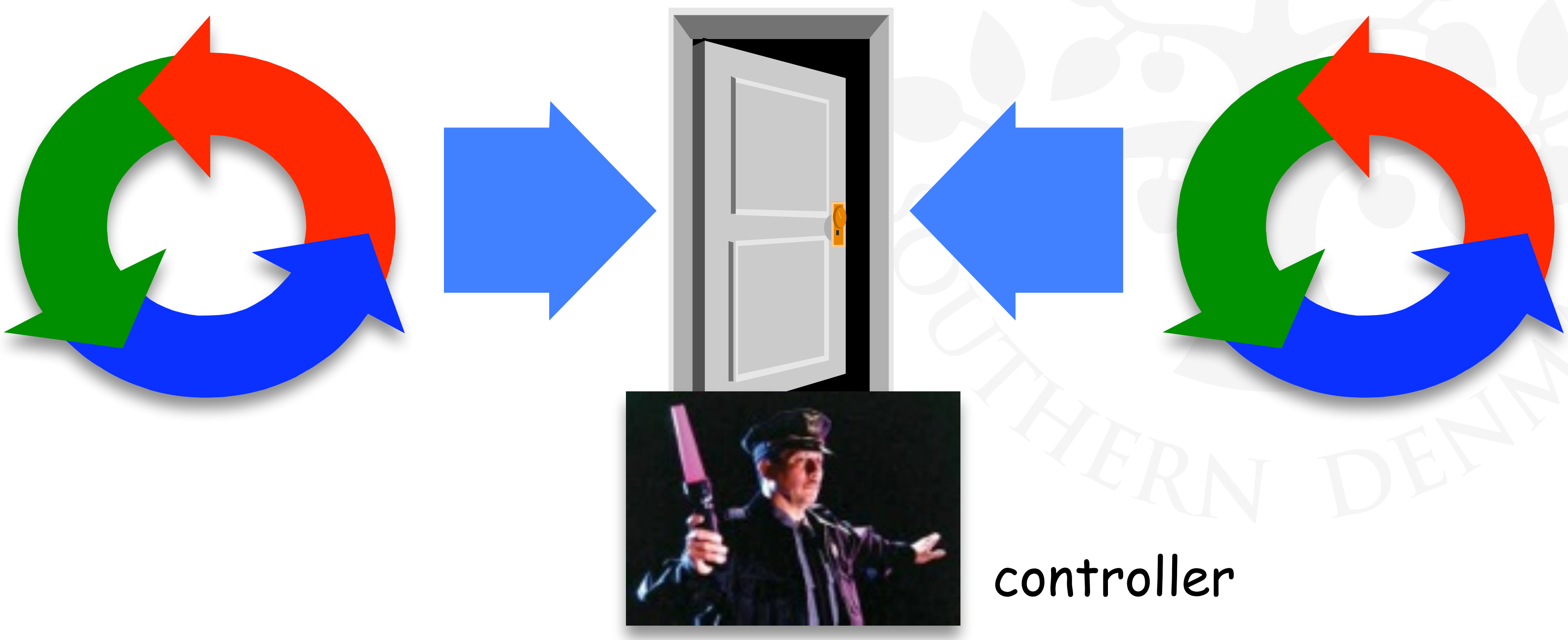
Monitors &
Condition Synchronisation



Monitors & Condition Synchronisation

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Concepts: monitors (and controllers):

encapsulated data + access procedures +
mutual exclusion + condition synchronisation +
single access procedure active in the monitor

nested monitors ("nested monitor problem")

Models: guarded actions

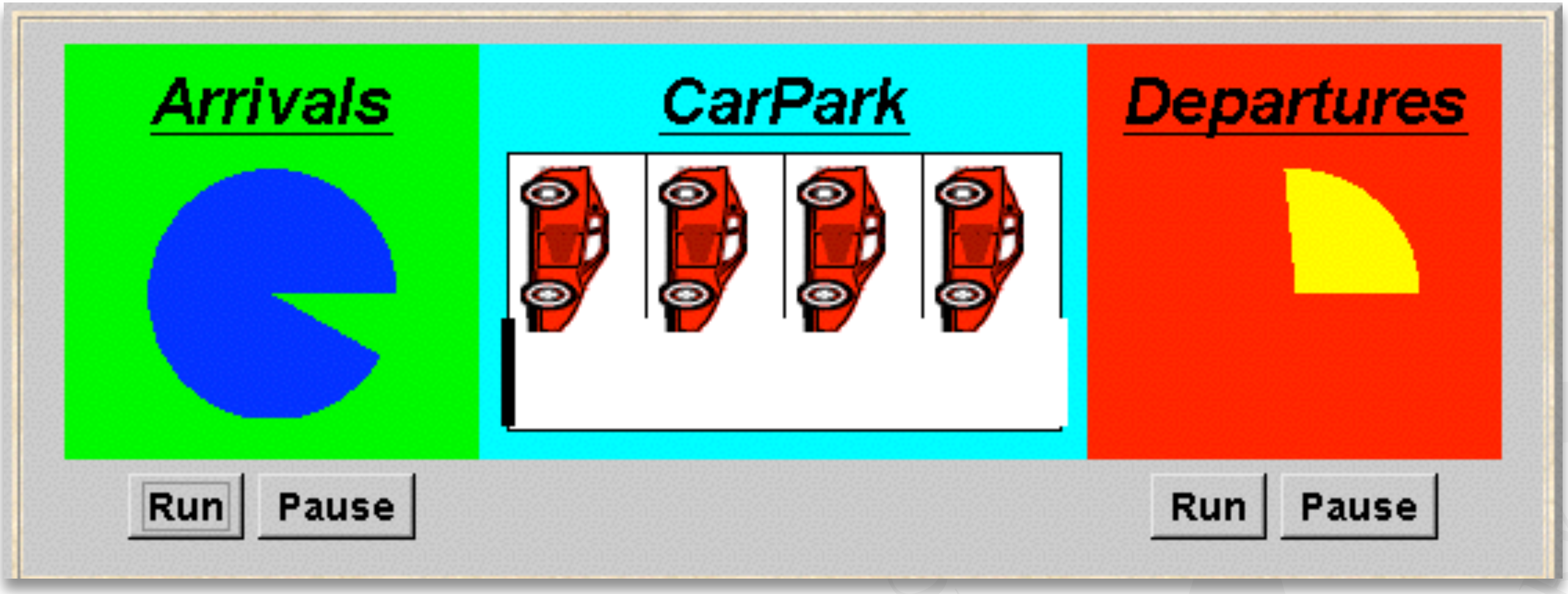
Practice: private data and synchronized methods (exclusion).

