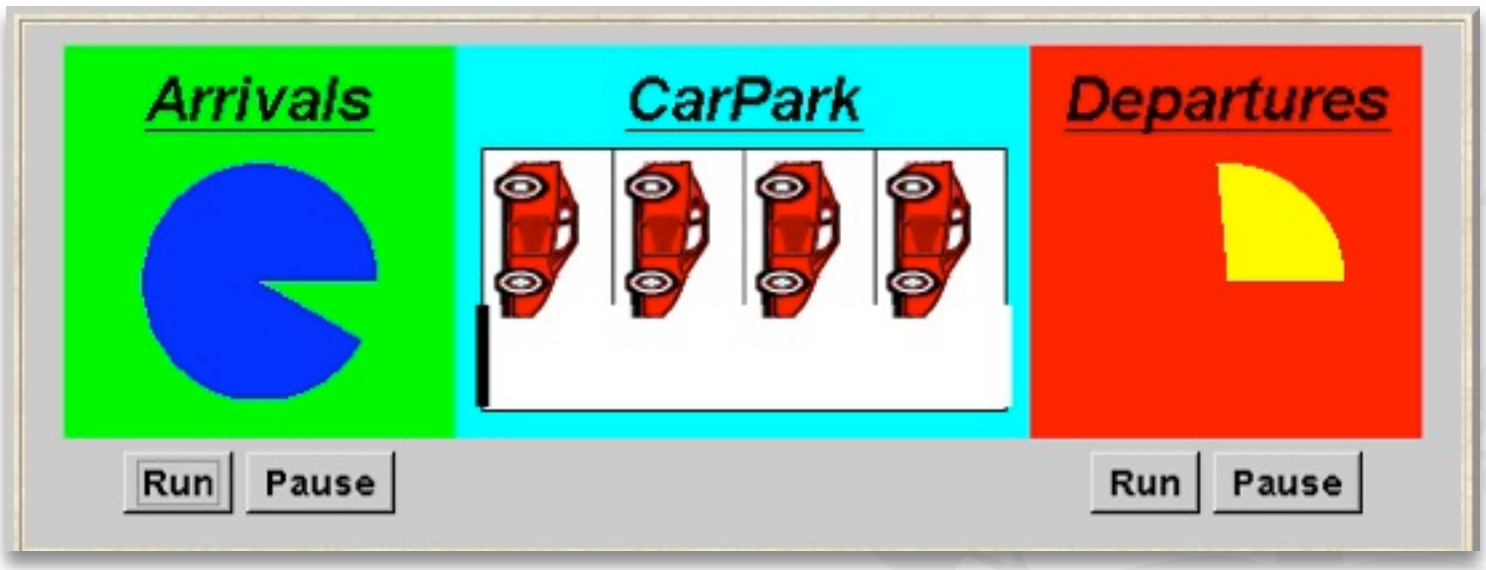

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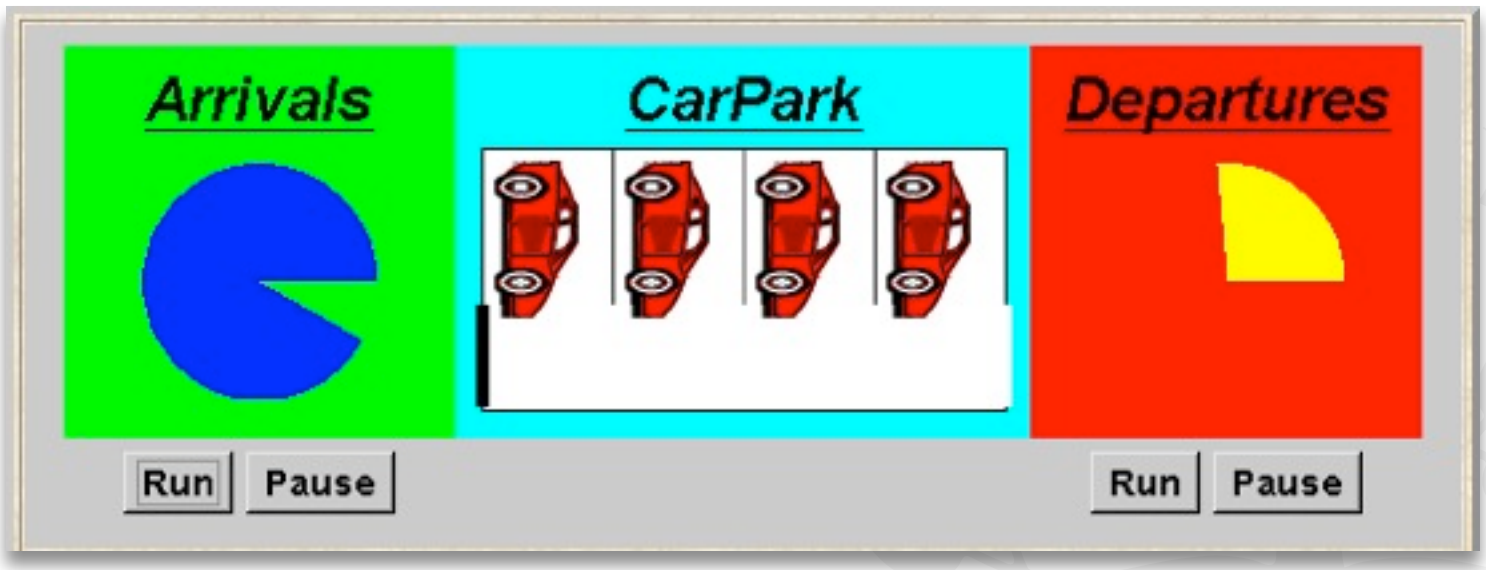

- Actions of interest:

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Car Park Model (Actions and Processes)

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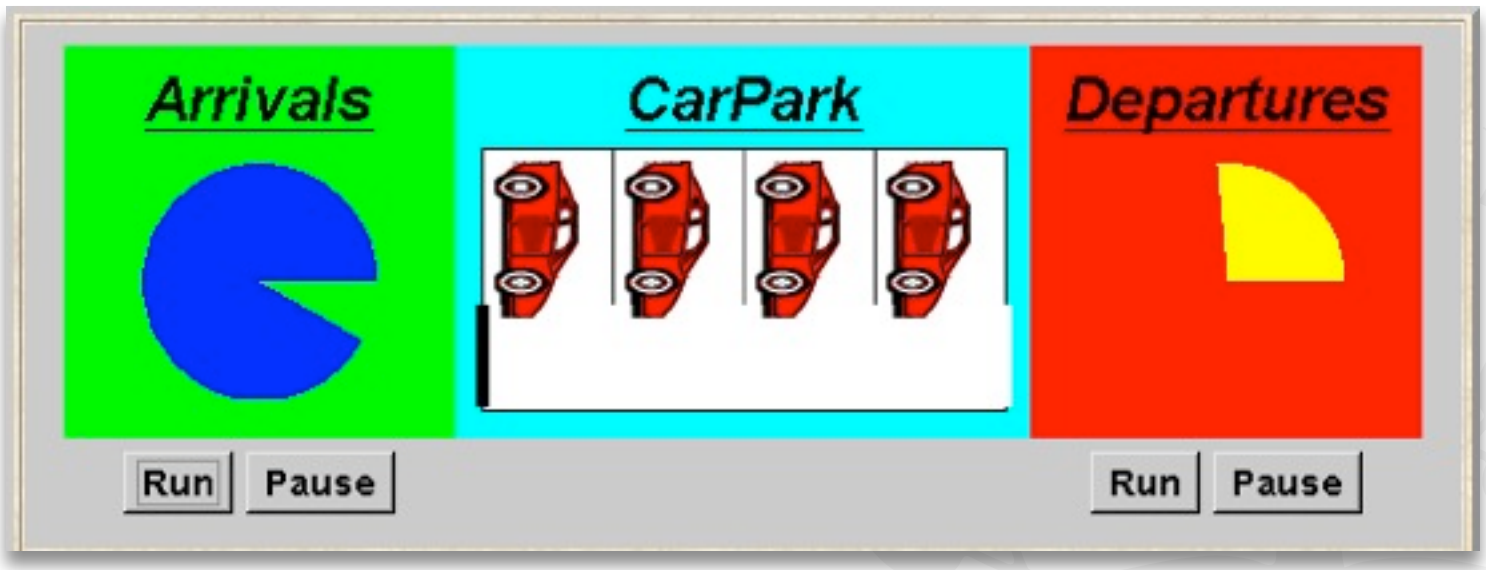

- Actions of interest:
  - `arrive`

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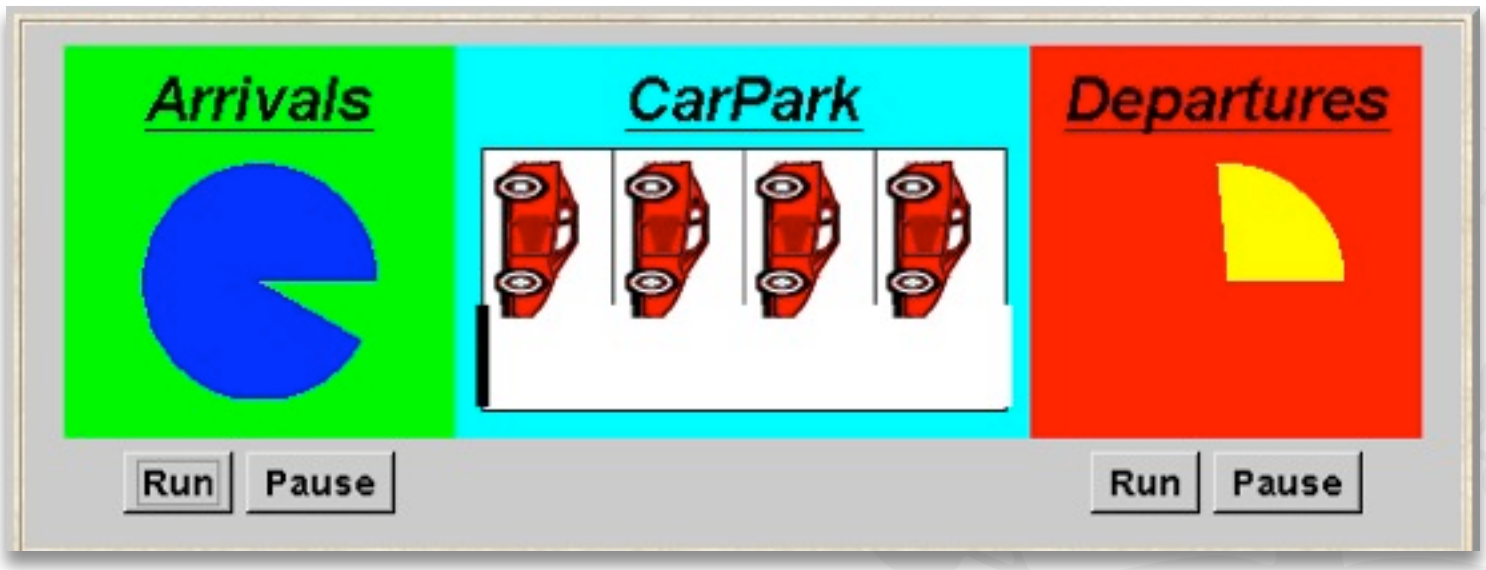
Car Park Model (Actions and Processes)

University of Southern Denmark



- Actions of interest:
  - arrive
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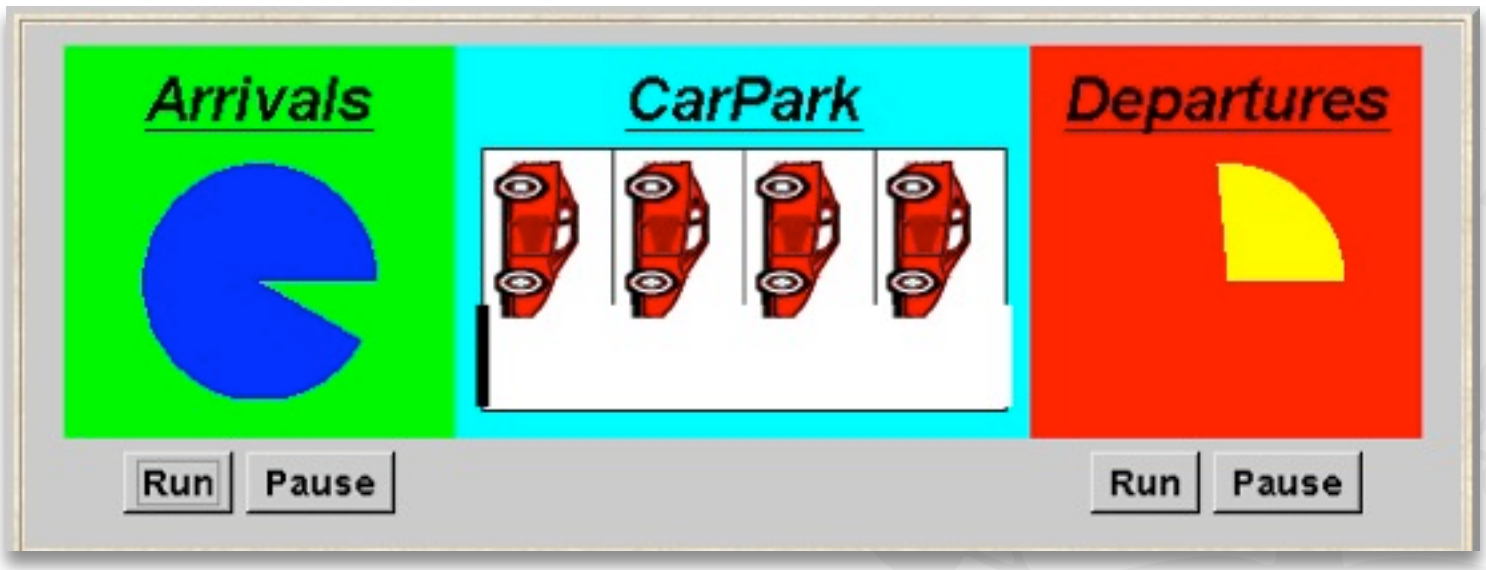

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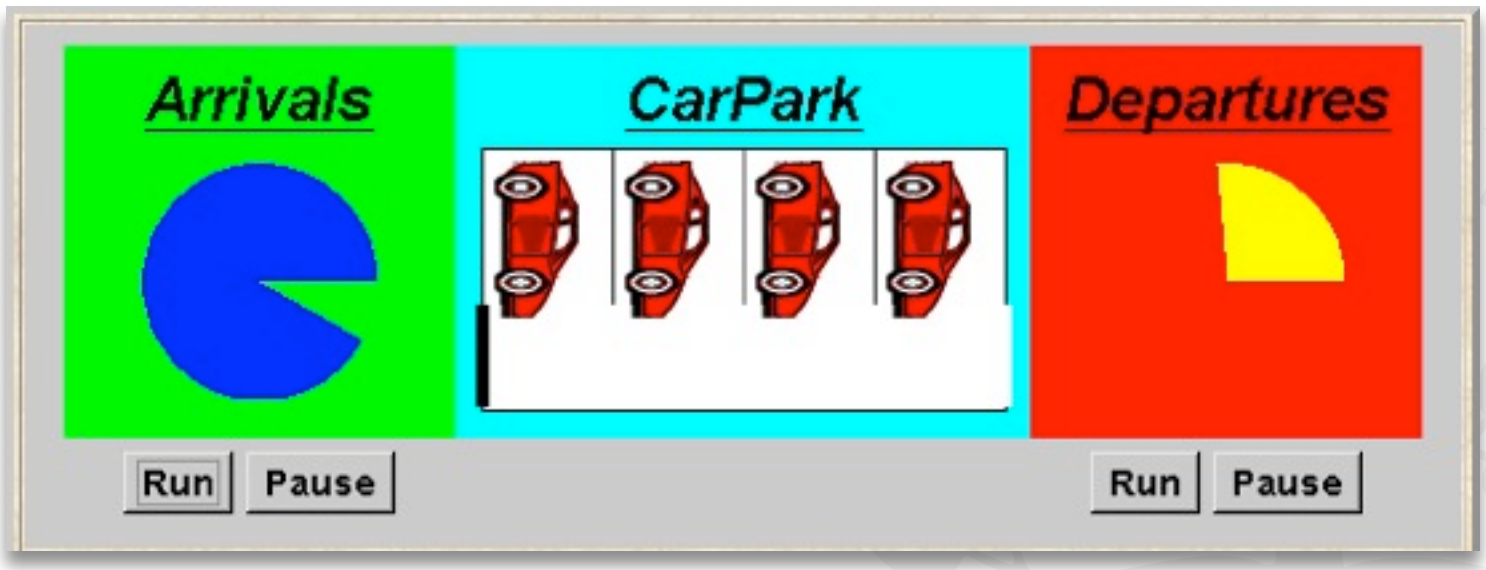

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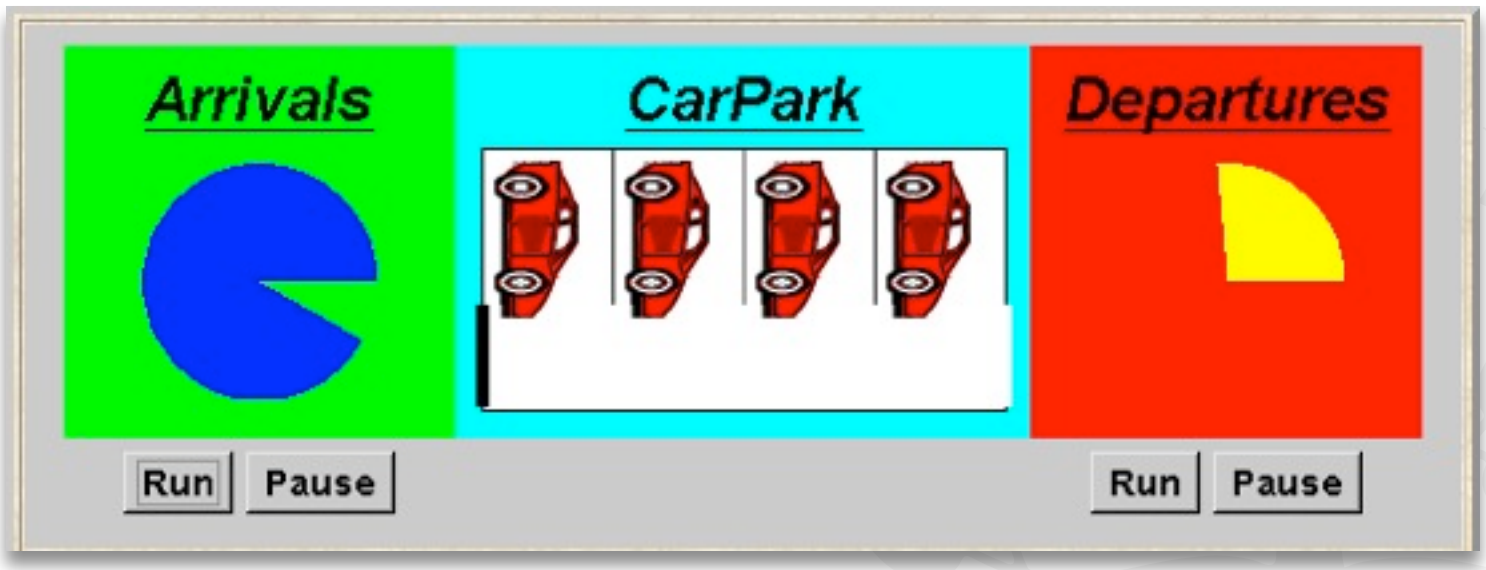