wait(), notify() and notifyAll() for condition synchronisation

single thread active in the monitor at a time

Condition Synchronisation

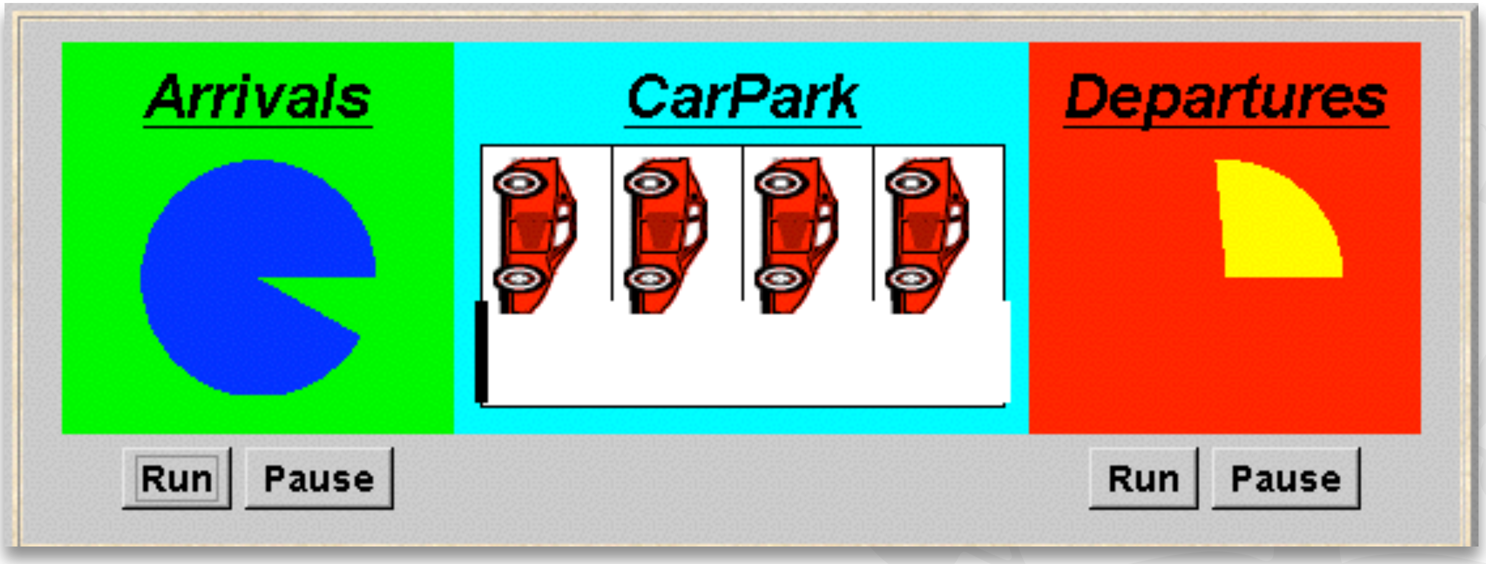
5.1 Condition Synchronisation (Car Park)



A controller is required to ensure:

- cars can only enter when not full
- cars can only leave when not empty

Car Park Model (Actions and Processes)



- **Actions of interest:**
  - `arrive`
  - `depart`

- **Processes:**
  - Arrivals
  - Departures
  - Carpark (Control)

Car Park Model (Structure Diagram)

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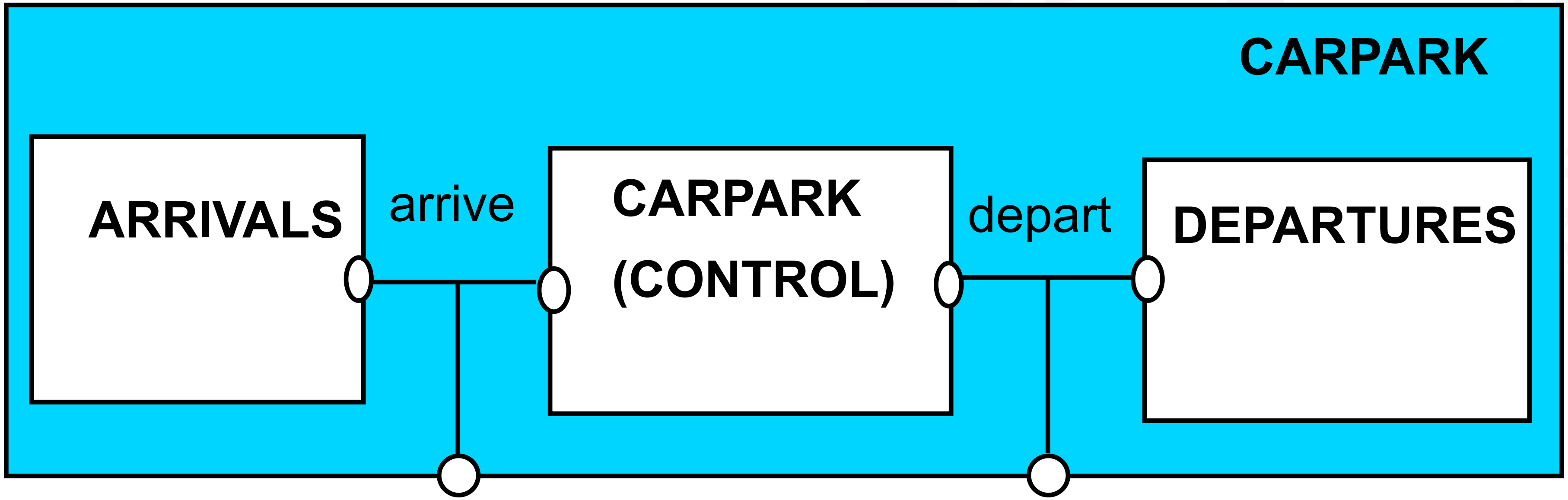
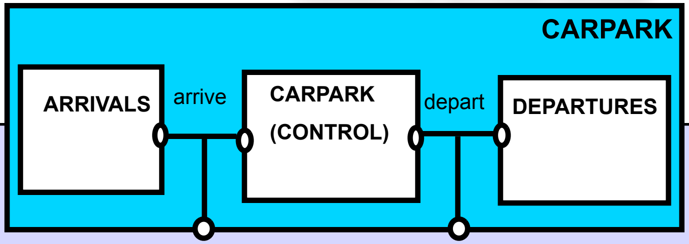
- **Actions of interest:**
  - `arrive`
  - `depart`

- **Identify processes:**
  - Arrivals
  - Departures
  - Carpark (Control)



Car Park Model (FSP)




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

DEPARTURES = (depart -> DEPARTURES).