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- Processes:
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Car Park Model (Structure Diagram)

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University of Southern Denmark

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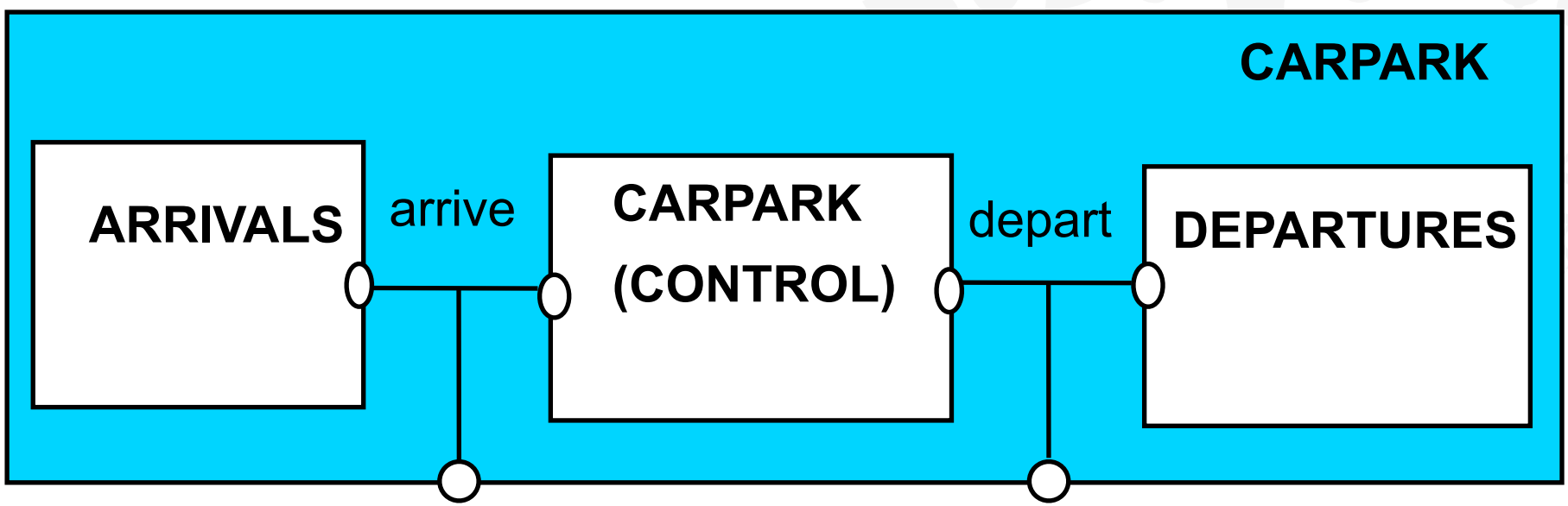
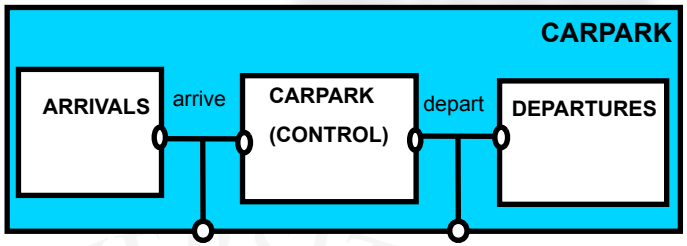


Car Park Model (FSP)



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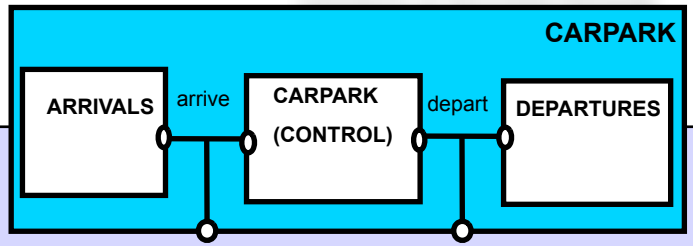


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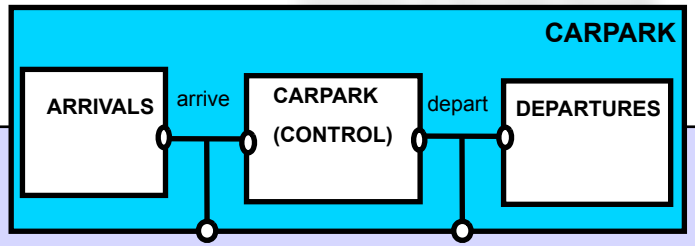
University of Southern Denmark

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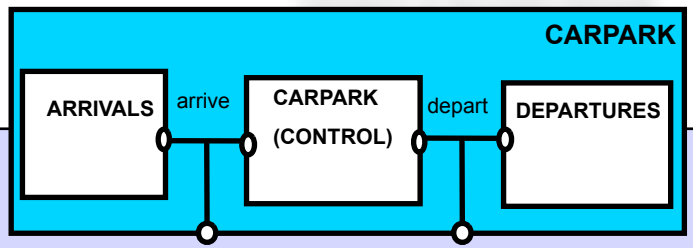


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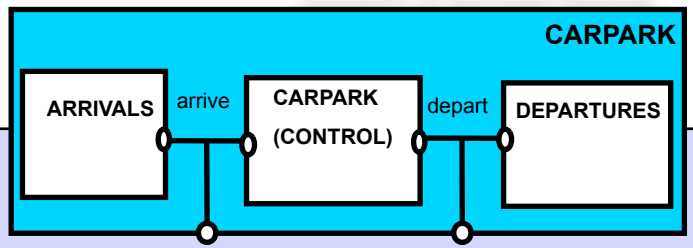


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Guarded actions are used to control **arrive** and **depart**

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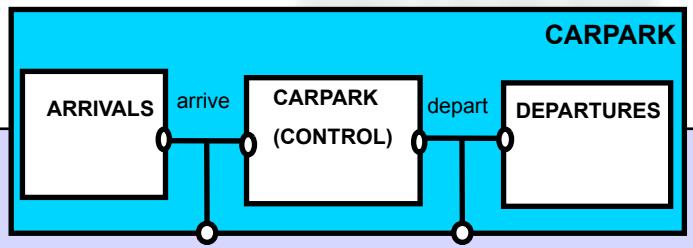


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LTS?

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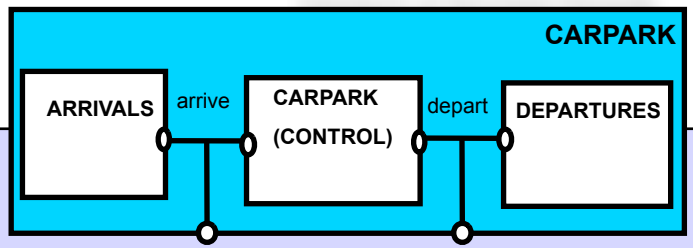


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Guarded actions are used to control **arrive** and **depart**

LTS?

What if we **remove ARRIVALS and DEPARTURES?**

Car Park Program

Car Park Program

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- Model:
  - all entities are processes interacting via **shared actions**

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  we need to identify threads and monitors:
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For the carpark?

- Arrivals:
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For the carpark?

- Arrivals: **active** => thread
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Car Park Program

University of Southern Denmark

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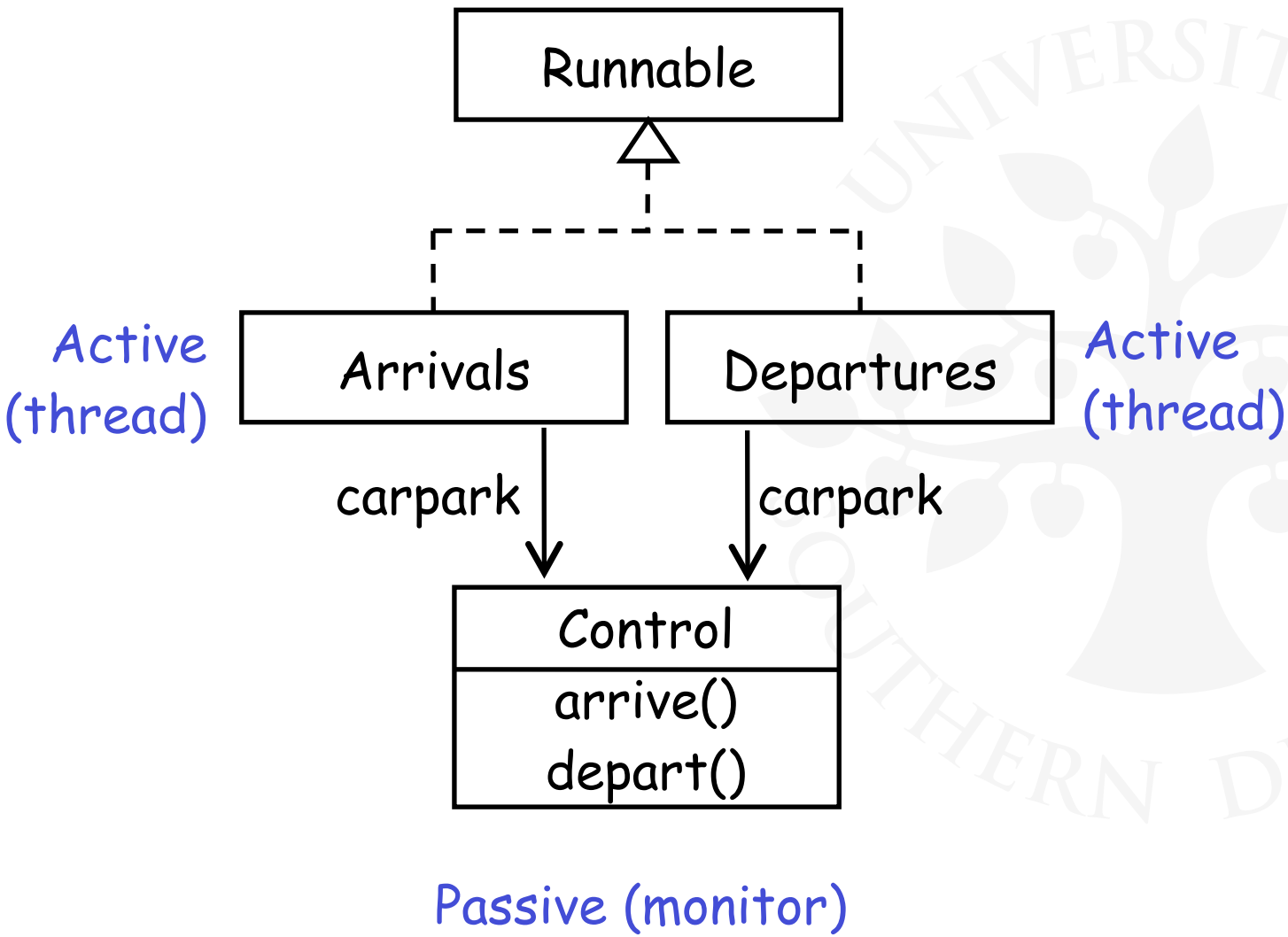
For the carpark?

• Arrivals:	**active**	=>	thread
• Departures:	**active**	=>	thread
• Control:	**passive**	=>	monitor

Car Park Program
(Interesting part of Class Diagram)



Car Park Program - `Main`

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The main() method creates:

- **Control** monitor
- **Arrivals** thread
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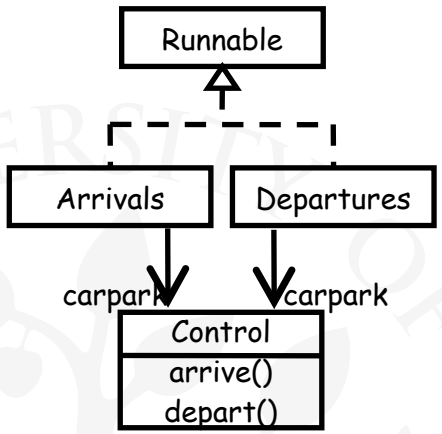

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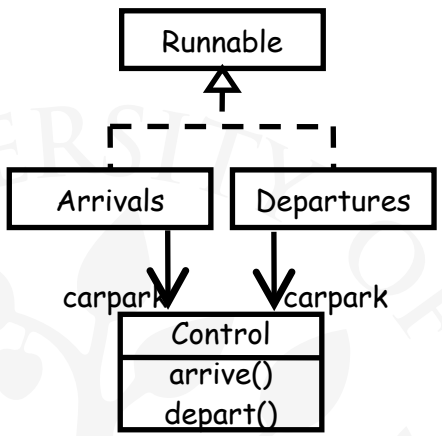


```
public static void main(String[] args) {
    Control c = new Control(CAPACITY);
    arrivals = new Thread(new Arrivals(c));
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    arrivals.start();
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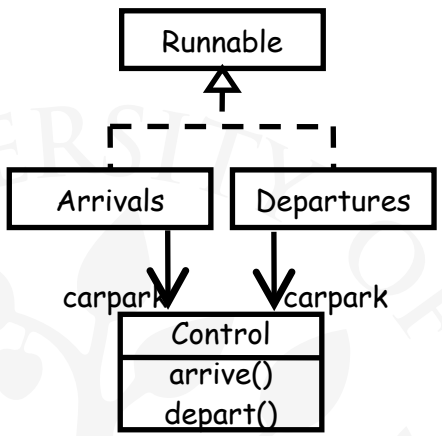


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The **Control** is shared by the **Arrivals** and **Departures** threads

Car Park Program - `Arrivals`

```
ARRIVALS = (arrive -> ARRIVALS).
```

```
class Arrivals implements Runnable {
    Control carpark;

    Arrivals(Control c) { carpark = c; }

    public void run() {
        try {
            while(true) {
                Thread.sleep(...);
                carpark.arrive();
            }
        } catch (InterruptedException _) {}
    }
}
```

... similar for Departures (calling *carpark.depart()*)

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Would like to somehow block Arrivals thread here…

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How do we implement the Carpark **Controller**'s control?

Control Monitor

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```

```
class Control {
                static final int CAPACITY;
                int spaces;

    Control(int n) {
        CAPACITY = spaces = n;
    }

                    void arrive() {
        ... --spaces; ...
    }

                    void depart() {
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Encapsulation

~ protected

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Encapsulation
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Mutual exclusion ~
synchronized

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Encapsulation
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Mutual exclusion ~ synchronized

Condition synchronisation:

Control Monitor

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Mutual exclusion ~ synchronized

Condition synchronisation:

Block, if full?
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Encapsulation
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Mutual exclusion ~ synchronized

Condition synchronisation:

Block, if full?
¬(spaces>0)

Block, if empty?
¬(spaces < CAPACITY)

Condition Synchronisation in Java

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Java provides one **thread wait queue** per **object** (not per class).

Condition Synchronisation in Java

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`Object` has the following methods:

Condition Synchronisation in Java

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Condition Synchronisation in Java

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```
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Waits to be notified ;
Releases the synchronisation lock associated with the object.

When notified, the thread must reacquire the synchronisation lock.

Condition Synchronisation in Java

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Java provides one **thread wait queue** per **object** (not per class).

`Object` has the following methods:

```
public final void wait() throws InterruptedException;
```

Waits to be notified ;
Releases the synchronisation lock associated with the object.

When notified, the thread must reacquire the synchronisation lock.

```
public final void notify();
```

```
public final void notifyAll();
```

Wakes up (notifies) thread(s) waiting on the object's queue.

Condition Synchronisation in Java (enter/exit)

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A thread:

- **Enters** a monitor when a thread acquires the lock associated with the monitor;
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Condition Synchronisation in Java (enter/exit)