CONTROL(CAPACITY=4) = SPACES[CAPACITY],
SPACES[spaces:0..CAPACITY] =
        (when (spaces>0)          arrive -> SPACES[spaces-1]
        |when (spaces<CAPACITY) depart -> SPACES[spaces+1]).

||CARPARK = (ARRIVALS || DEPARTURES || CONTROL(4)).
```

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

LTS?

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

Car Park Program

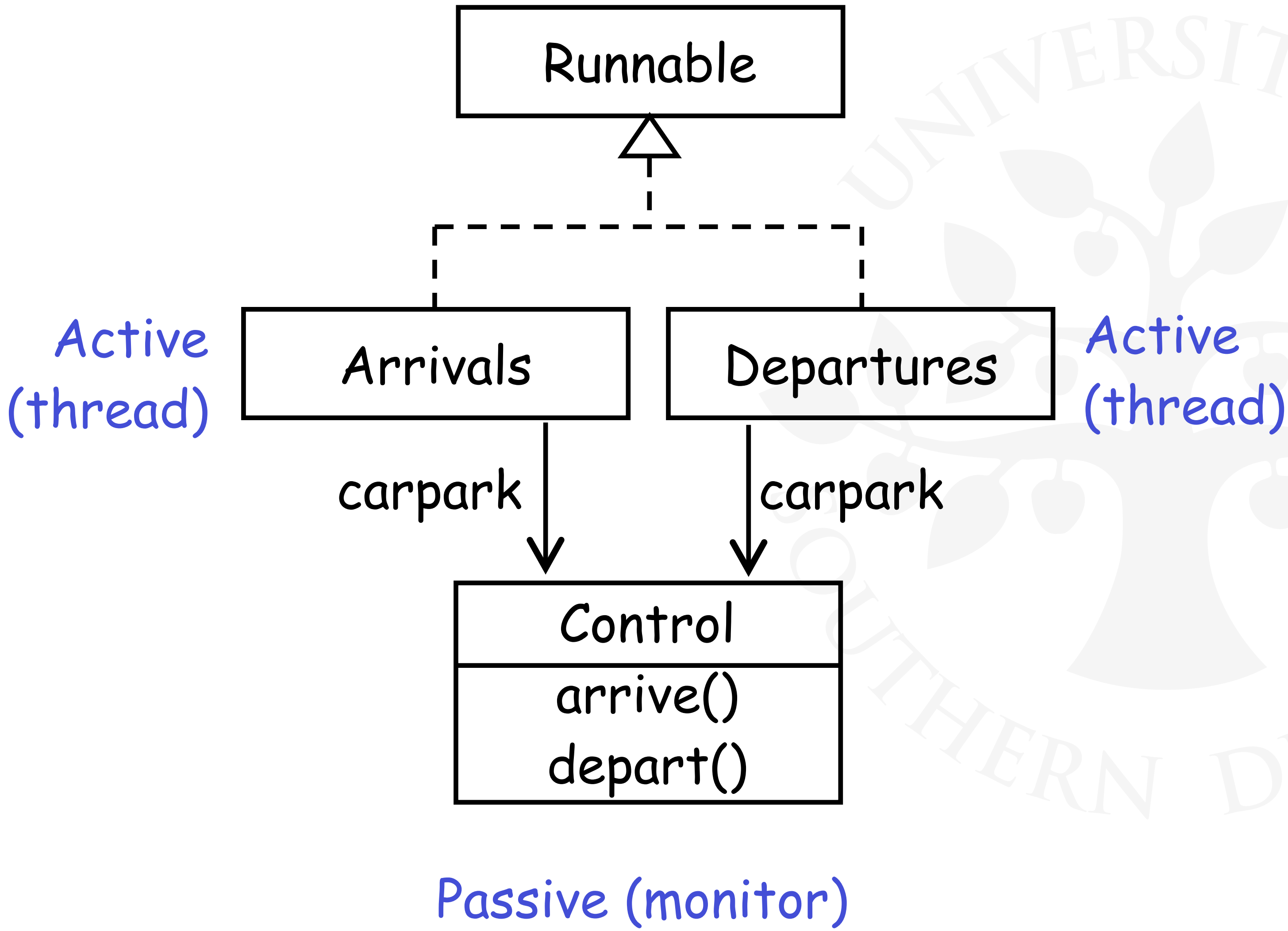
- Model:
  - all entities are processes interacting via **shared actions**
- Implementation:

  we need to identify threads and monitors:
  - thread - **active** entity which initiates (output) actions
  - monitor - **passive** entity which responds to (input) actions.

For the carpark?

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

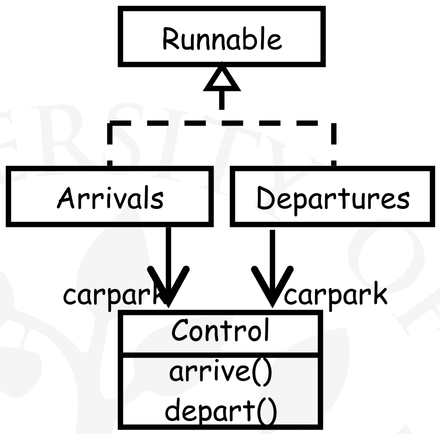
Car Park Program
(Interesting part of Class Diagram)



Car Park Program - Main

The main() method creates:

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




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

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 _
    }
}
```

Would like to somehow block Arrivals thread here…

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

Where should we do the “blocking”?