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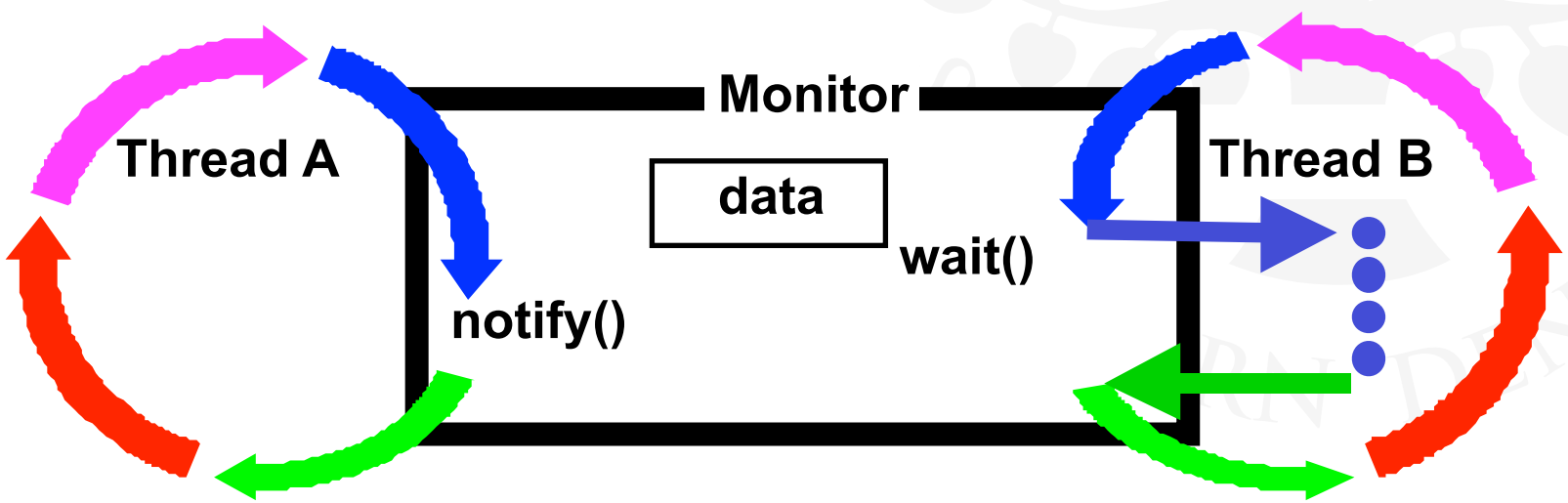
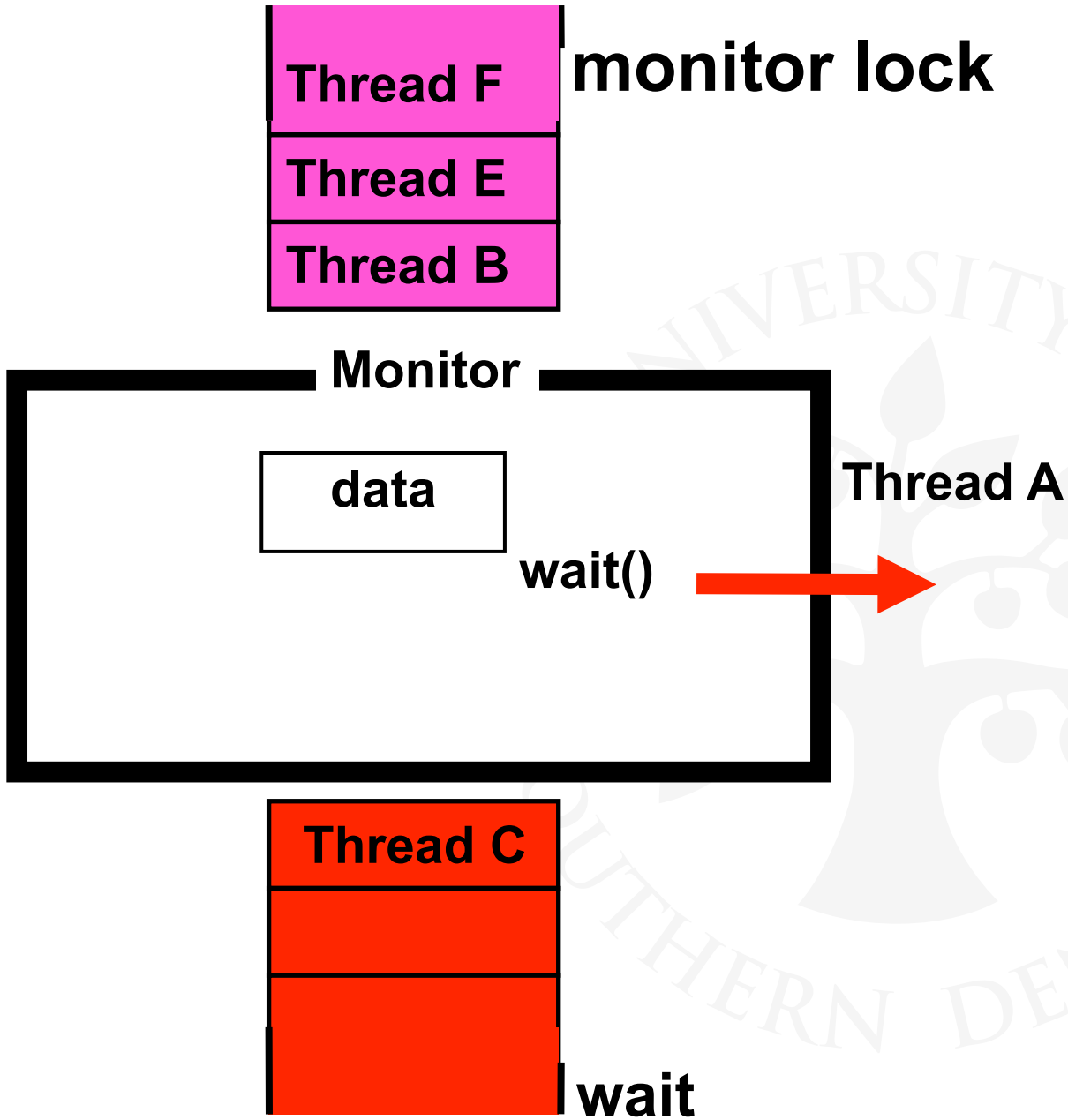
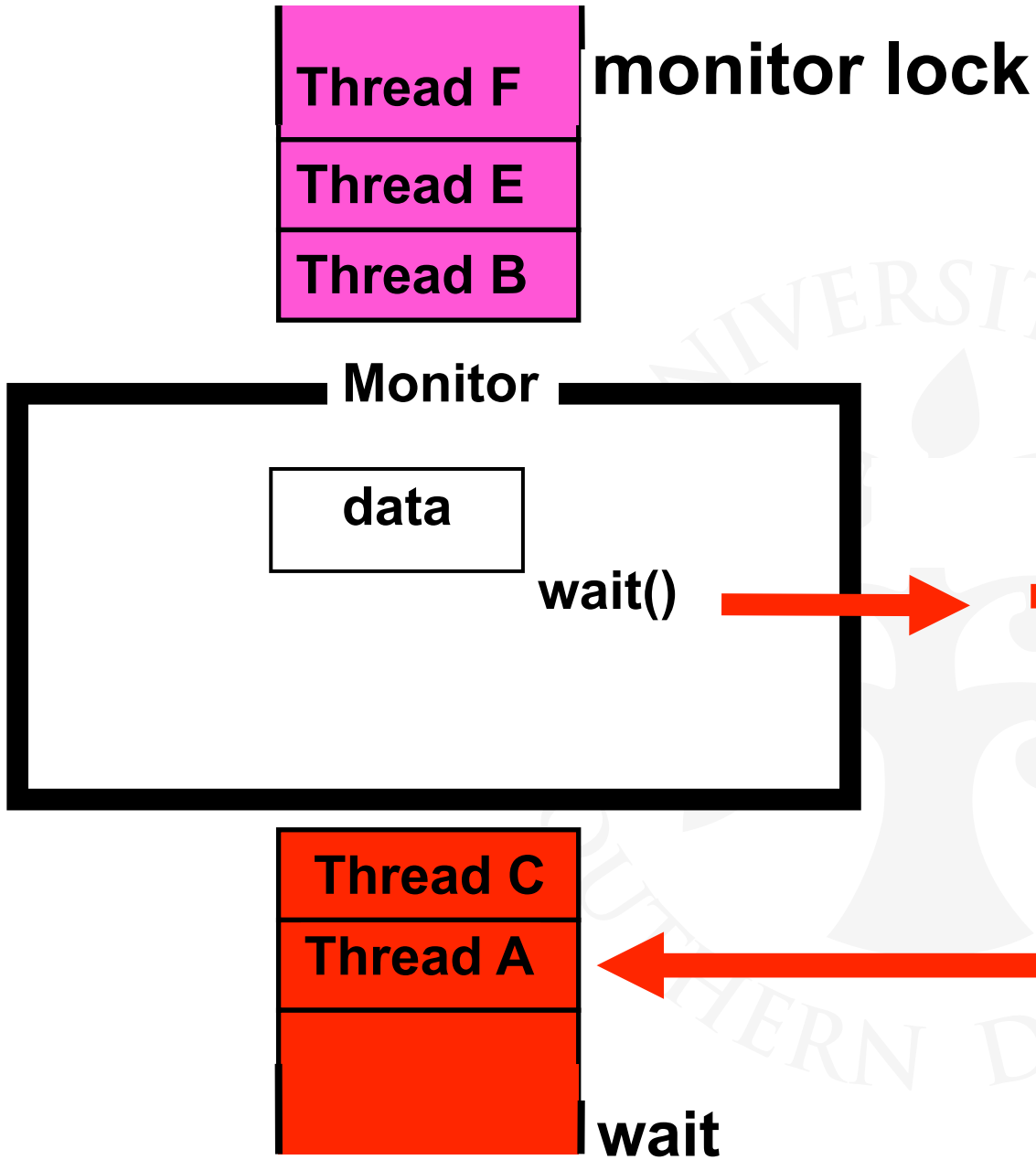



Thread F
monitor lock
Thread E
Thread B
Monitor
data
Thread A
wait()
Thread C
wait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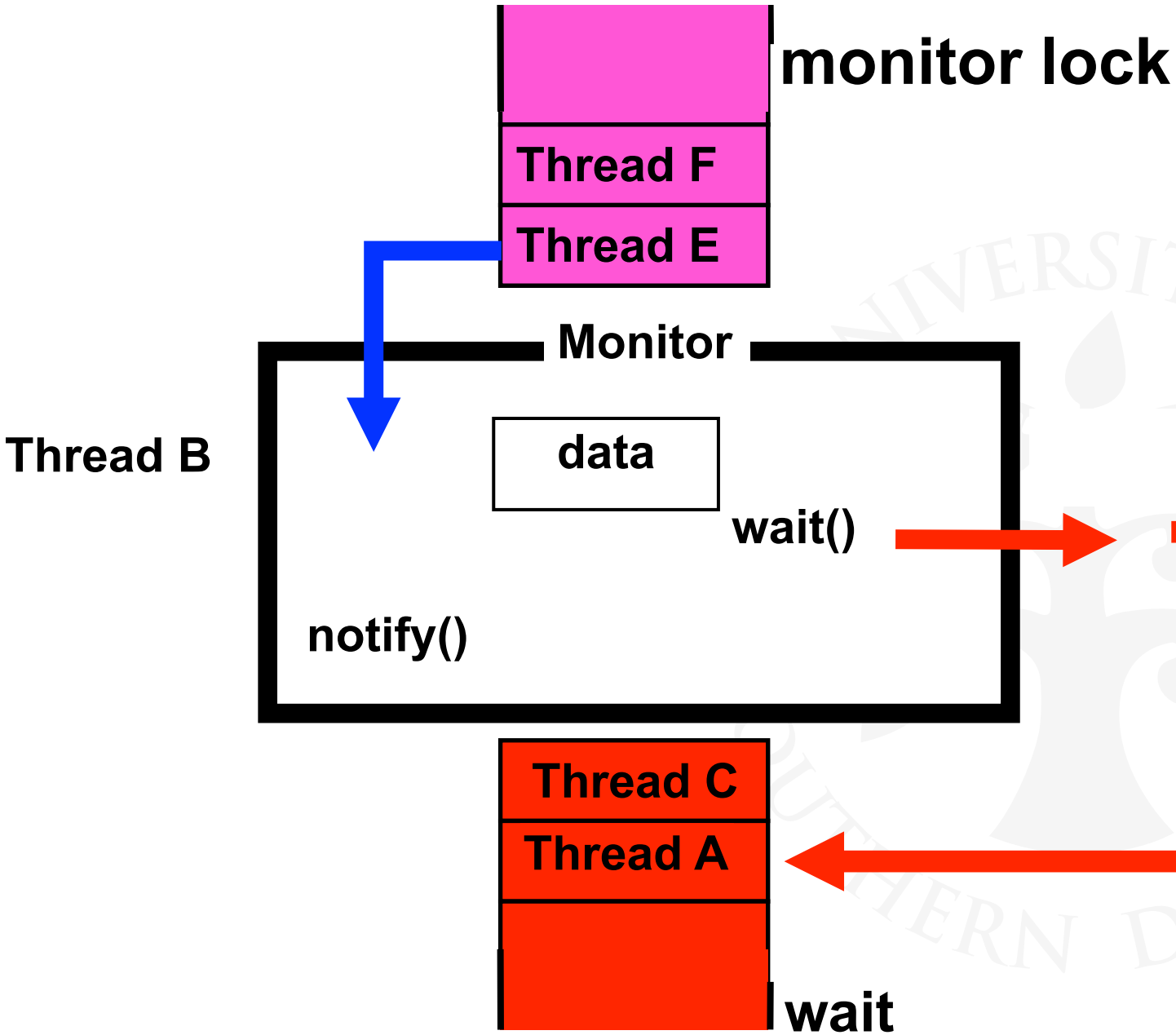
monitor lock
Thread F
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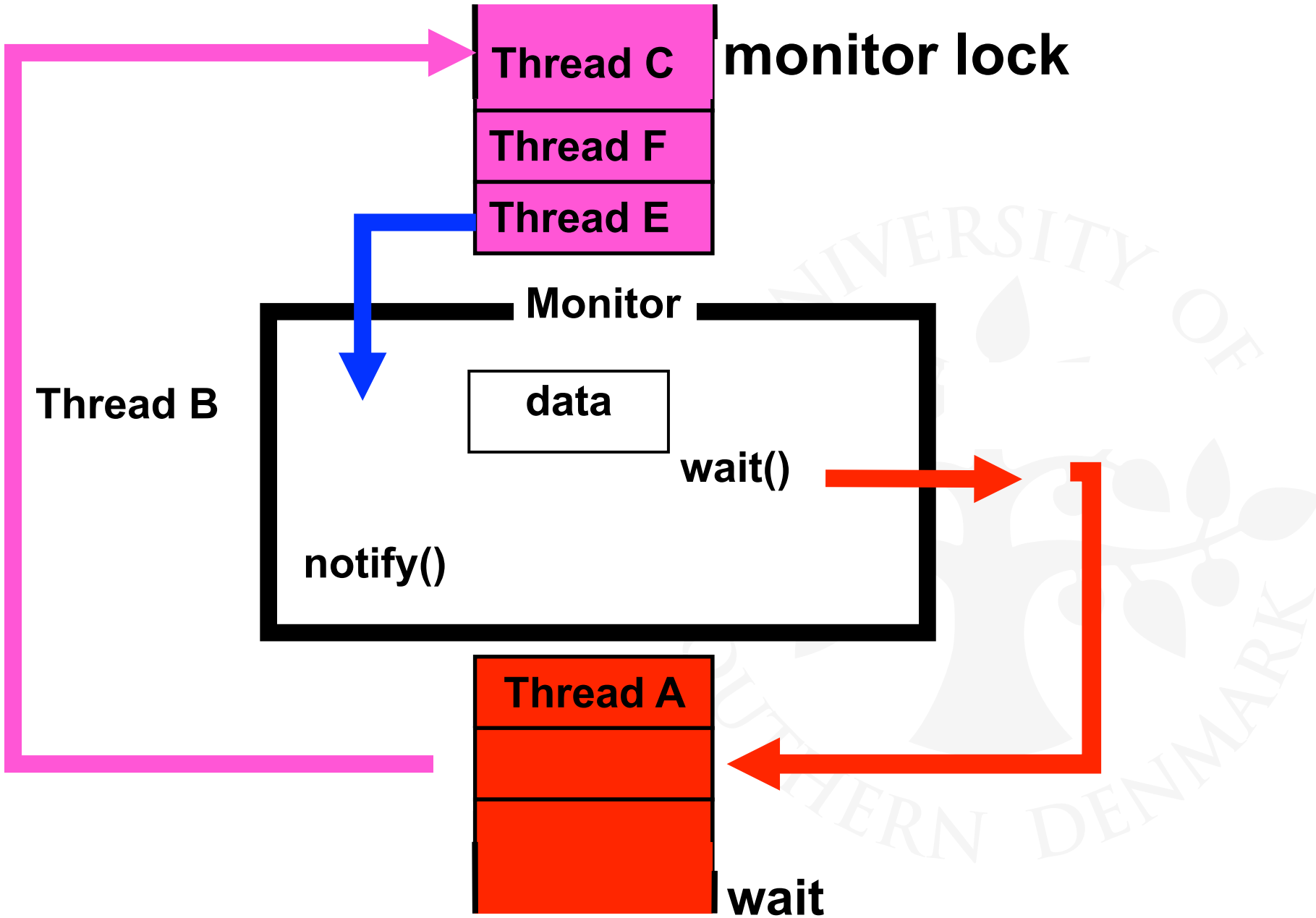
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Condition Synchronisation in FSP and Java

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The **while** loop is necessary to re-test the condition cond to ensure that cond is indeed satisfied when it re-enters the monitor.

notifyAll() is necessary to awaken other thread(s) that may be waiting to enter the monitor now that the monitor data has been changed.

CarParkControl - Condition Synchronisation


```
CONTROL(CAPACITY=4) = SPACES[CAPACITY],
SPACES[spaces:0..CAPACITY] =
              (when(spaces>0)          arrive -> SPACES[spaces-1]
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class Control {
    protected static final int CAPACITY;
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```