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

Control Monitor

```
CONTROL(CAPACITY=4) = SPACES[CAPACITY],
SPACES[spaces:0..CAPACITY] =
       (when(spaces>0)         arrive -> SPACES[spaces-1]
       |when(spaces<CAPACITY) depart -> SPACES[spaces+1]).
```

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

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

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

    synchronized void depart() {
        ... ++spaces; ...
    }
}
```

Encapsulation ~ protected

Mutual exclusion ~ synchronized

Condition synchronisation:

- Block, if full? ¬(spaces>0)
- Block, if empty? ¬(spaces < CAPACITY)

Condition Synchronisation in Java

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();
```

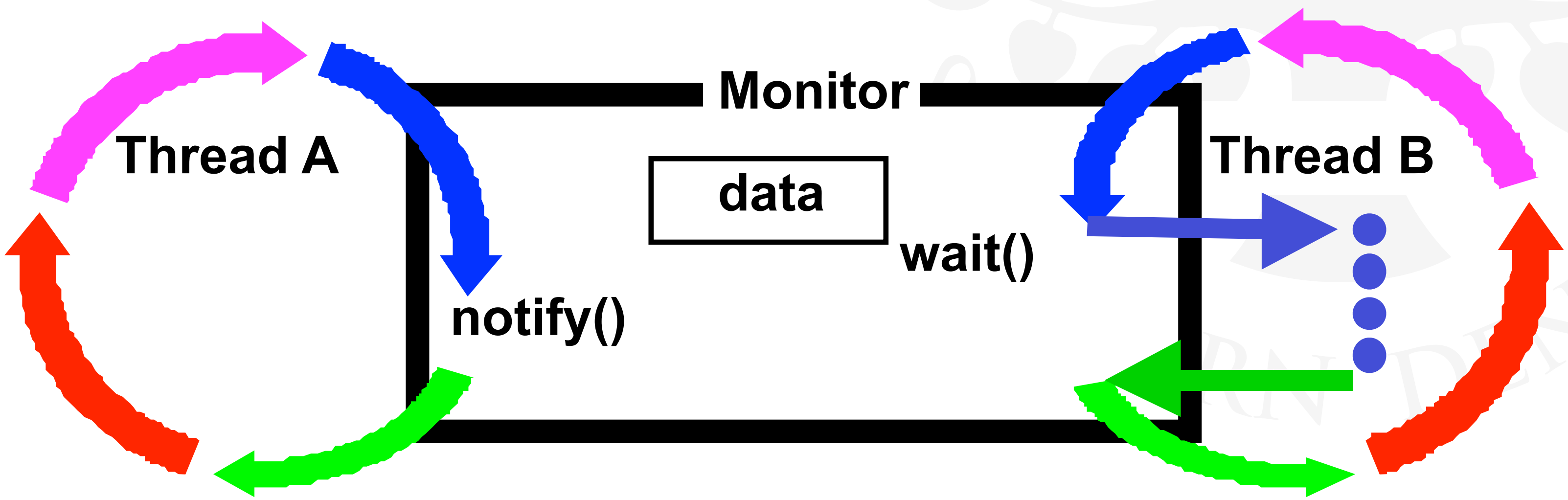
Wakes up (notifies) thread(s) waiting on the object's queue.

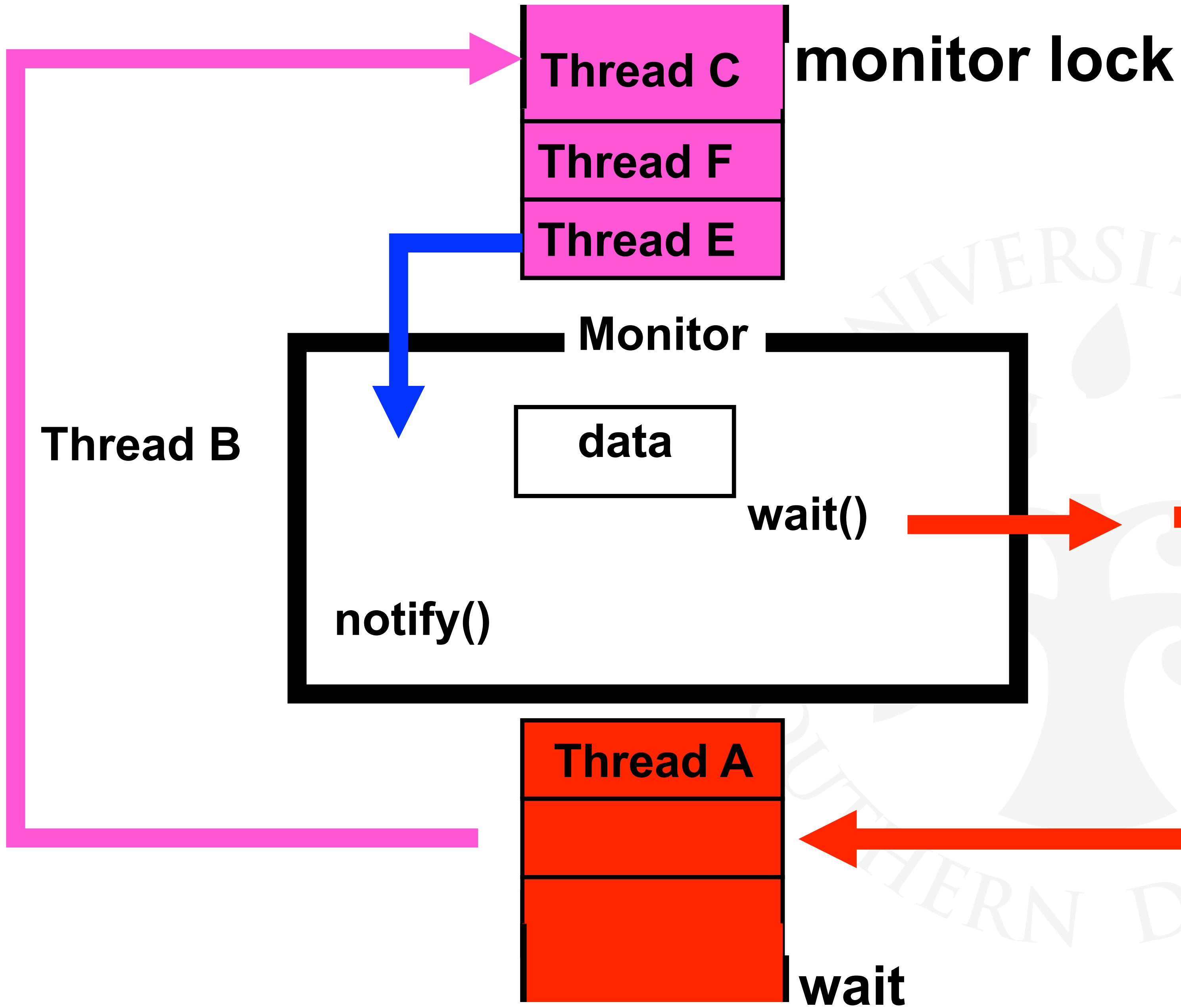
Condition Synchronisation in Java (enter/exit)

A thread:

- **Enters** a monitor when a thread acquires the lock associated with the monitor;
- **Exits** a monitor when it releases the lock.

Wait() causes the thread to **exit** the monitor, permitting other threads to **enter** the monitor




Thread C
monitor lock
Thread F
Thread E
Monitor
Thread B
data
wait()
notify()
Thread A
wait

Condition Synchronisation in FSP and Java

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```
FSP:   when (cond) action -> NEWSTATE
```

```
synchronized void action() throws Int'Exc' {
         if (!cond) wait();
    // modify monitor data
    notifyAll();
}
```

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

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```
CONTROL(CAPACITY=4) = SPACES[CAPACITY],
SPACES[spaces:0..CAPACITY] =
               (when(spaces>0)          arrive -> SPACES[spaces-1]
               |when(spaces<CAPACITY)   depart -> SPACES[spaces+1]).
```

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

    synchronized void arrive() throws Int'Exc' {
        while (!(spaces>0)) wait();
        --spaces;
        notifyAll();
    }

    synchronized void depart() throws Int'Exc' {
        while (!(spaces<CAPACITY)) wait();
        ++spaces;
        notifyAll();
    }
}
```

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

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

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notify() can be used instead of notifyAll() only when both of these conditions hold:

Uniform waiters. Only one condition predicate and each thread executes the same logic upon returning from wait(); and

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**.
- **Passive** entities (that respond to actions) are implemented as **monitors**.

Each guarded action in the model of a monitor is implemented as a **synchronized** method which uses a while loop and **wait()** to implement the guard.

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

Semaphores are widely used for dealing with inter-process synchronisation in operating systems.

Semaphore s : integer var that can take only non-negative values.

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

Usually implemented as blocking wait:

s.down(): **if** (s>0) **then** decrement(s);
else block execution of calling process

s.up(): **if** (processes blocked on s) **then** awake one of them
else increment(s);

Modelling Semaphores

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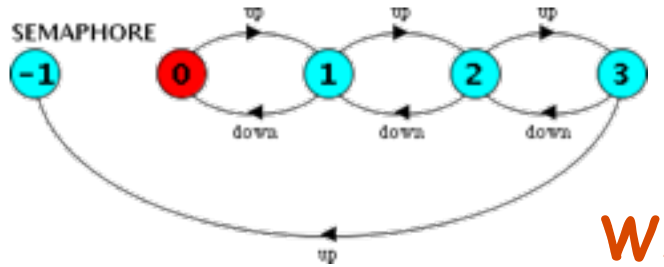
To ensure analysability, we only model semaphores that take a finite range of values. If this range is exceeded then we regard this as an ERROR.

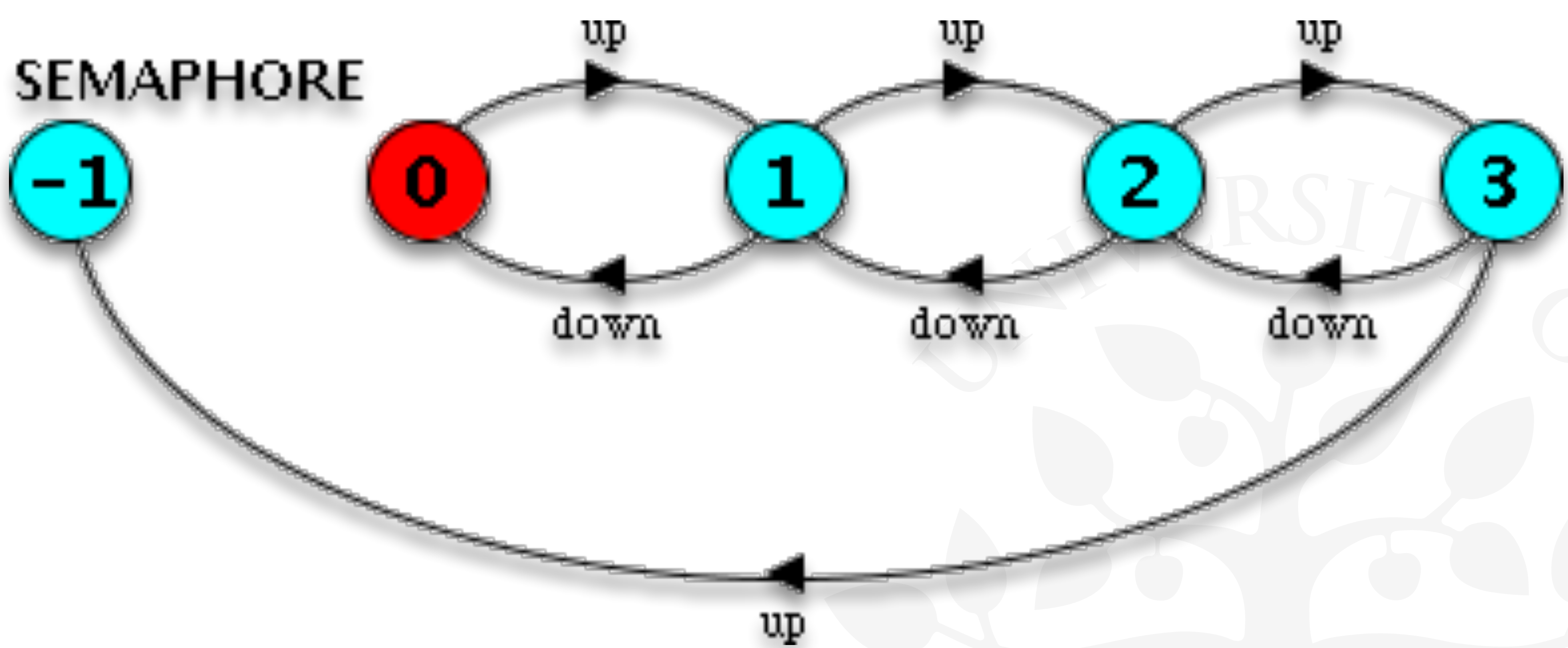
```
const Max = 3
range Int = 0..Max