```
class Control {
    protected static final int CAPACITY;
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    synchronized void arrive() throws Int'Exc' {
        while (!(spaces>0)) wait();
        --spaces;
        notifyAll();
    }
```

CarParkControl - Condition Synchronisation

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```

Would it be sensible here to use `notify()` rather than `notifyAll()`?

More about Object.notify() and Object.notifyAll()

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More about Object.notify() and Object.notifyAll()

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One-in, one-out. A notification enables at most one thread to proceed.

Prevailing wisdom: use notifyAll() in preference to single notify() when you are not sure.

Models to Monitors - Guidelines

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- **Active** entities (that initiate actions) are implemented as **threads**.
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The while loop condition is the negation of the model guard condition.

Changes in the state of the monitor are signalled to waiting threads using **notifyAll()** (or **notify()**).

Semaphores

5.2 Semaphores

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else block execution of calling process

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s.down(): **when** (s>0) **do** decrement(s); Aka. "P" ~ Passern

s.up(): increment(s); Aka. "V" ~ Vrijgeven

Usually implemented as blocking wait:

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Modelling Semaphores

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LTS?

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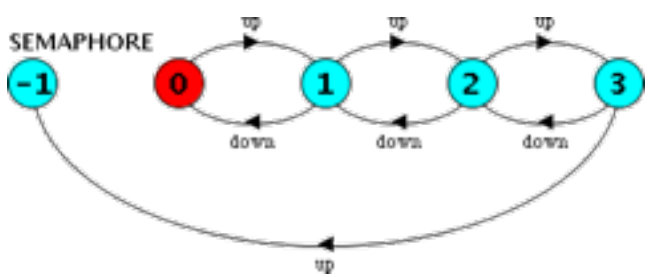

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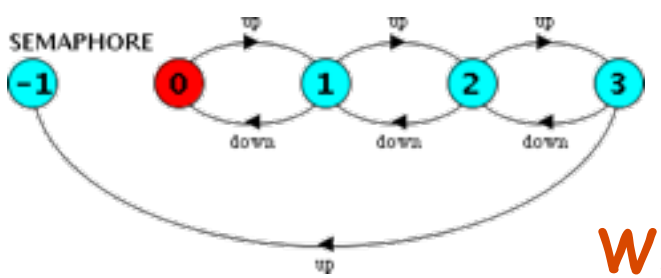
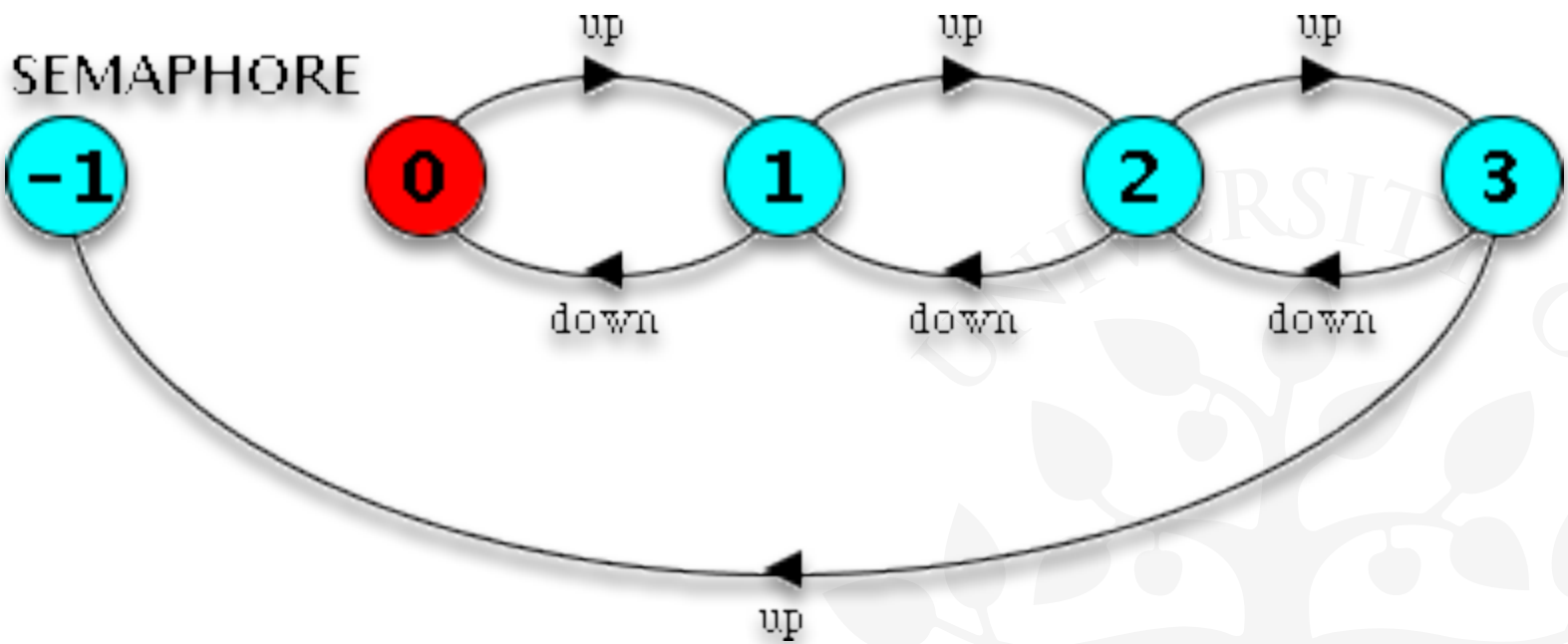


What if we omit the last line above?

Modelling Semaphores

University of Southern Denmark



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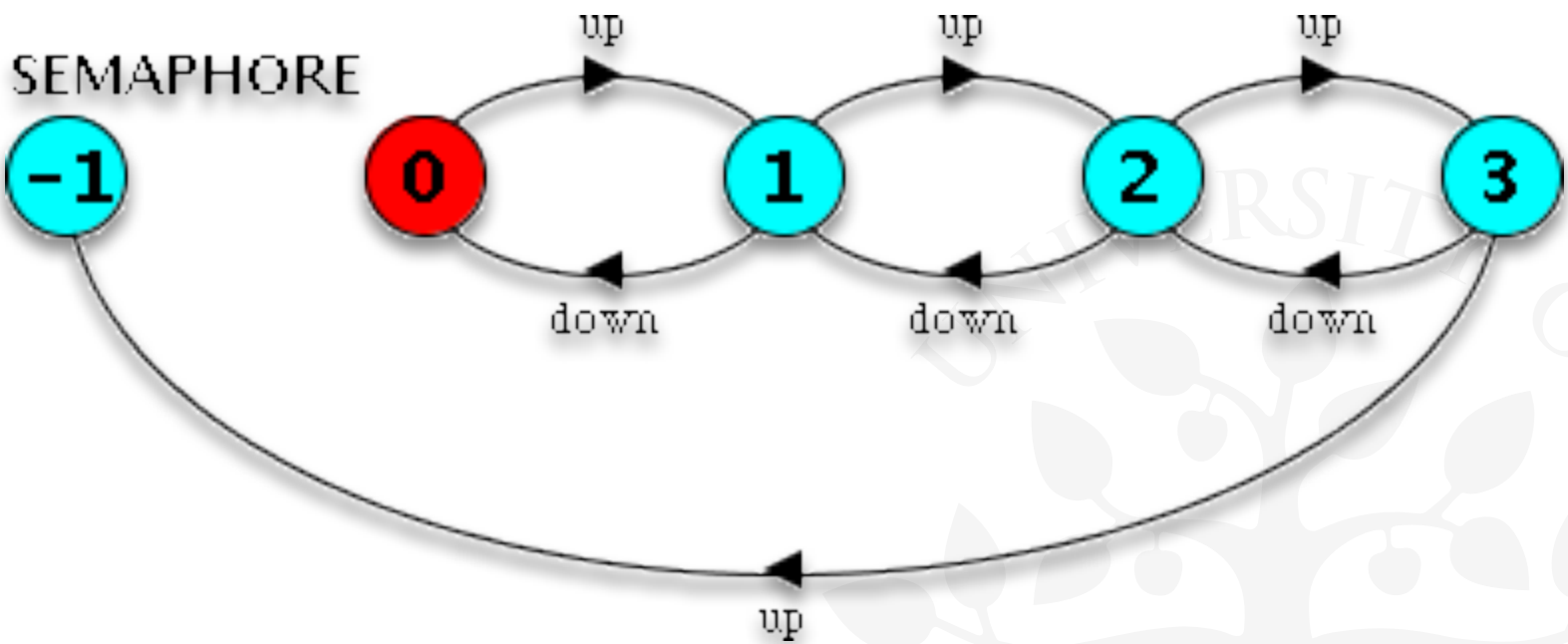

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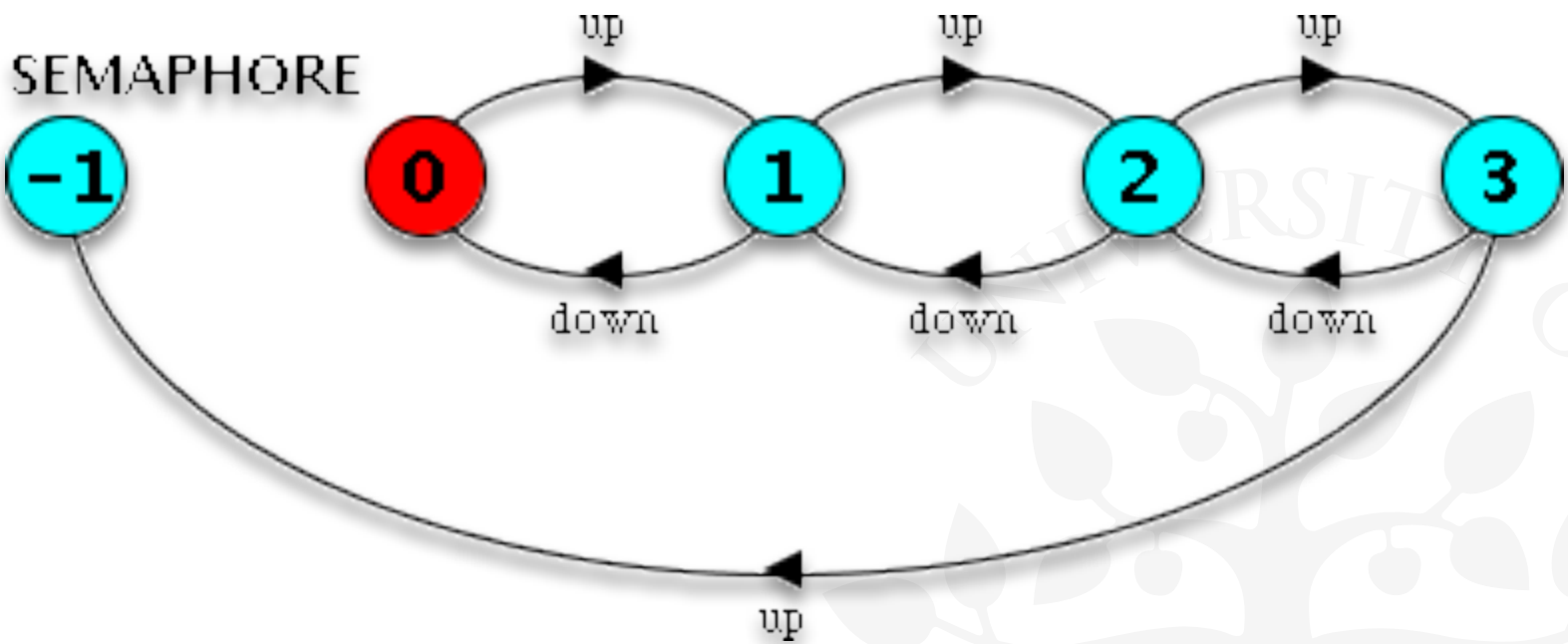
Modelling Semaphores



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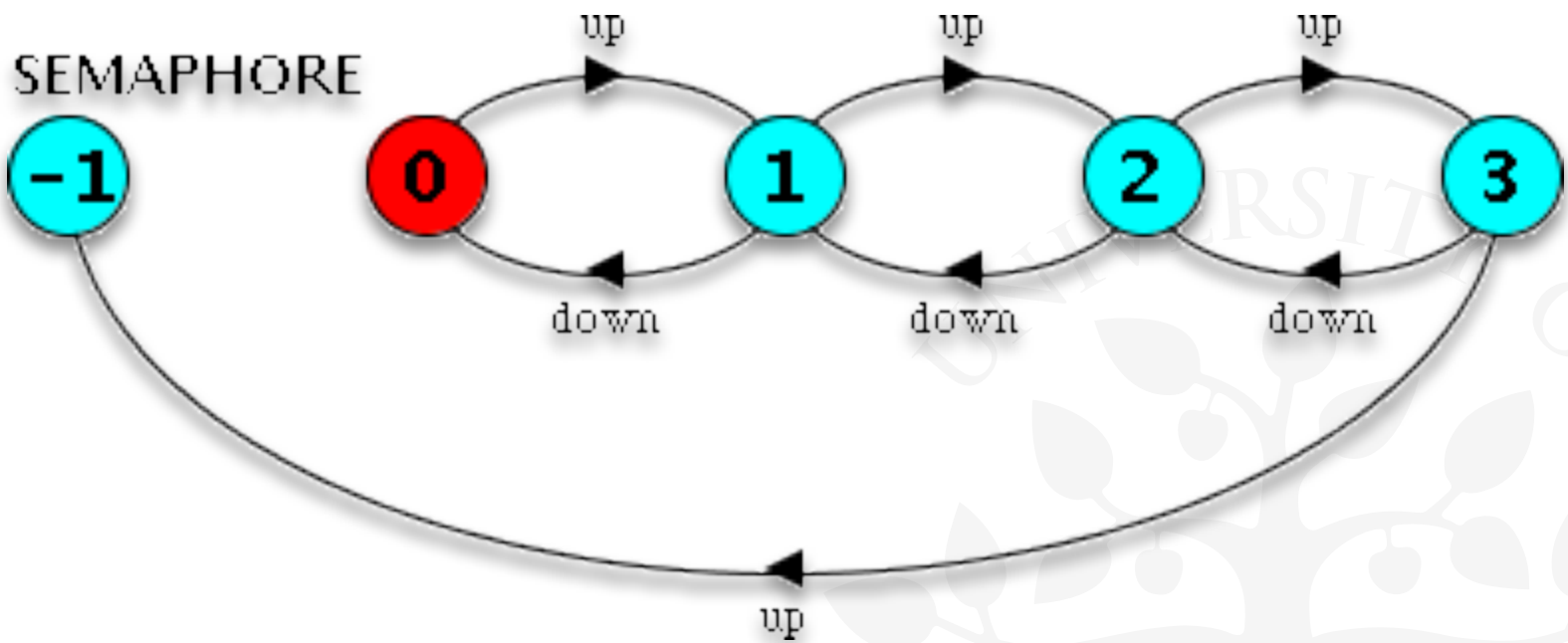

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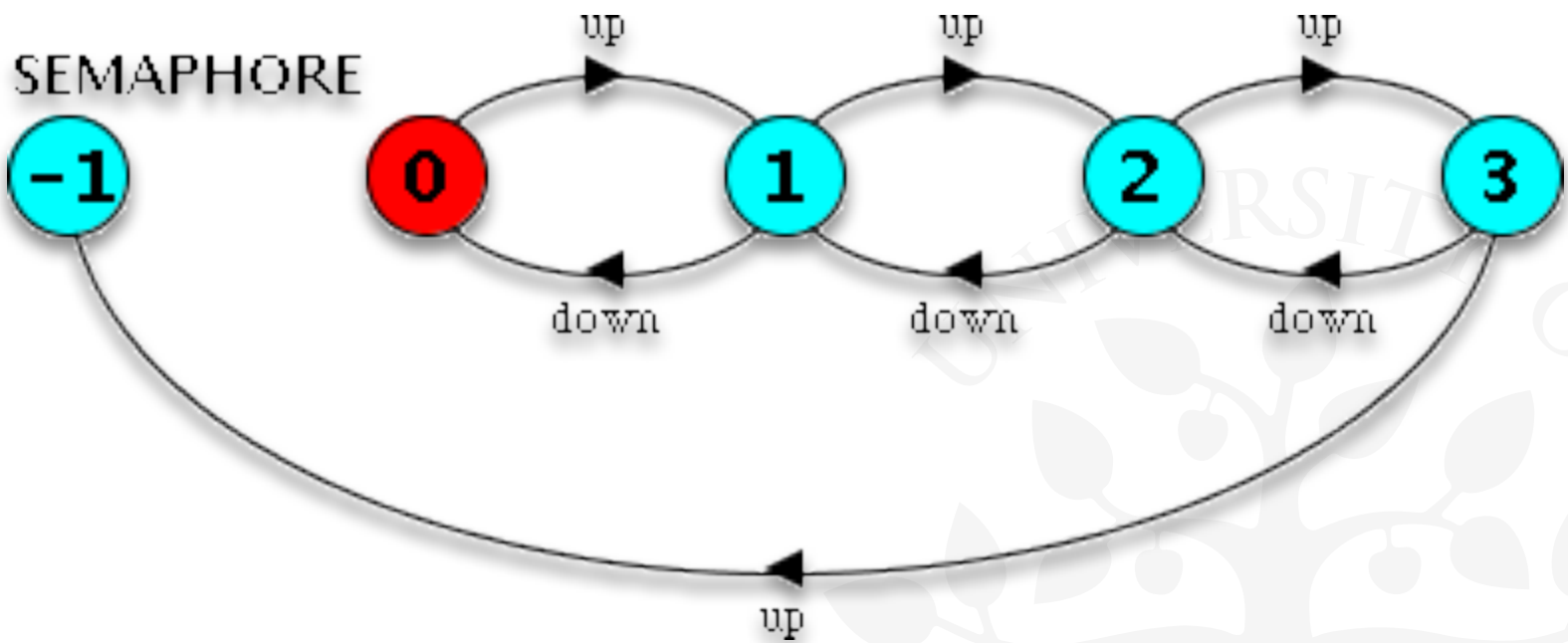
Trace to a violation:

Modelling Semaphores



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up → up → up → up

Semaphore Demo - Model

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Three processes `p[1..3]` use a shared semaphore **`mutex`** to ensure mutually exclusive access (action "**`critical`**") to some resource.

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LTS?

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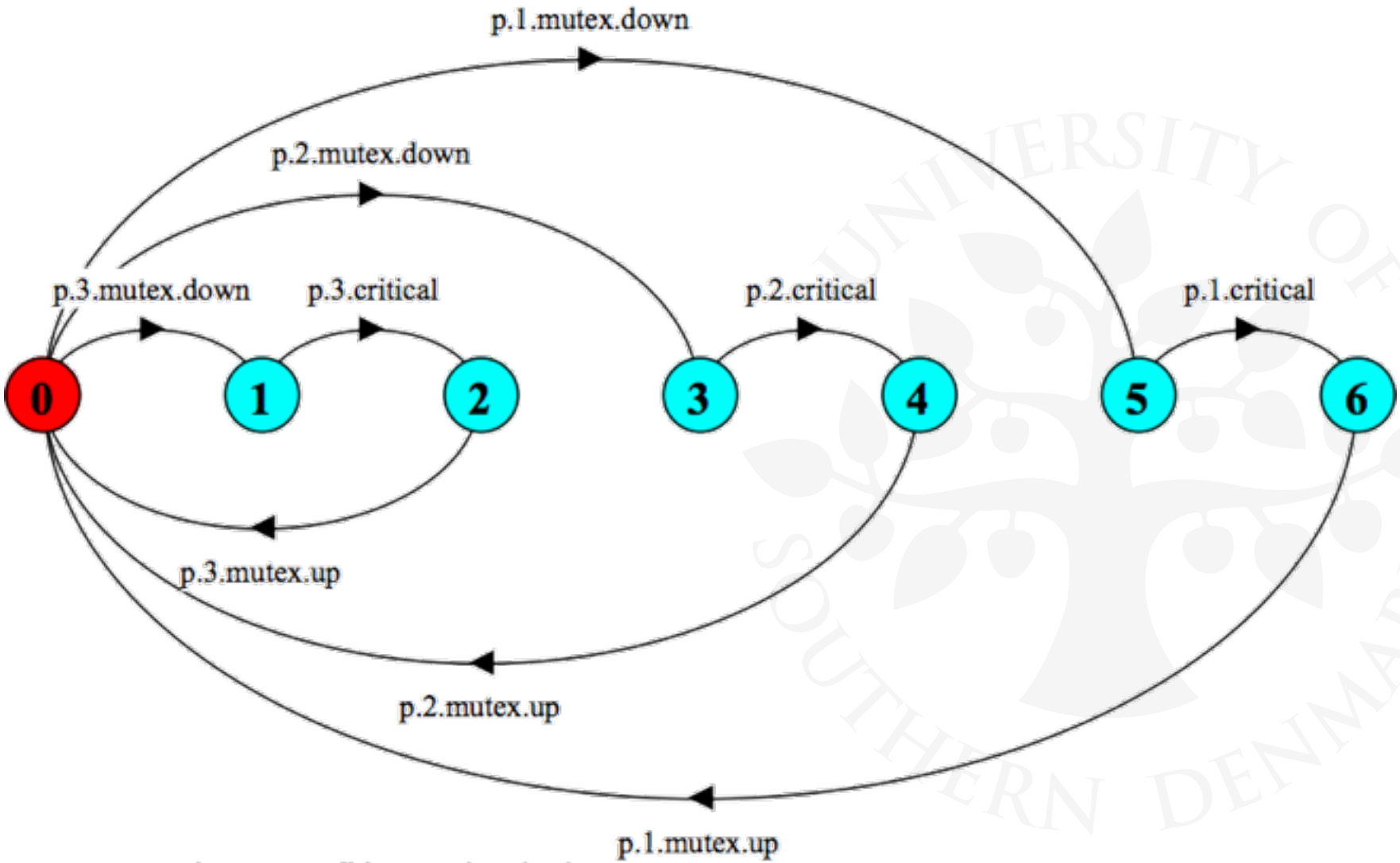

Semaphores in Java

University of Southern Denmark

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Semaphores in Java

University of Southern Denmark

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SEMA[v:Int] = (when(v>0) down->SEMA[v-1]
              |          up->SEMA[v+1]),
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```
public class Semaphore {
    protected int value;

    public Semaphore (int n) { value = n; }

    synchronized public void down() throws Int'Exc' {
        while (!(value > 0)) wait();
        --value;
```

Semaphores in Java

University of Southern Denmark

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Do we need `notifyAll()` here?

Semaphores in Java

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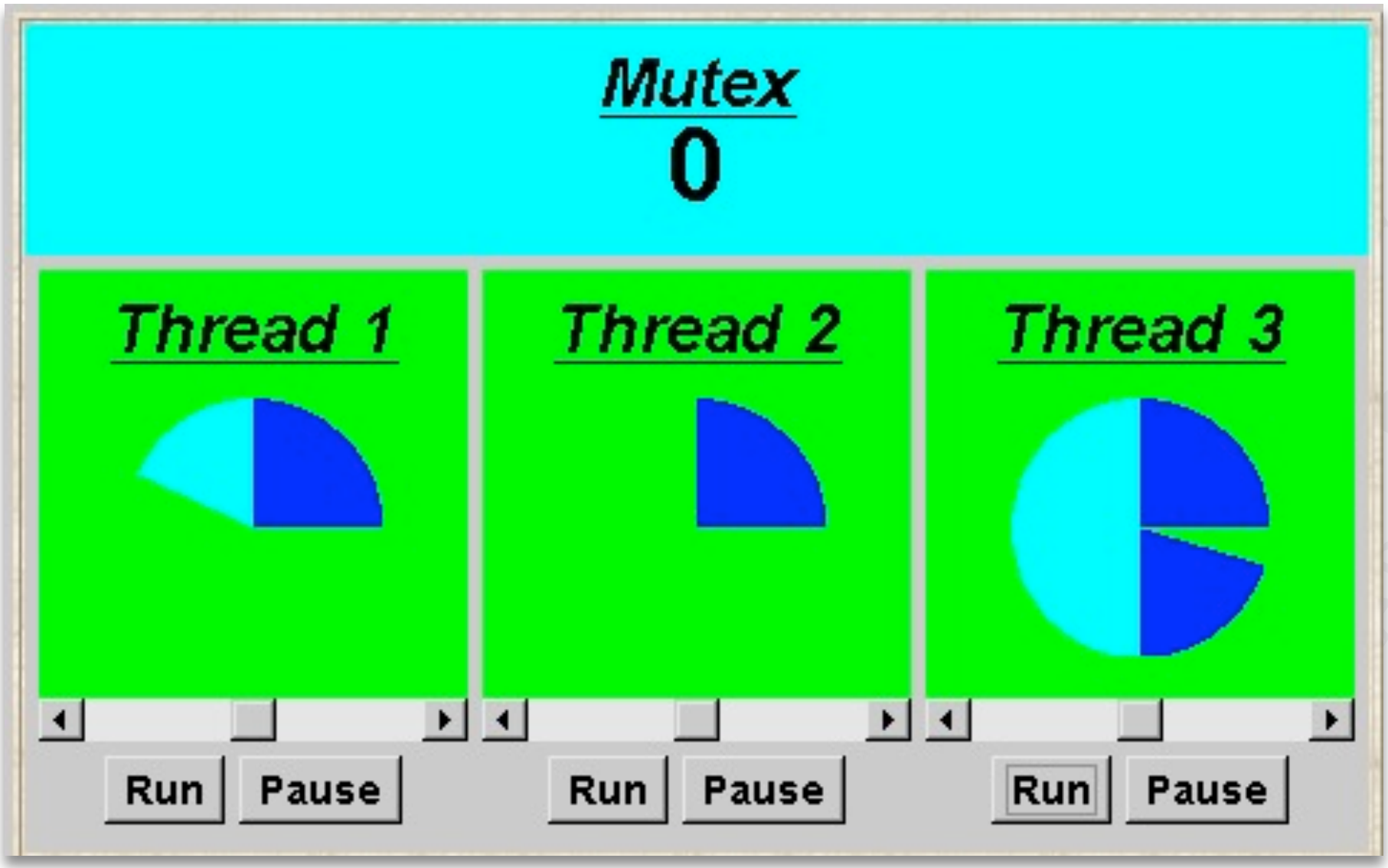
Do we need `notifyAll()` here?

...what about here?

SEMADEMO Display

University of Southern Denmark



SEMADEMO Program - MutexLoop

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```
LOOP = (mutex.down->critical->mutex.up->LOOP).
```

```
class MutexLoop implements Runnable {
    Semaphore mutex; // shared semaphore

    MutexLoop (Semaphore sem) { mutex=sem; }

    public void run() {
        try {
            while(true)  {
                // non-critical actions
                mutex.down();              // acquire
                // critical actions
                mutex.up();                // release
            }
        } catch(InterruptedException _) {}
    }
}
```

SEMADEMO Program - MutexLoop

University of Southern Denmark

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                mutex.up();                // release
            }
        } catch(InterruptedException _) {}
    }
}
```

However (in practice), semaphore is a **low-level** mechanism often used in implementing **higher-level** monitor constructs.

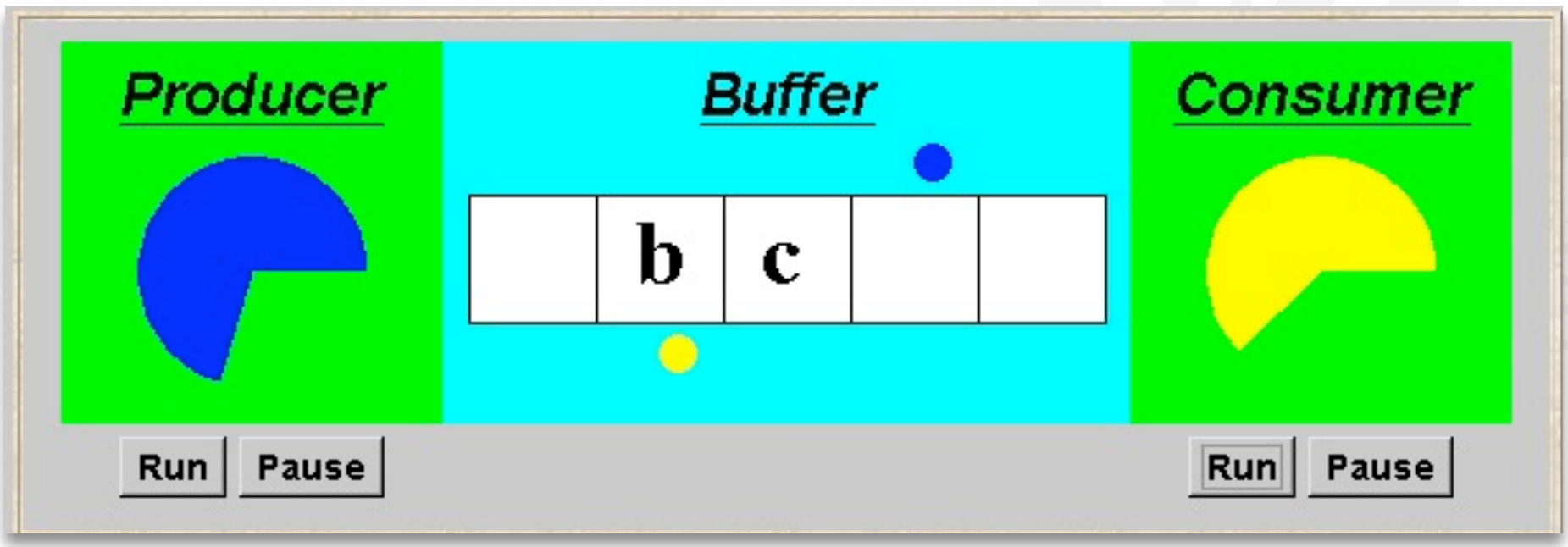
Producer / Consumer

5.3 Producer / Consumer

University of Southern Denmark

A **bounded buffer** consists of a fixed number of slots.

Items are put into the buffer by a **producer** process and removed by a **consumer** process:



5.3 Producer / Consumer

University of Southern Denmark

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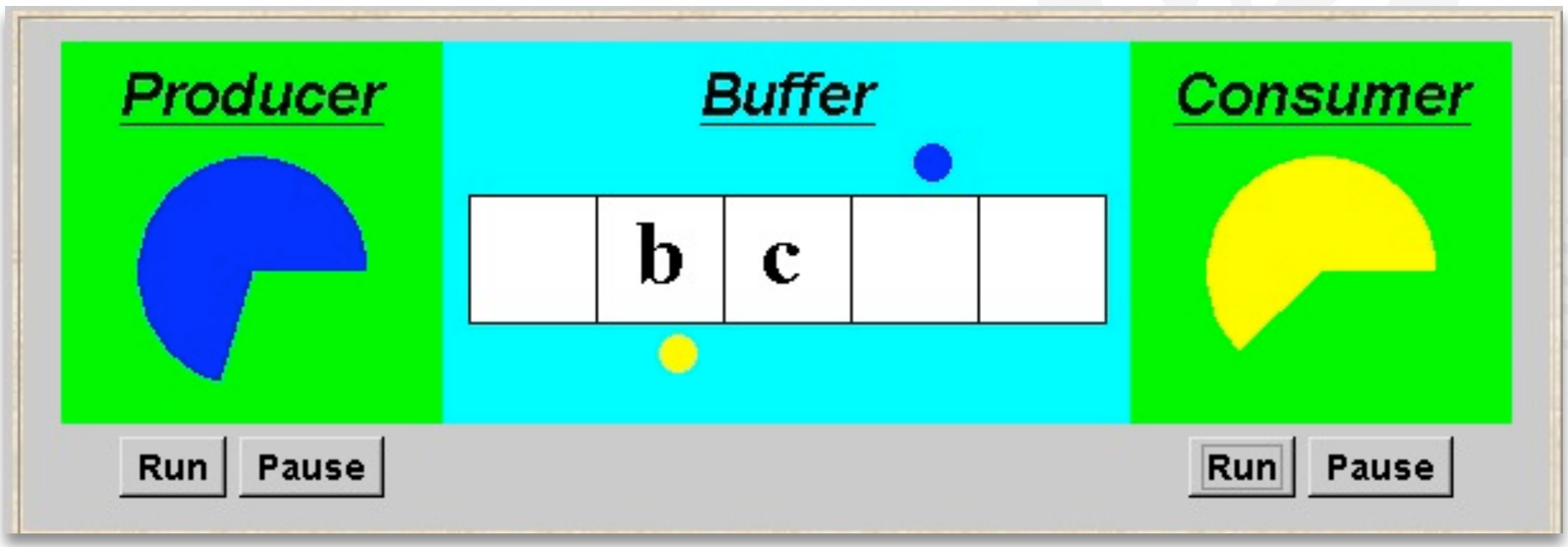
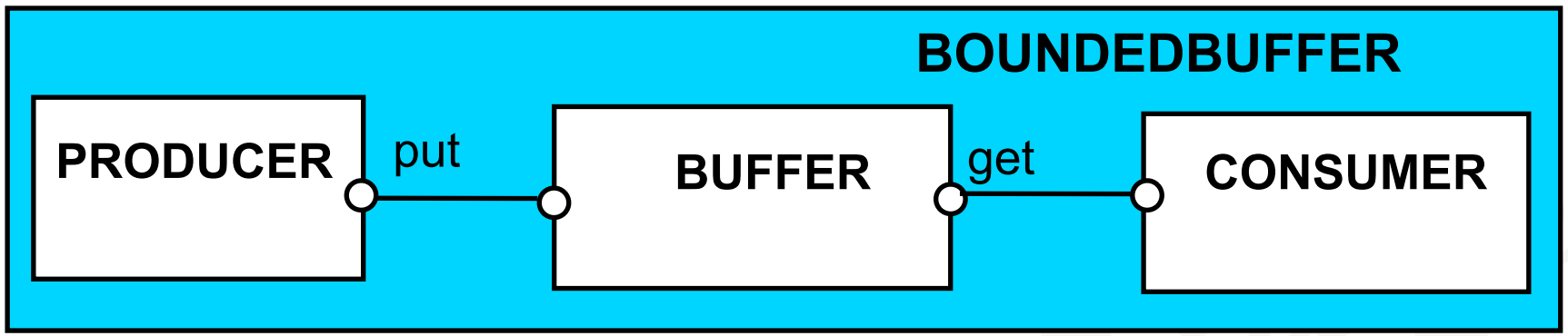
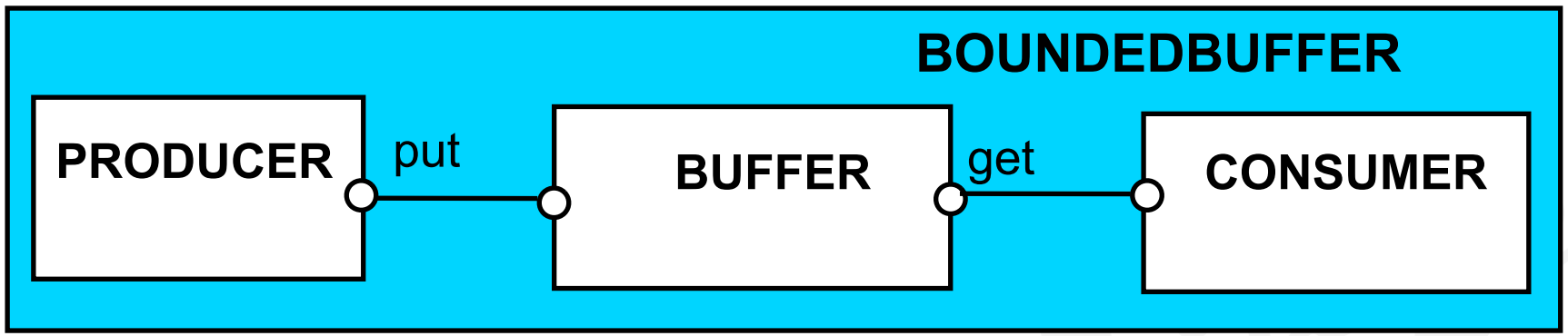


≈ Car Park Example!

Producer / Consumer
- a Data-Independent Model

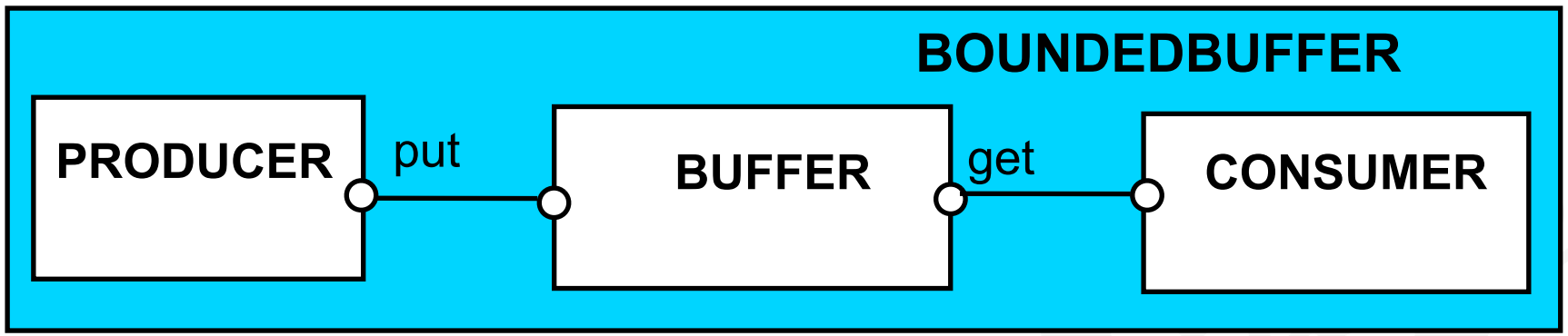


Producer / Consumer
- a Data-Independent Model



The behaviour of BOUNDEDBUFFER is independent of the actual data values, and so can be modelled in a data-independent manner (i.e., we abstract away the letters).

Producer / Consumer
- a Data-Independent Model



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LTS?

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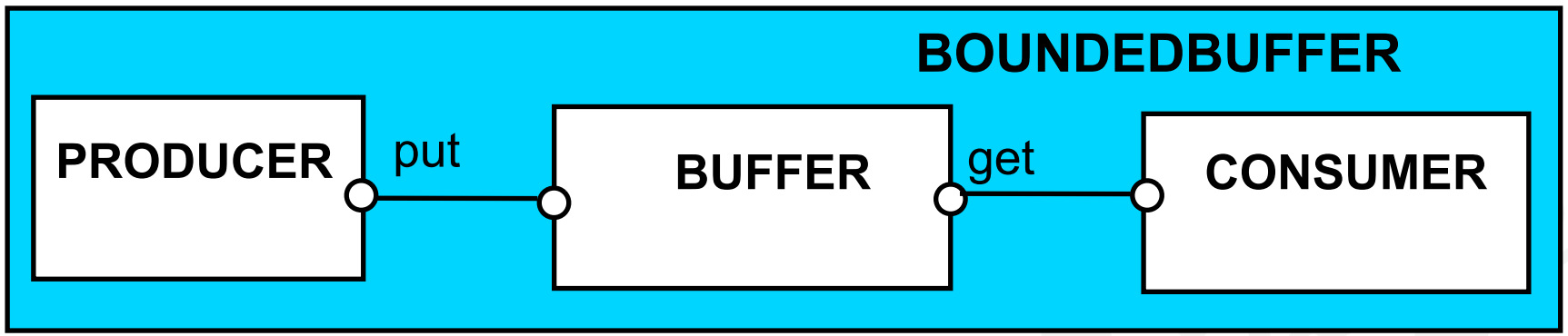

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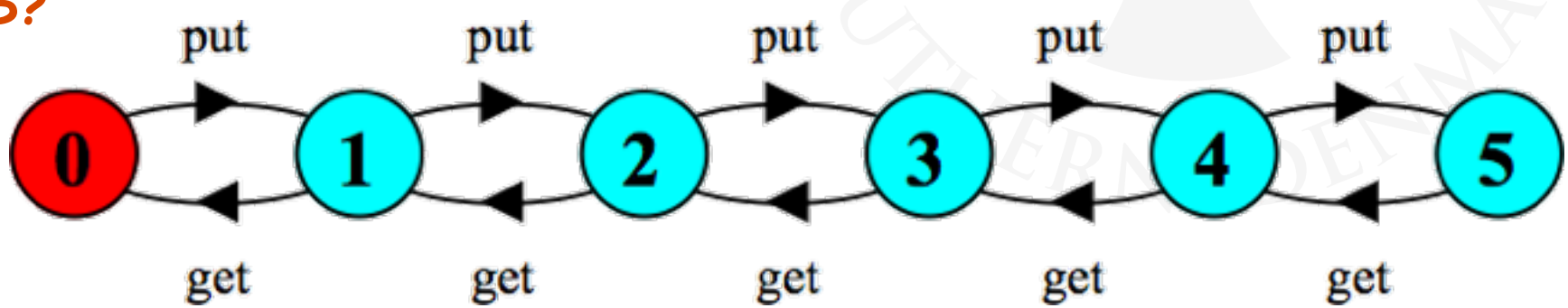
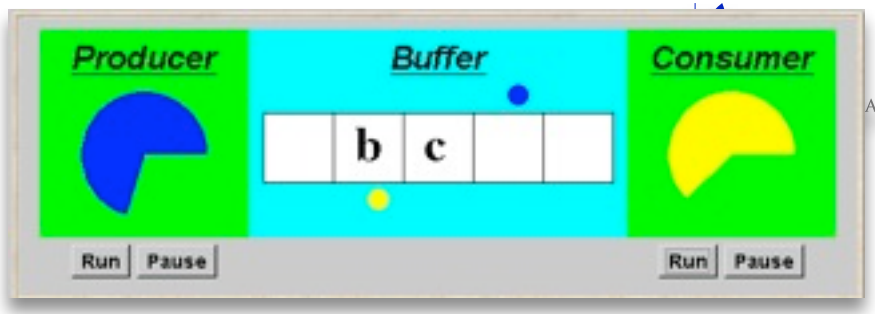
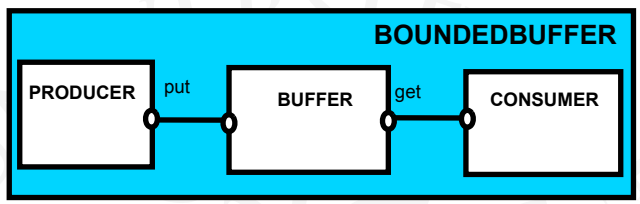


Producer / Consumer





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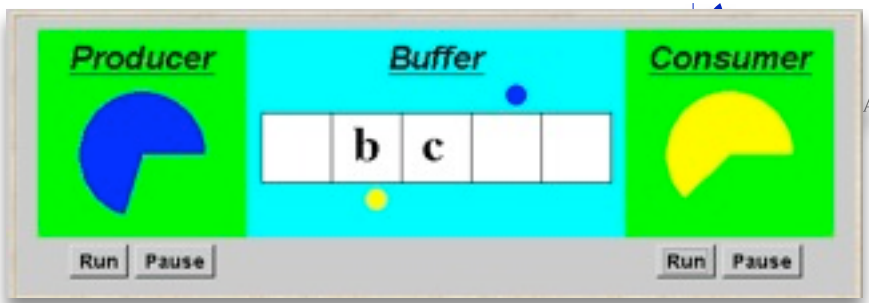