SEMAPHORE(N=0) = SEMA[N], // N initial value
SEMA[v:Int]    = (up->SEMA[v+1]
                 |when(v>0) down->SEMA[v-1]),
SEMA[Max+1]    = ERROR.
```

LTS?



What if we omit the last line above?

Modelling Semaphores



Action down is only accepted when value (v) of the semaphore is greater than 0.

Action up is not guarded.

Trace to a violation:

up → up → up → up

Semaphore Demo - Model

```
SEMAPHORE(N=0) = SEMA[N], // N initial value
SEMA[v:Int]    = (up->SEMA[v+1]
                 |when(v>0) down->SEMA[v-1]),
```

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

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

||SEMADEMO = (p[1..3]:LOOP
             || {p[1..3]}::mutex:SEMAPHORE(1)).
```

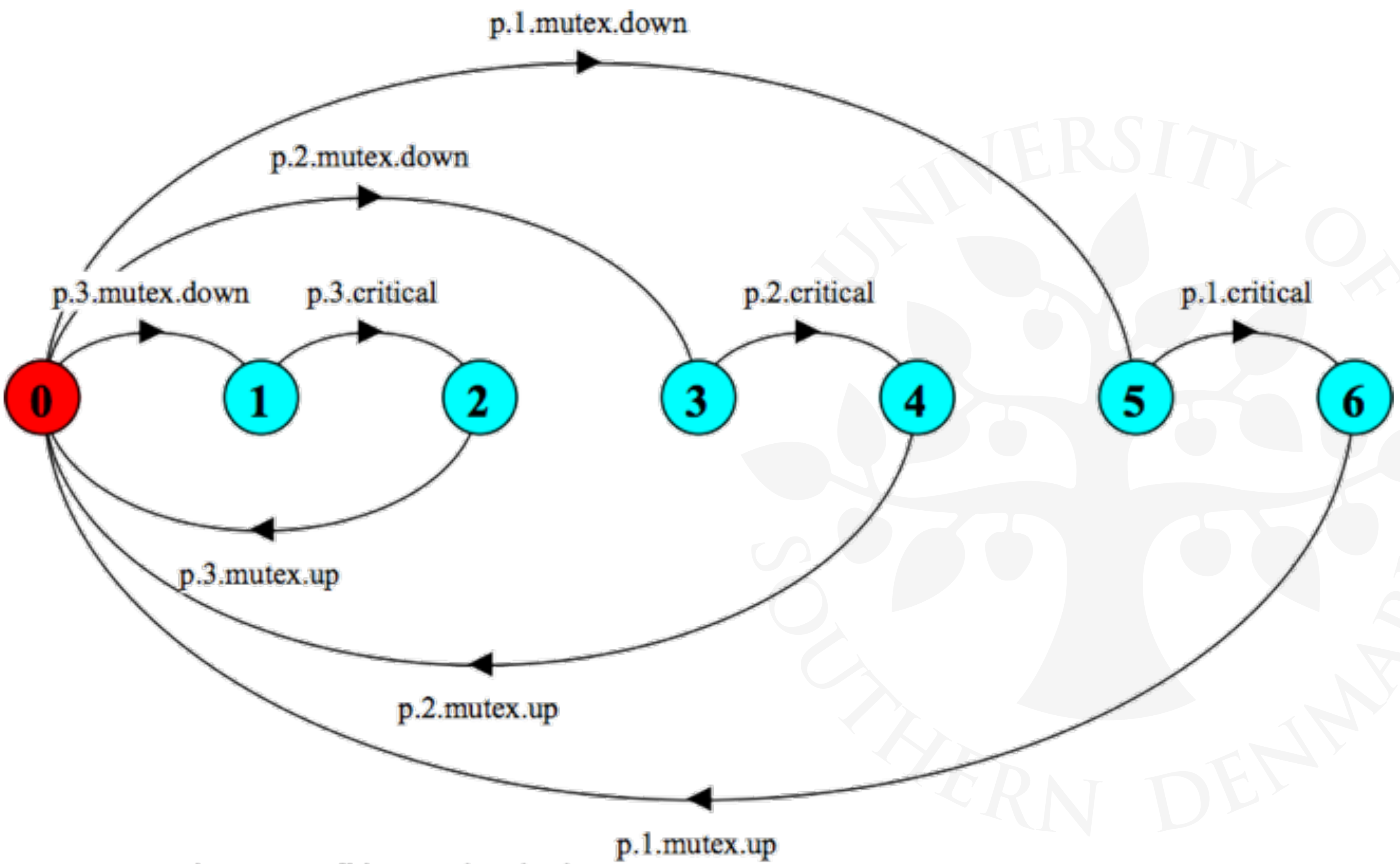
For mutual exclusion, the semaphore initial value is 1. **Why?**

Is the **ERROR** state reachable for **SEMADEMO**?

Is a binary semaphore sufficient (i.e. **Max=1**) ?

LTS?