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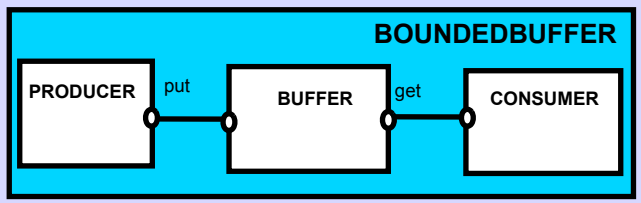
```



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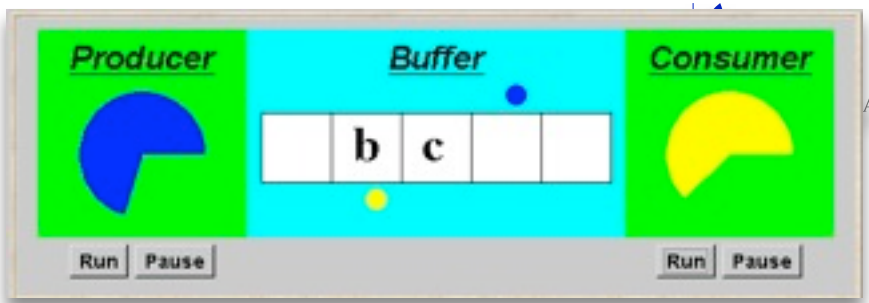


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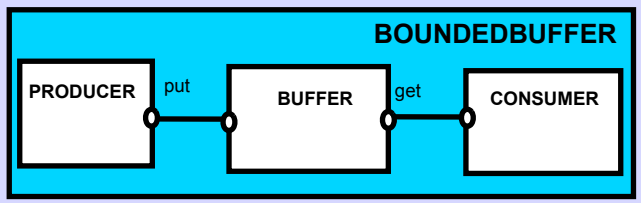

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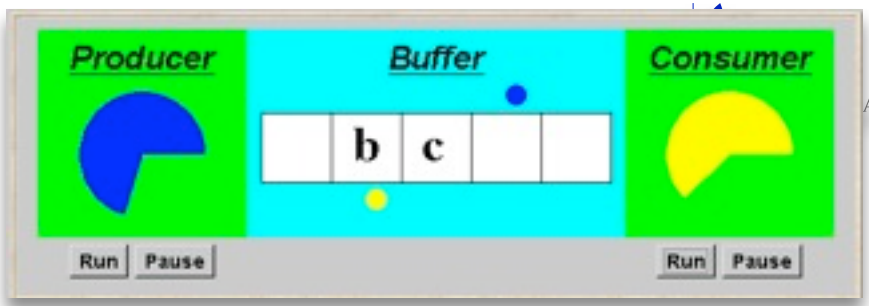


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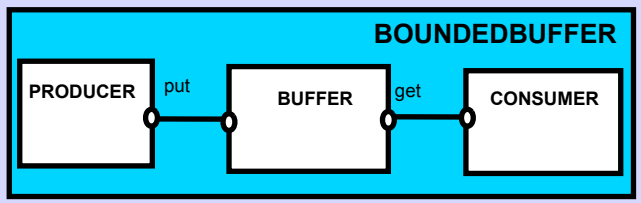

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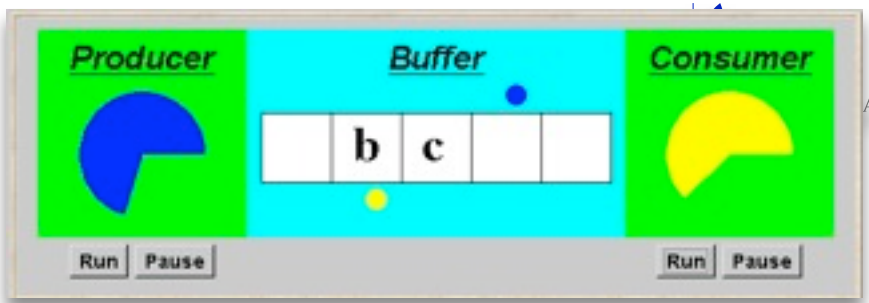


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||BOUNDEDBUFFER =
         (PRODUCER || BUFFER || CONSUMER).
```

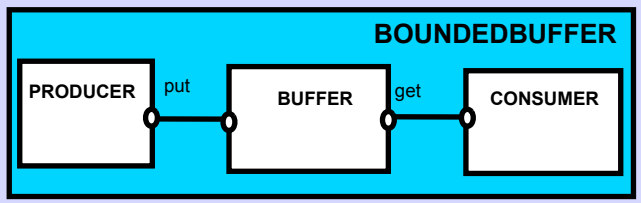

Bounded Buffer Program - Buffer Monitor

University of Southern Denmark

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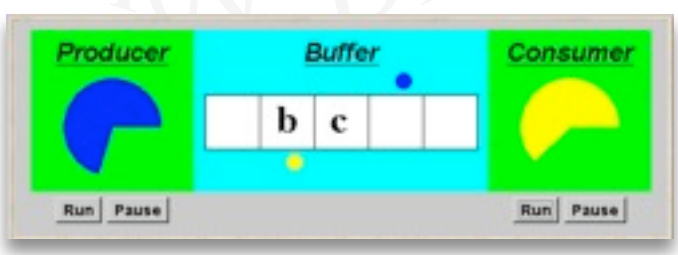

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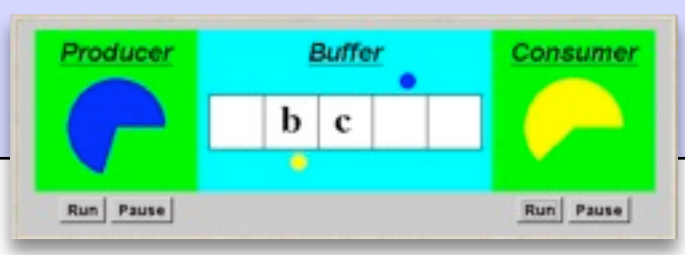

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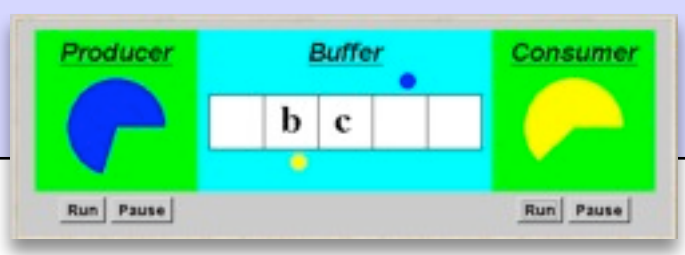

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        count++;
        in = (in+1) % SIZE;
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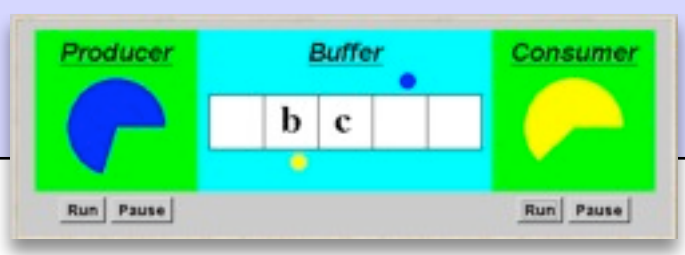

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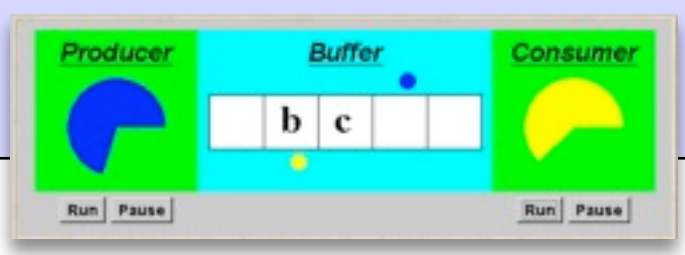

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University of Southern Denmark

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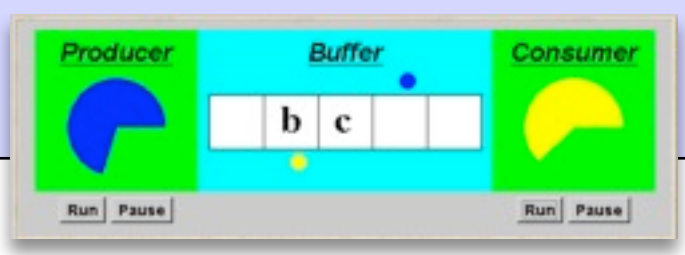
Can we use notify()?



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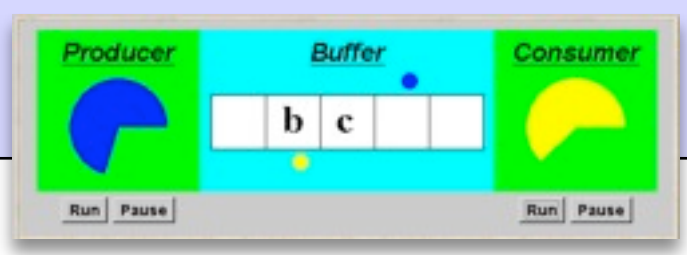
if(count == 1)



Similarly for get()

University of Southern Denmark

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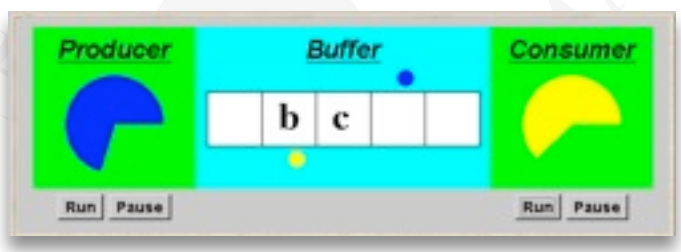

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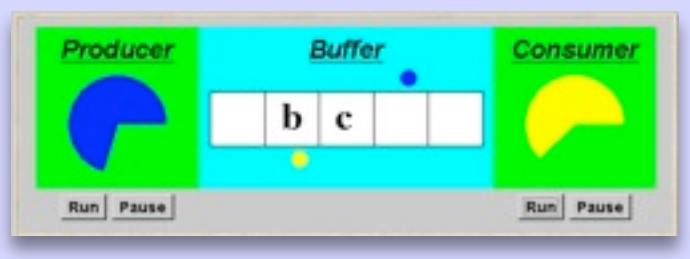

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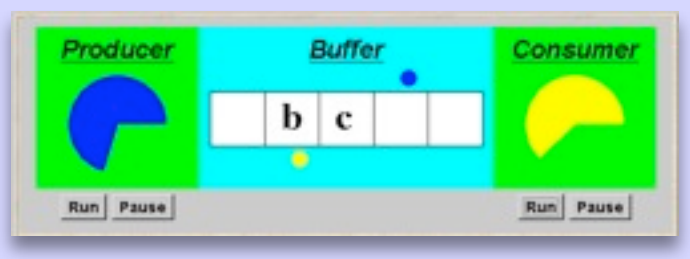

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3.      count--;
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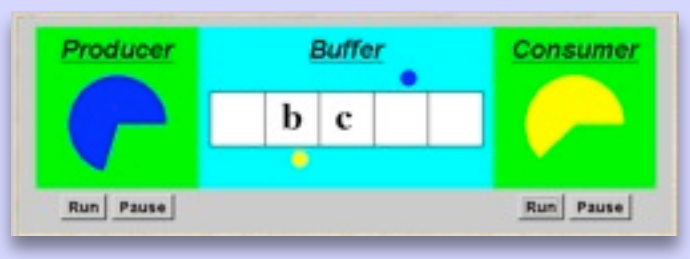

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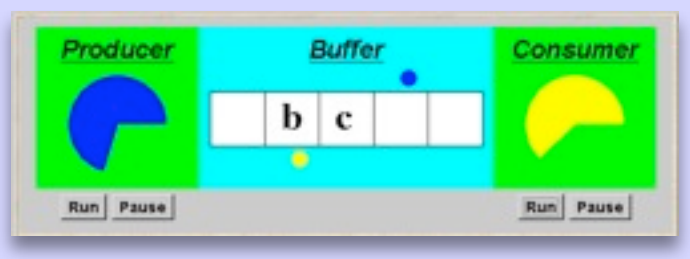

Similarly for get()

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```
BUFFER(SIZE=5) = COUNT[0],
COUNT[count:0..SIZE] =
        (when (count<SIZE) put -> COUNT[count+1]
        |when (count>0)    get -> COUNT[count-1]).
```

```
public interface Buffer<E> {
    public void put(E o)      throws InterruptedException;
    public E get()            throws InterruptedException;
}
```

```
    …
    synchronized E get() throws Int'Exc' {
1.      while (!(count>0)) wait();
2.      E obj = queue[out];
 < 2½.  queue[out] = null;              // WHY(?)
3.      count--;
4.      out = (out+1) % SIZE;
5.      notifyAll();
6.      return obj;
    }
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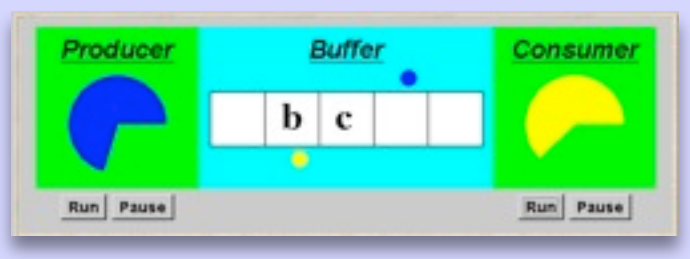

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University of Southern Denmark

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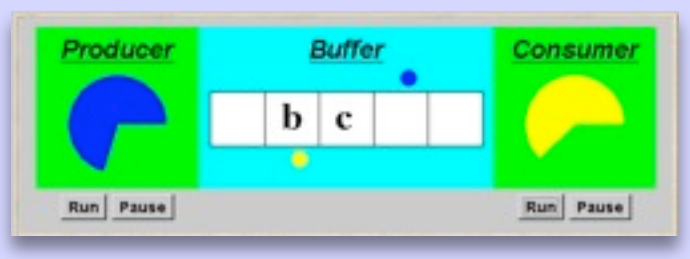


```
if(count == queue.length-1)
```

Producer Process

```
PRODUCER = (put->PRODUCER).
```

```
class Producer implements Runnable {
    Buffer<Character> buf;
    String alpha = "abcdefghijklmnopqrstuvwxyz";

    Producer(Buffer<Character> b) { buf = b; }

    public void run() {
        try {
            int i = 0;
            while(true) {
                Thread.sleep(...);
                buf.put(new Character(alpha.charAt(i)));
                i=(i+1) % alpha.length();
            }
        } catch (InterruptedException _) {}
    }
}
```

Producer Process

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PRODUCER = (put->PRODUCER).
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```
class Producer implements Runnable {
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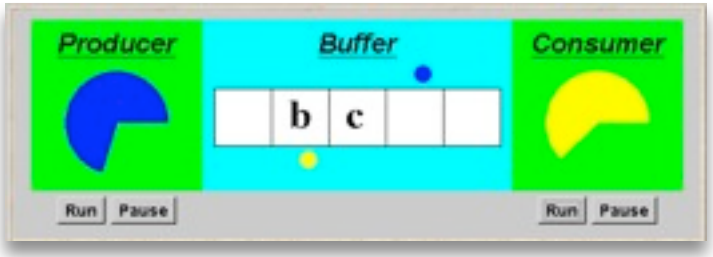
    }
}
```

Similar, **Consumer** calls **buf.get()**

The Nested Monitor Problem

5.4 Nested Monitors (Semaphores)



Suppose that, instead of using the **count** variable and condition synchronisation, we instead use 2 semaphores **full** and **empty** to reflect the state of the buffer:

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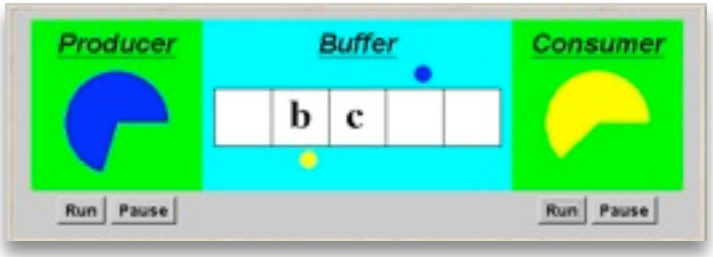
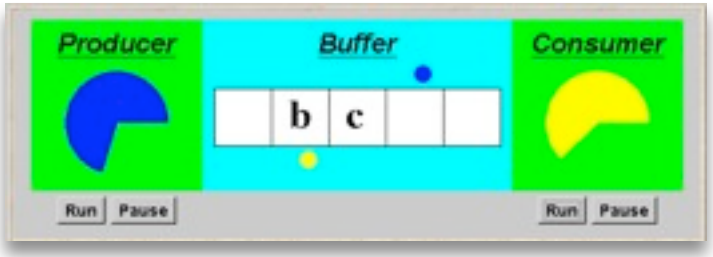


Suppose that, instead of using the **count** variable and condition synchronisation, we instead use 2 semaphores **full** and **empty** to reflect the state of the buffer:

```
class SemaBuffer implements Buffer {
    protected Object queue[];
    protected int in, out, count, SIZE;
    Semaphore empty; // block put appropriately
    Semaphore full;  // block get appropriately
```

5.4 Nested Monitors (Semaphores)



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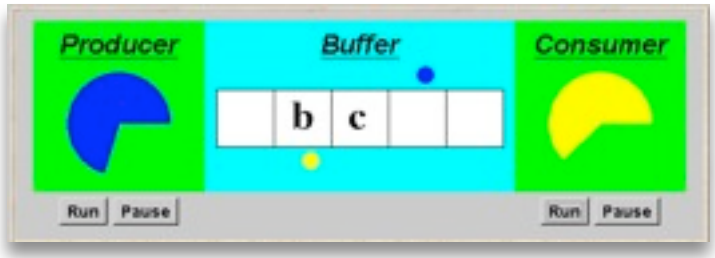
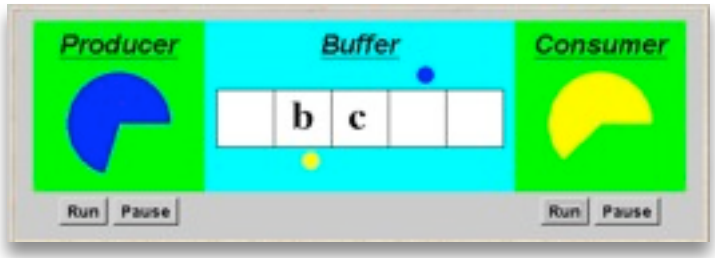
```
class SemaBuffer implements Buffer {
    protected Object queue[];
    protected int in, out, count, SIZE;
    Semaphore empty; // block put appropriately
    Semaphore full;  // block get appropriately