Semaphore Demo - Model



Semaphores in Java

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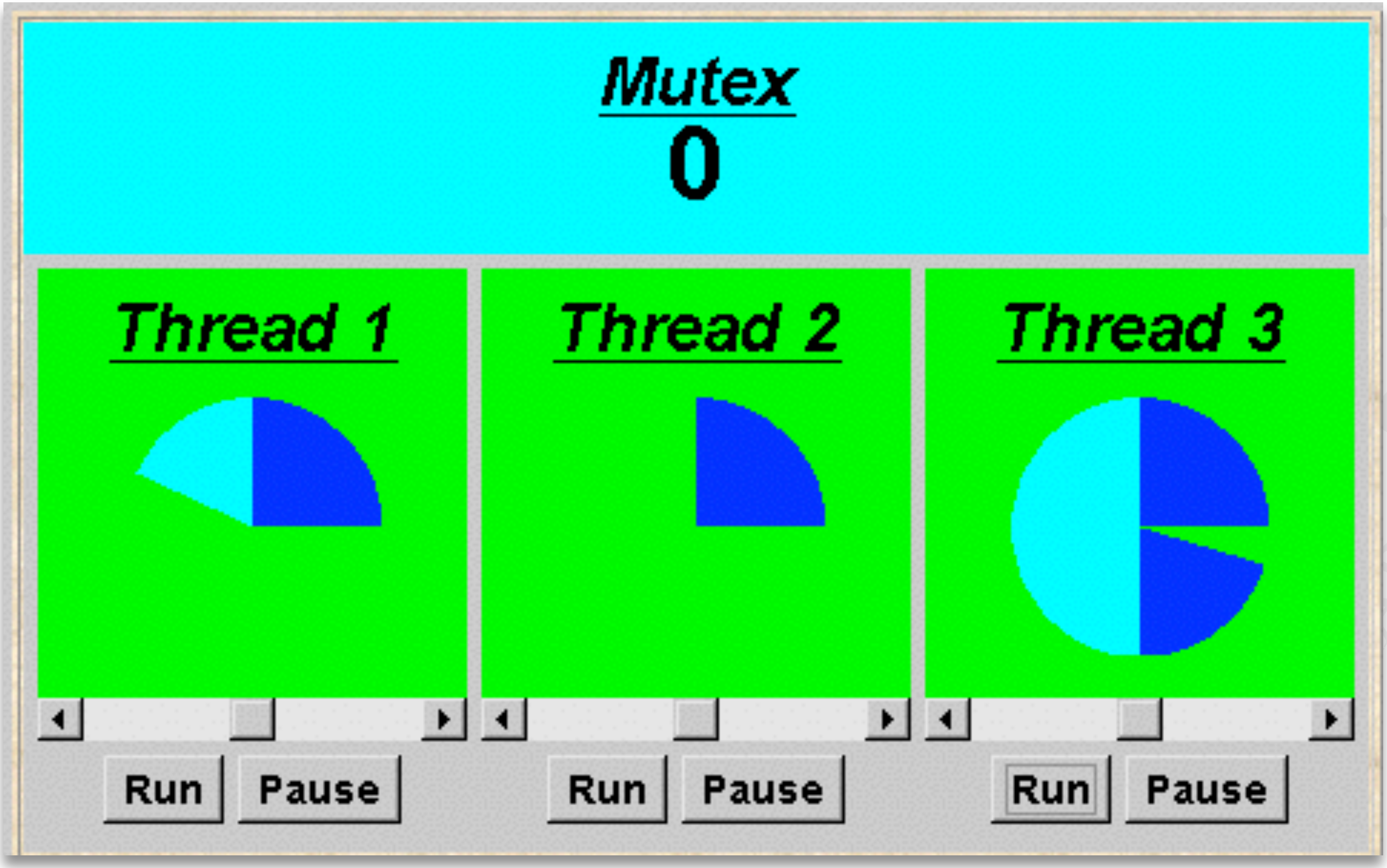
```
SEMA[v:Int] = (when(v>0) down->SEMA[v-1]
              |          up->SEMA[v+1]),
```

```
public class Semaphore {
    protected int value;

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

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

    synchronized public void up() {
        ++value;
        notifyAll();
    }
}
```

Do we need `notifyAll()` here?

...what about here?

`SEMADEMO` Display



SEMADEMO Program - MutexLoop


```
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 _) {}
    }
}
```

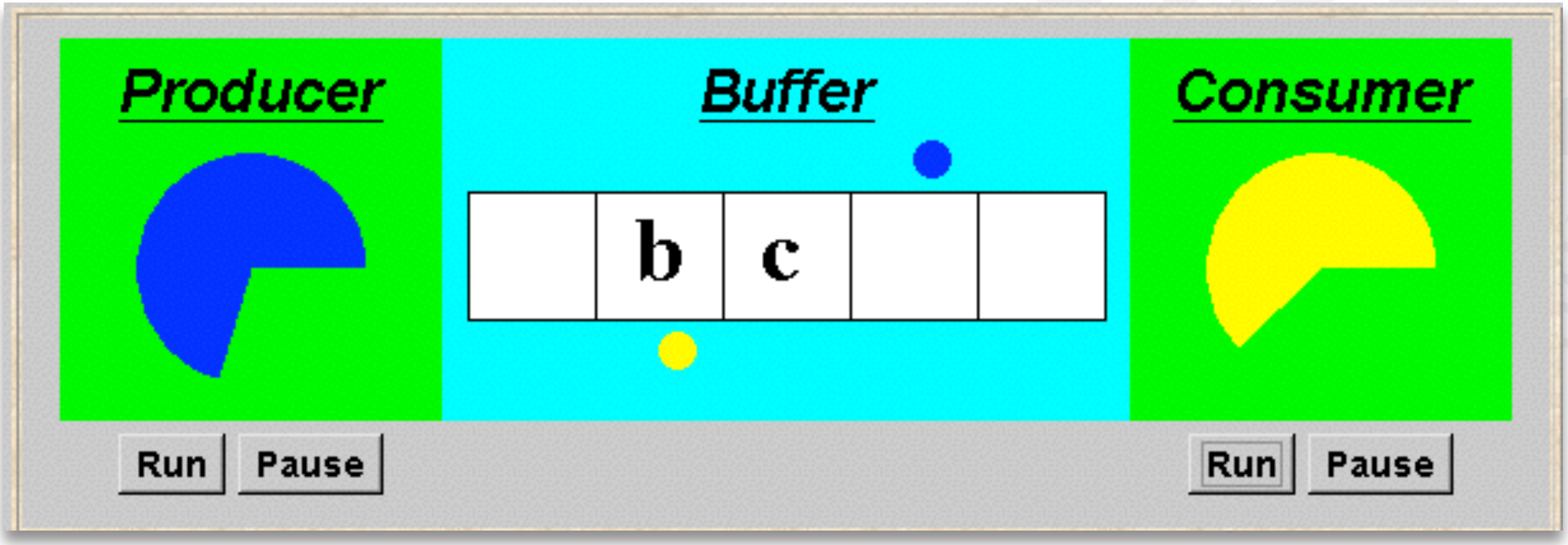
However (in practice), semaphore is a **low-level** mechanism often used in implementing **higher-level** monitor constructs.