    SemaBuffer(int s) {
        size  = s;
        in    = out = count = 0;
        queue = new Object[SIZE];
        empty = new Semaphore(SIZE);
        full  = new Semaphore(0);
    }
```

Nested Monitors Java Program

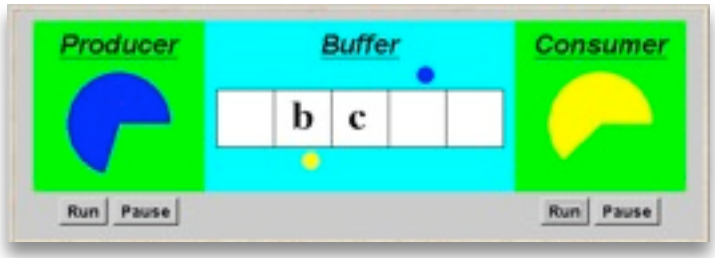


Nested Monitors Java Program




```
synchronized public void put(E o) throws Int'Exc' {
    empty.down();
    queue[in] = o;
    count++;
    in = (in+1) % SIZE;
    full.up();
}
```

Nested Monitors Java Program

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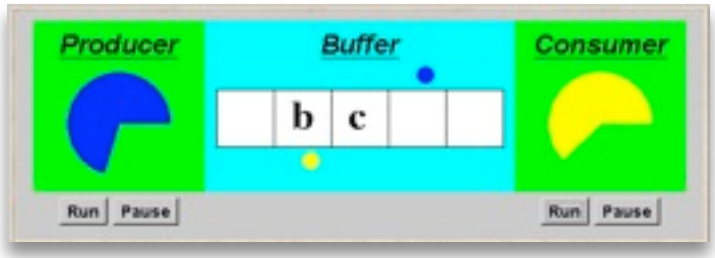
empty is decremented during a **put**, which is blocked if empty is zero, i.e., no spaces are left.

Nested Monitors Java Program

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    full.down();
    E o = queue[out];
    queue[out] = null;
    count--;
    out = (out+1) % SIZE;
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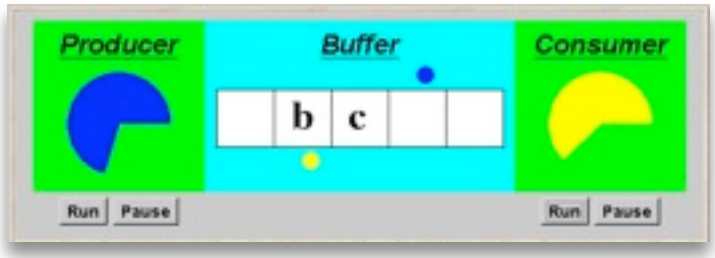


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empty is decremented during a **put**, which is blocked if **empty** is zero, i.e., no spaces are left.

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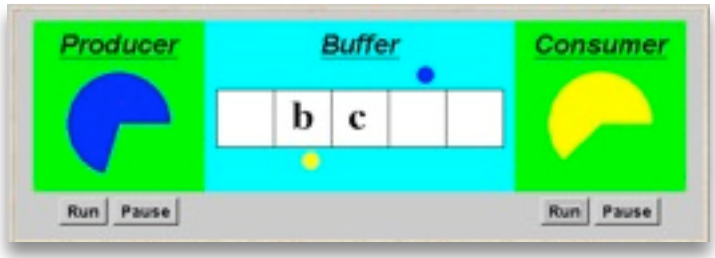


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    E o = queue[out];
    queue[out] = null;
    count--;
    out = (out+1) % SIZE;
    empty.up();
    return o;
}
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empty is decremented during a **put**, which is blocked if **empty** is zero, i.e., no spaces are left.

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Does this behave as desired?

Nested Monitors Model

Nested Monitors Model

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```
PRODUCER = (put -> PRODUCER).

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Nested Monitors

University of Southern Denmark

LTSA analysis predicts a DEADLOCK:

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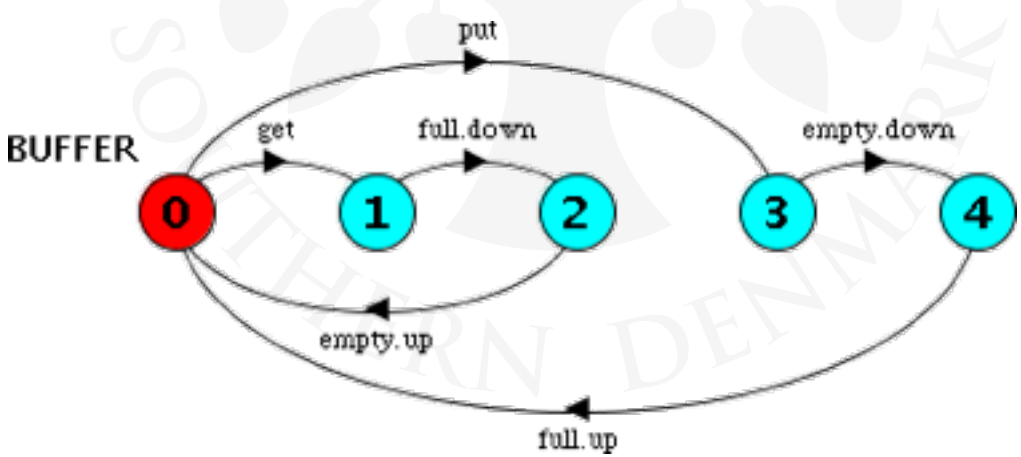

Nested Monitors

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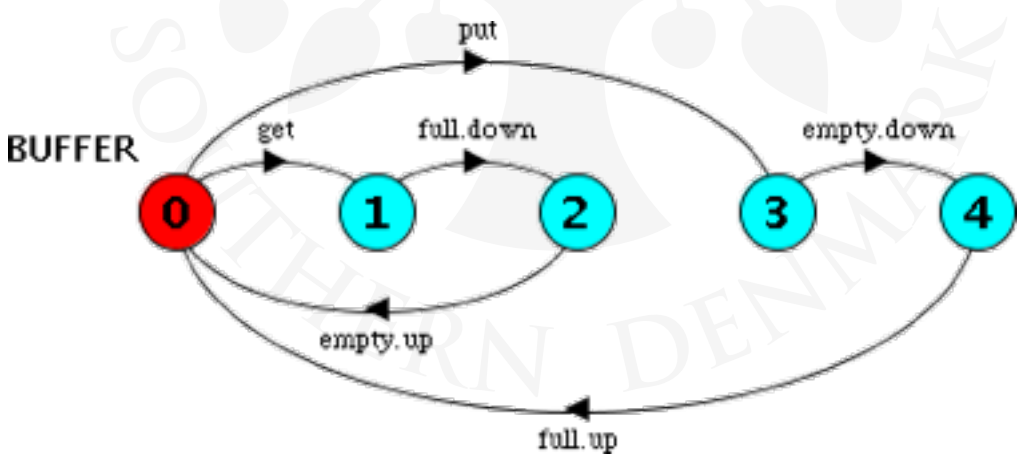
After **get** the next action is **full.down** (blocks).



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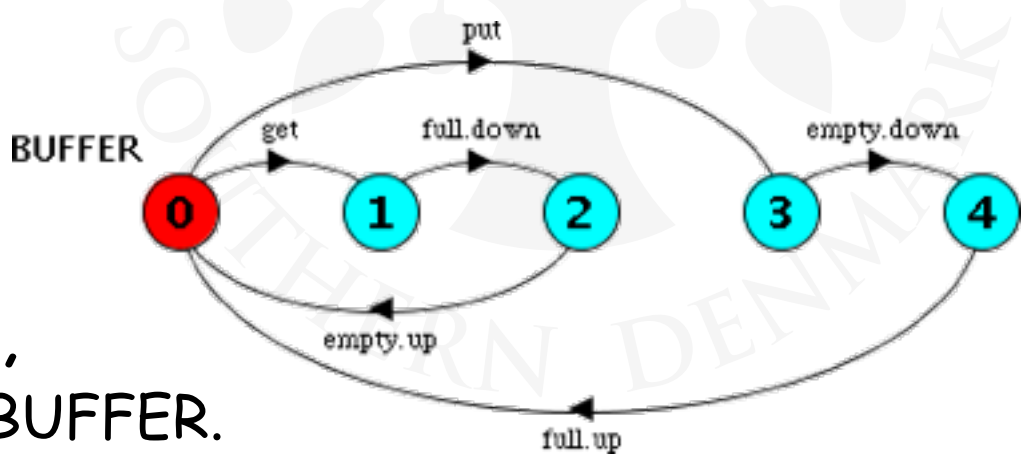

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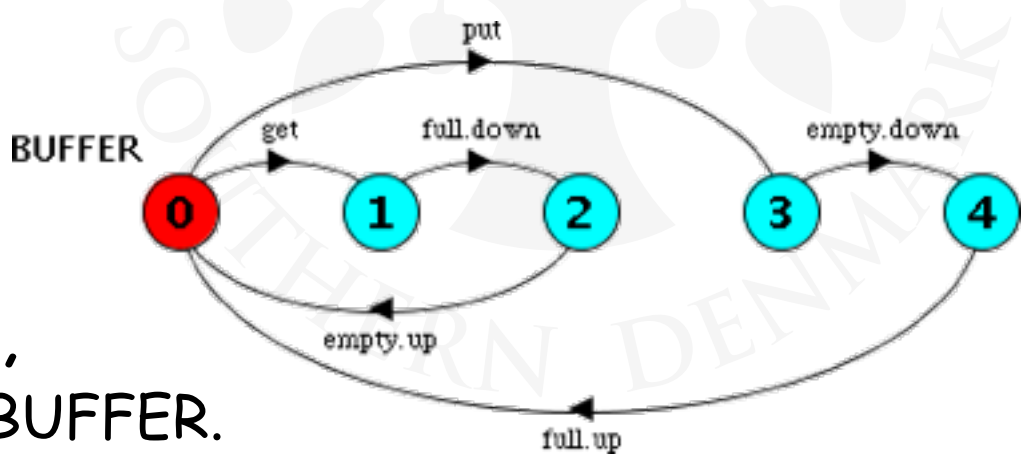

We cannot do **put** (and unblock full), since we have the "semaphore" for BUFFER.

This situation is known as the **nested monitor problem**!

Nested Monitor Problem

University of Southern Denmark

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synchronized public E get()
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     full.down(); // if no items, block!
     ...
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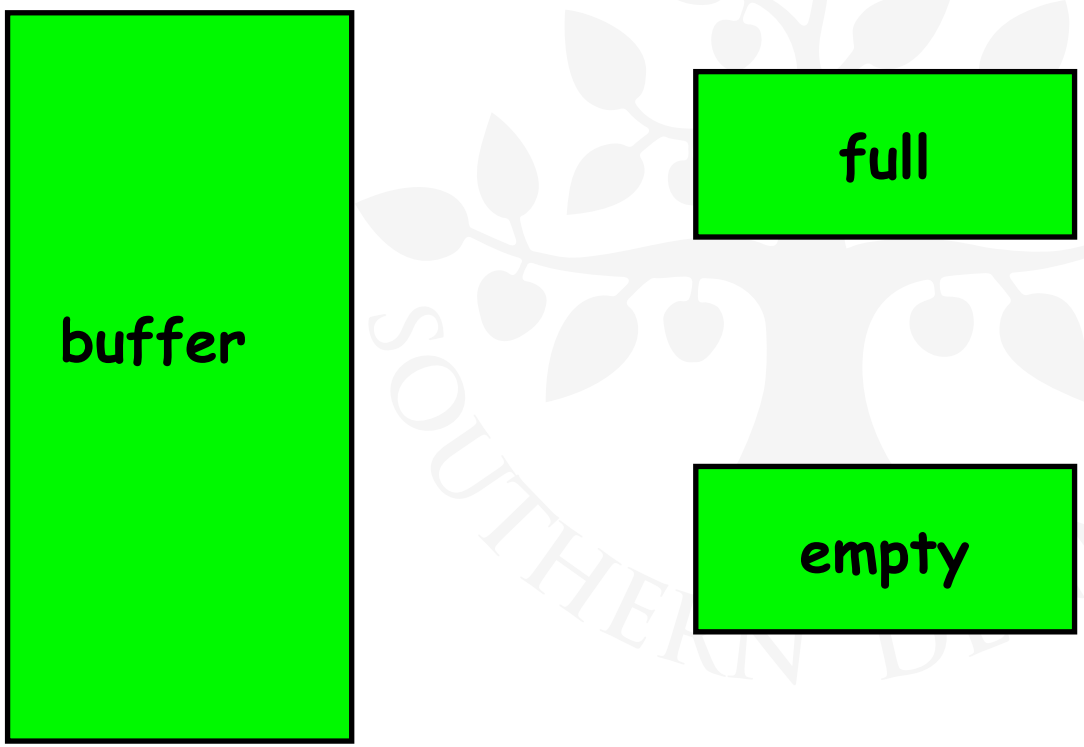
```



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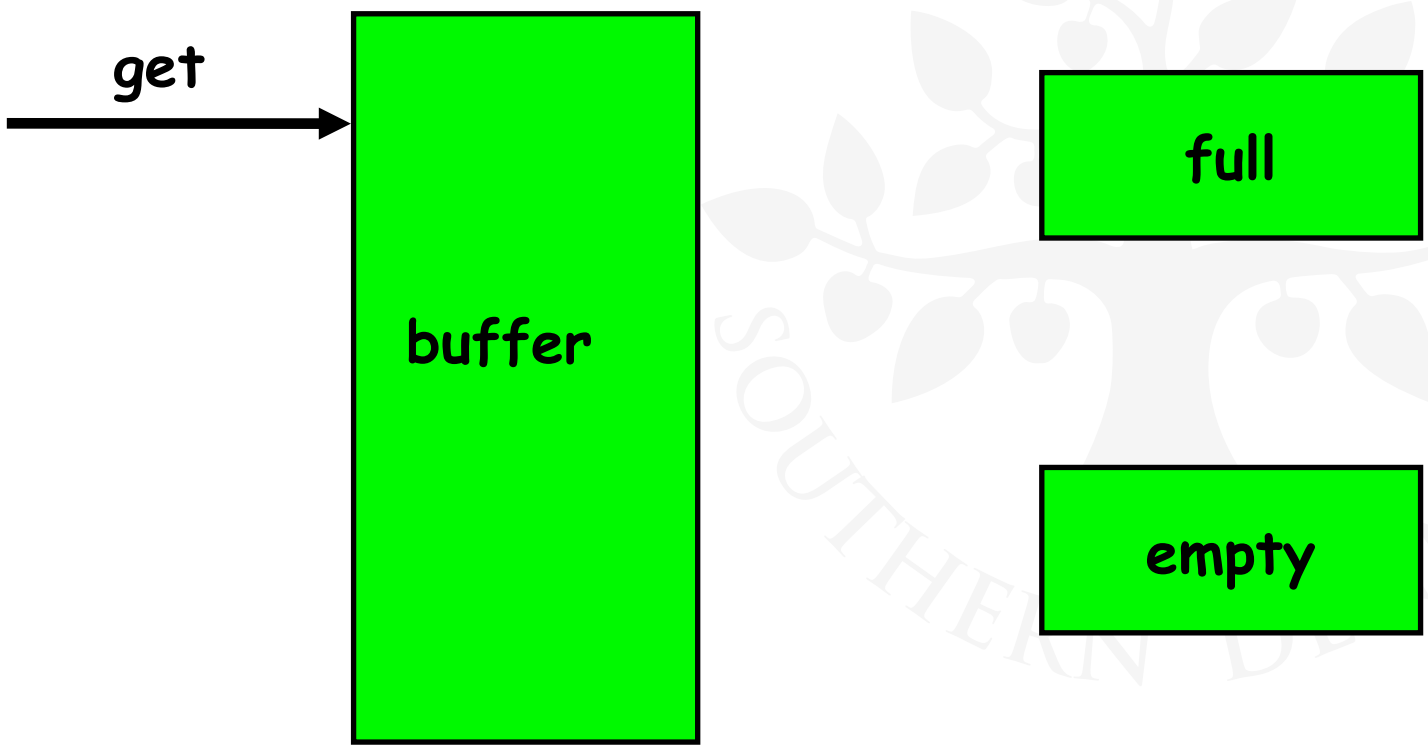

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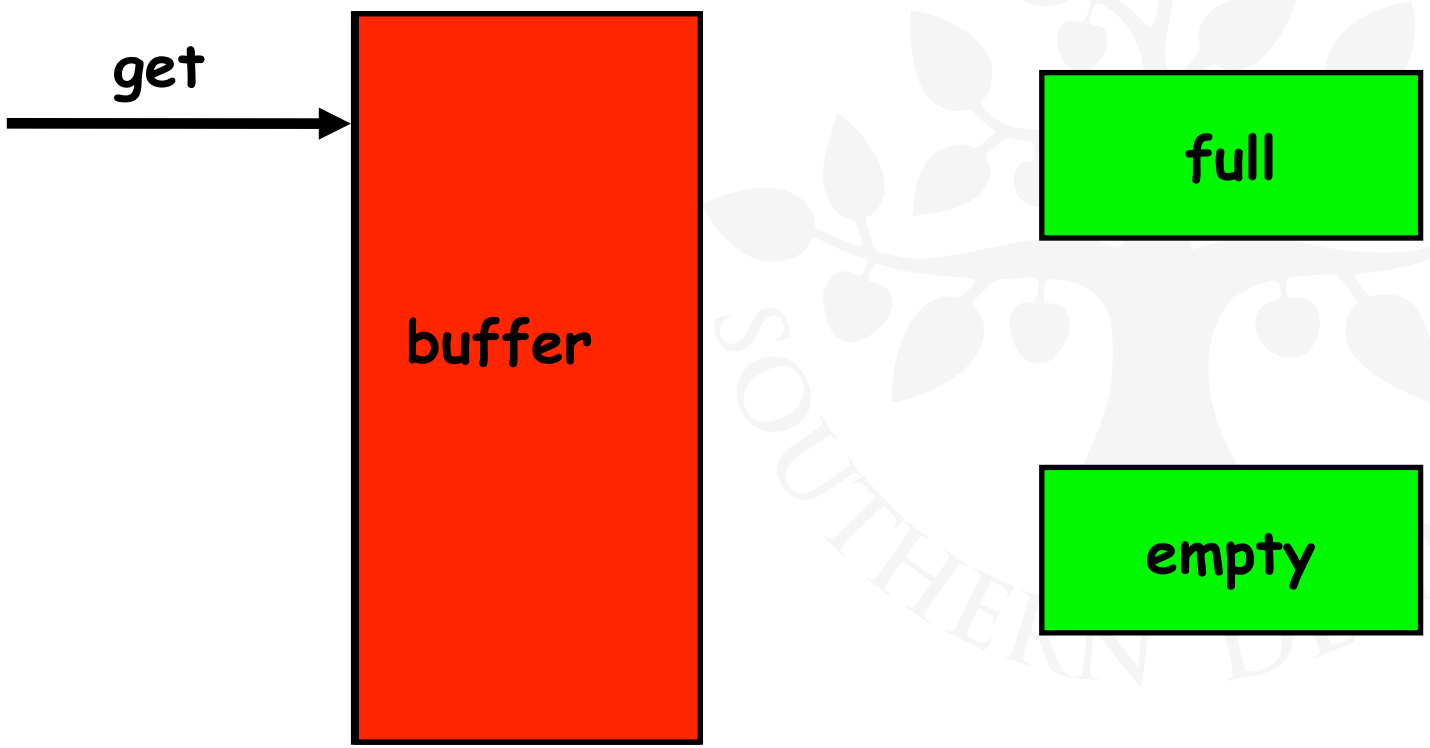

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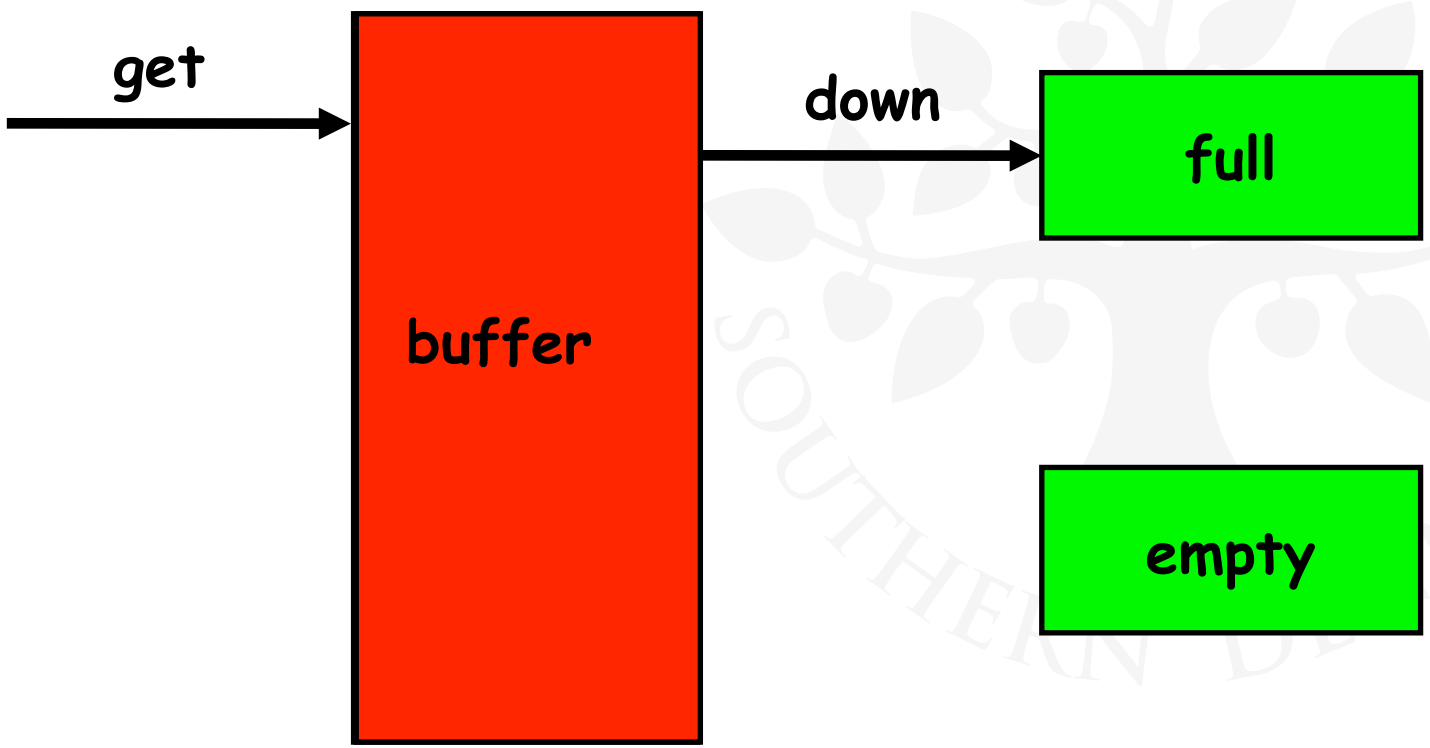

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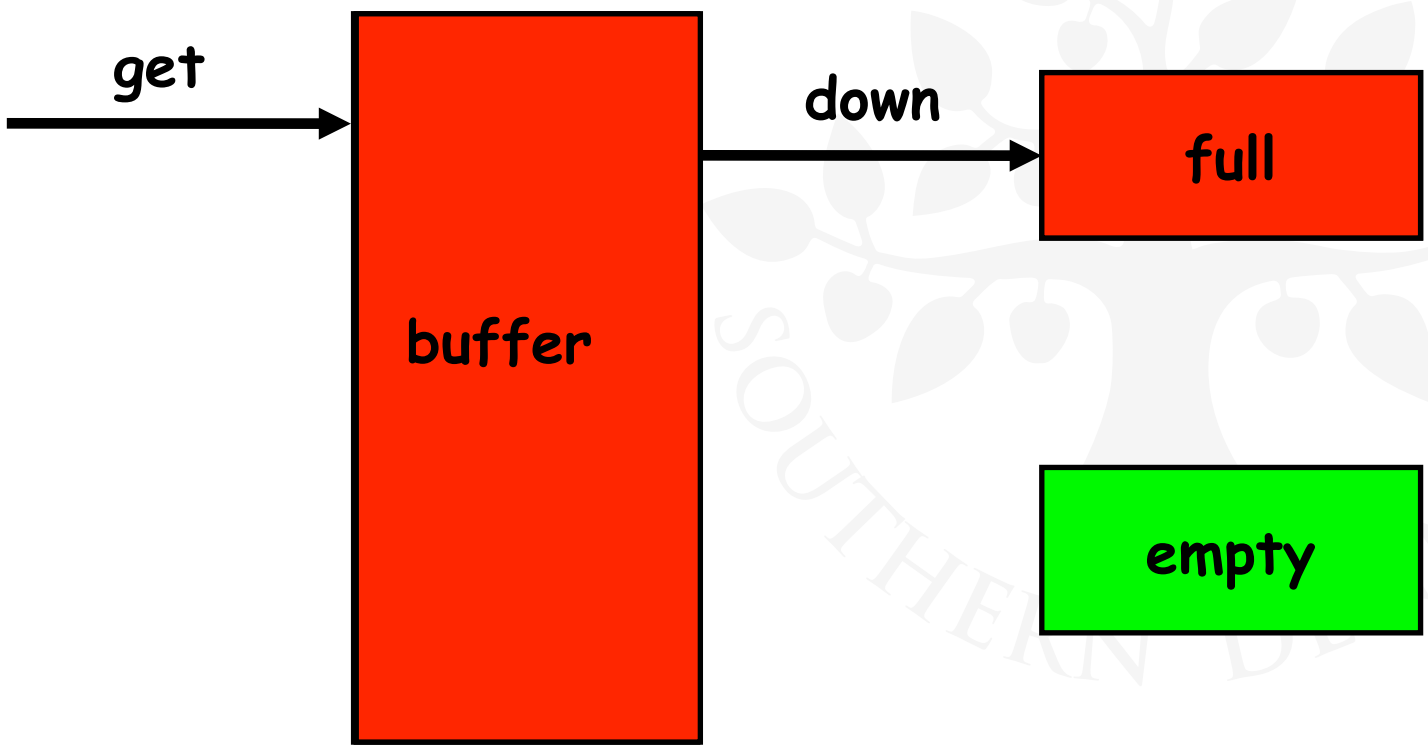

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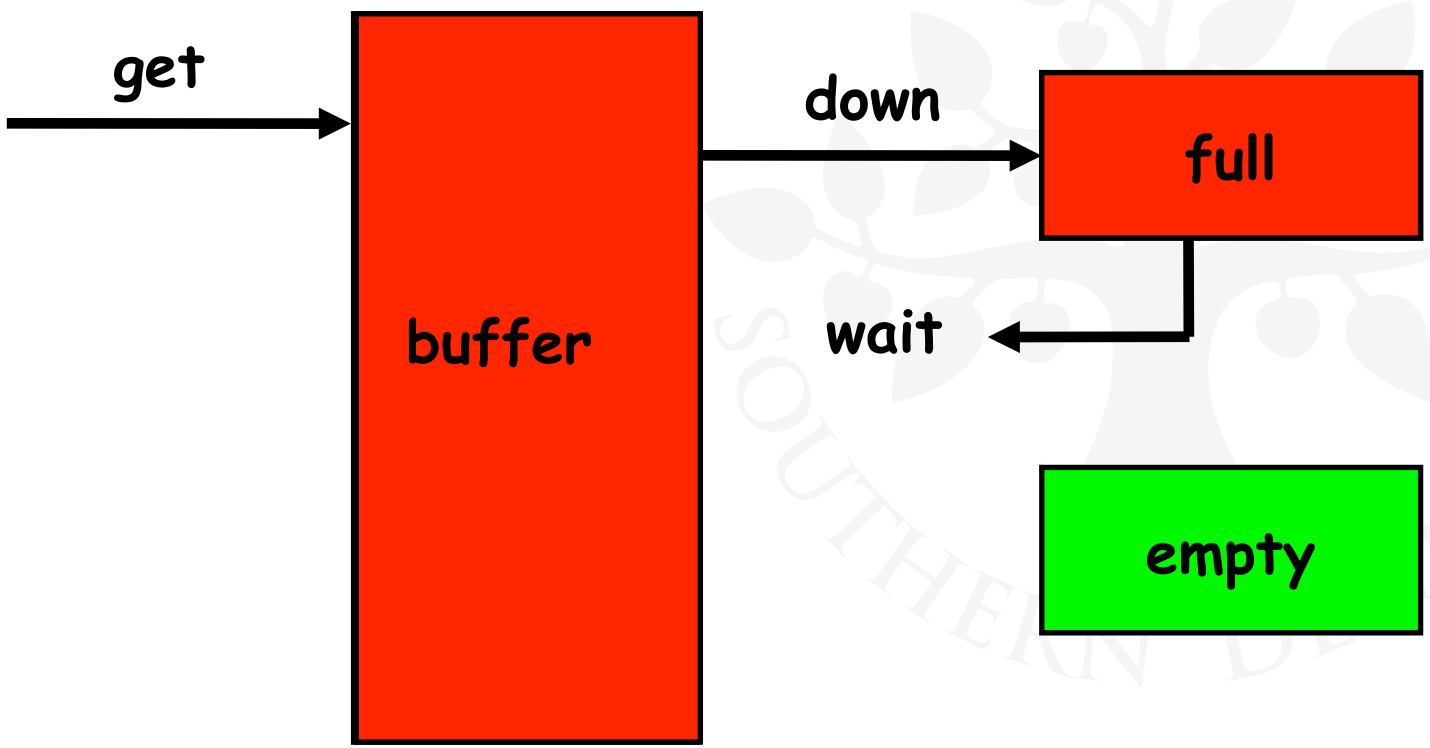

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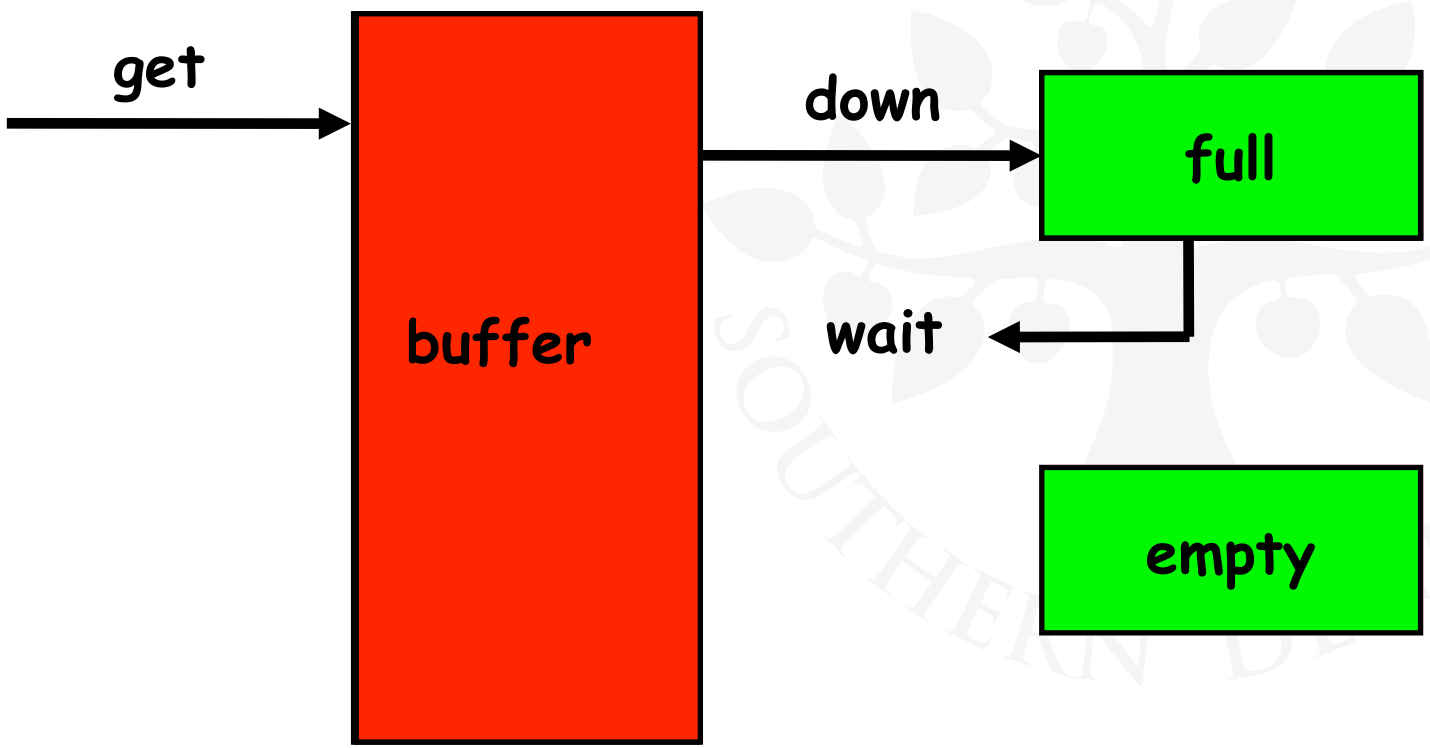

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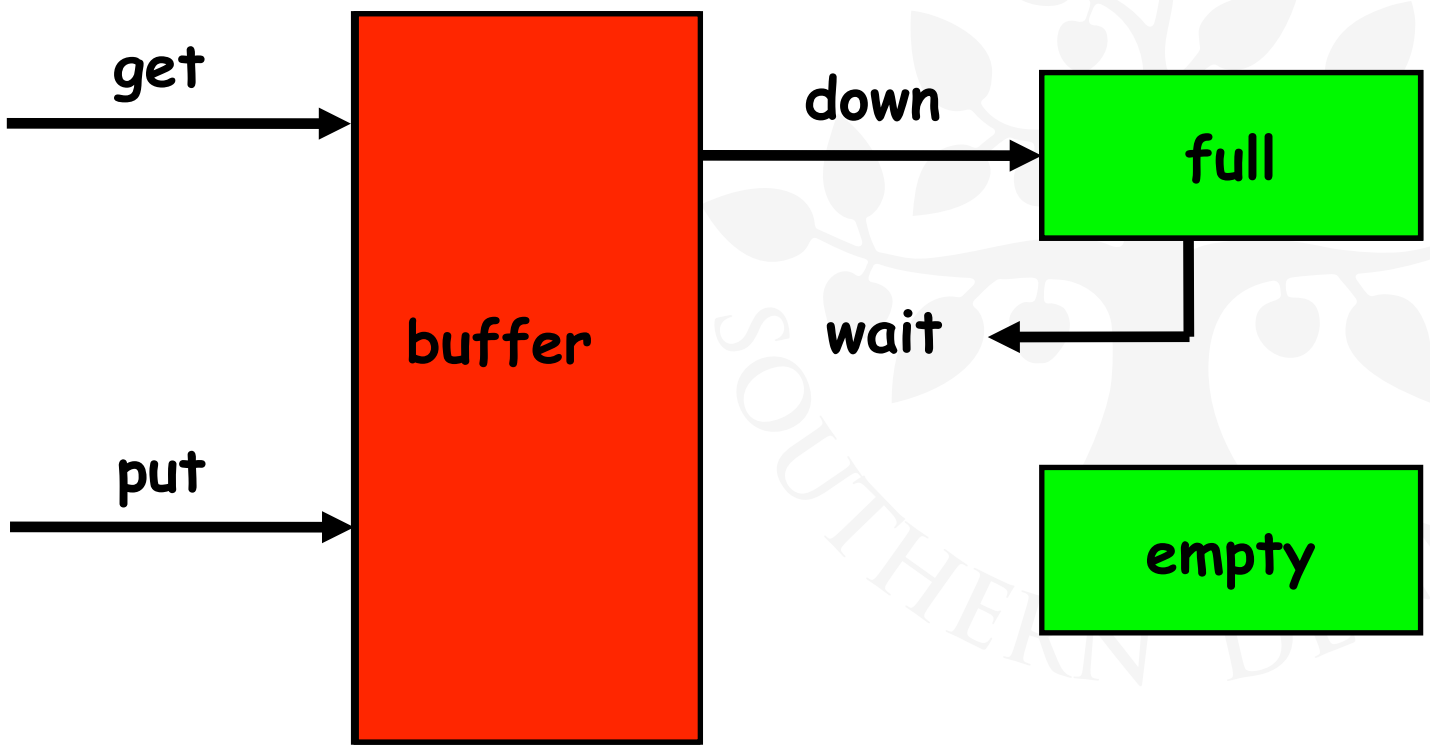

Nested Monitors - Revised Bounded Buffer Program

University of Southern Denmark

The only way to avoid it in Java is by **careful design** :

Nested Monitors - Revised Bounded Buffer Program

University of Southern Denmark

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synchronized public void put(E o)
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    empty.down();
    queue[in] = o;
    count++;
    in = (in+1) % SIZE;
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public void put(E o) throws Int'Exc' {
    empty.down();
    synchronized (this) {
        queue[in] = o;
        count++;
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In this example, the deadlock can be removed by ensuring that the monitor lock for the buffer is not acquired until **after** semaphores are decremented.

Nested Monitors
- Revised Bounded Buffer Model

University of Southern Denmark

The semaphore actions have been moved **outside** the monitor,
i.e., conceptually, to the producer and consumer:

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The semaphore actions have been moved **outside** the monitor,
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```
BUFFER =   (put -> BUFFER
           |get -> BUFFER).

PRODUCER = (empty.down -> put -> full.up  -> PRODUCER).
CONSUMER = (full.down  -> get -> empty.up -> CONSUMER).
```

Nested Monitors
- Revised Bounded Buffer Model

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BUFFER =   (put -> BUFFER
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PRODUCER = (empty.down -> put -> full.up  -> PRODUCER).
CONSUMER = (full.down  -> get -> empty.up -> CONSUMER).
```

Does this behave as desired?

Nested Monitors
- Revised Bounded Buffer Model

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The semaphore actions have been moved **outside** the monitor,
i.e., conceptually, to the producer and consumer:

```
BUFFER =   (put -> BUFFER
           |get -> BUFFER).

PRODUCER = (empty.down -> put -> full.up  -> PRODUCER).
CONSUMER = (full.down  -> get -> empty.up -> CONSUMER).
```

Does this behave as desired?

```
No deadlocks/errors
```

5.5 Monitor invariants

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Like normal invariants, but must also hold when lock is released (wait)!

Summary

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Concepts: monitors (and controllers):

encapsulated data + access procedures +
mutual exclusion + condition synchronisation +
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Models: guarded actions

Practice: private data and synchronized methods (exclusion).
wait(), notify() and notifyAll() for condition synchronisation
single thread active in the monitor at a time