Producer / Consumer

5.3 Producer / Consumer

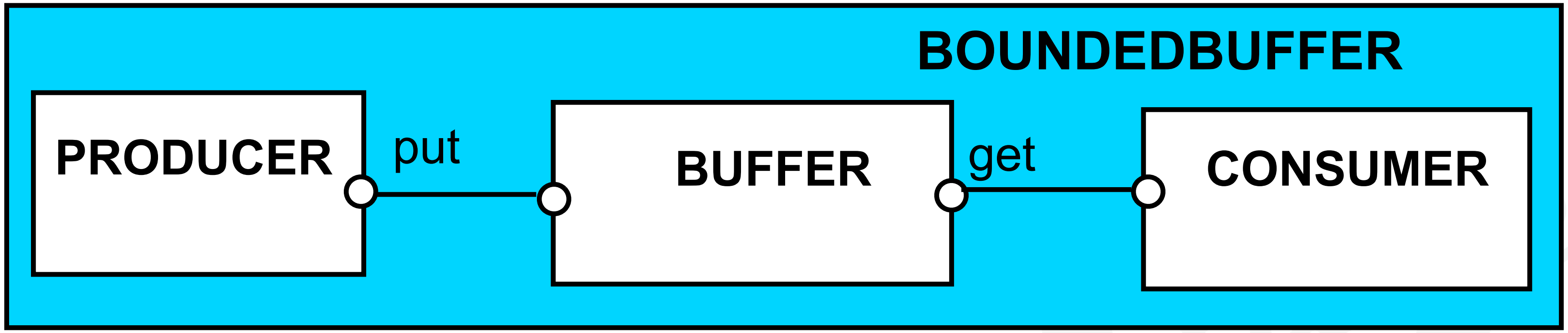
A **bounded buffer** consists of a fixed number of slots.

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



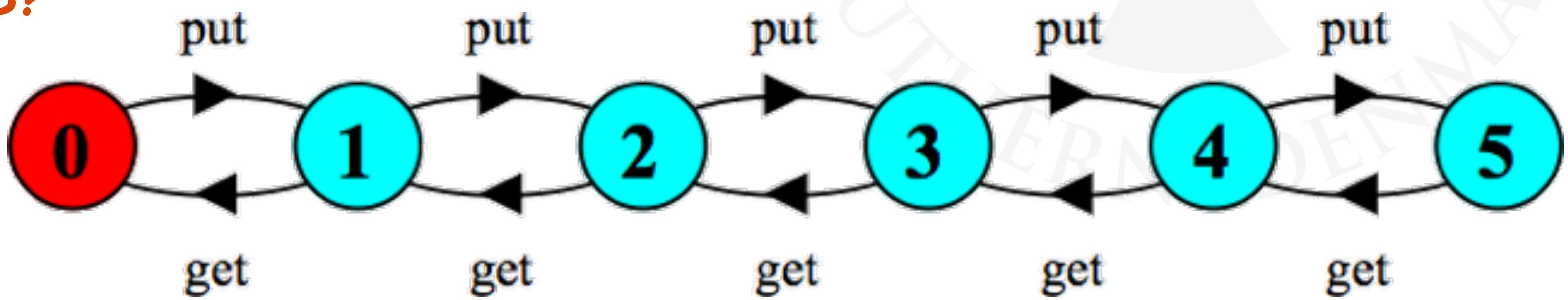
≈ Car Park Example!

Producer / Consumer
- a Data-Independent Model

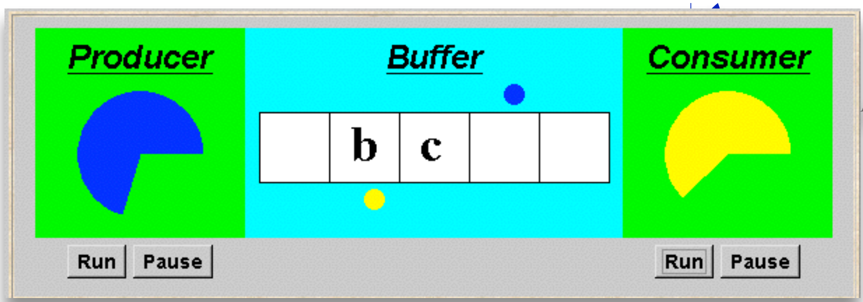


The behaviour of BOUNDEDBUFFER is independent of the actual data values, and so can be modelled in a data-independent manner (i.e., we abstract away the letters).

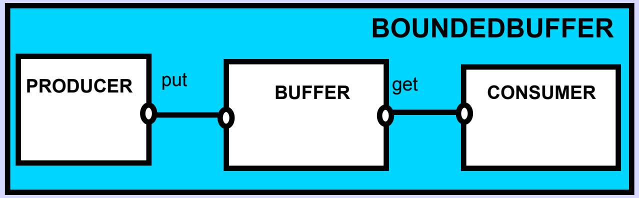
LTS?



Producer / Consumer




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

CONSUMER = (get->CONSUMER).

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

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



Bounded Buffer Program - Buffer Monitor

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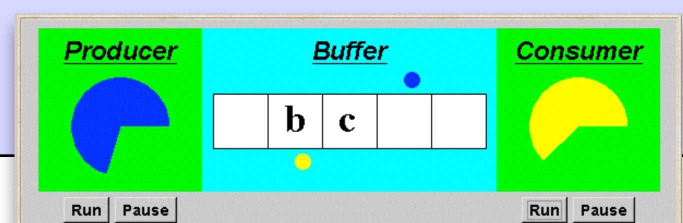
```
BUFFER(SIZE=5) = COUNT[0],
COUNT[count:0..SIZE] =
        (when (count<SIZE) put -> COUNT[count+1]
        |when (count>0)    get -> COUNT[count-1]).
```

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

```
class BufferImpl<E> implements Buffer<E> {
    protected E[] queue;
    protected int in, out, count, SIZE;
    …
    synchronized void put(E o) throws Int'Exc' {
        while (!(count<SIZE)) wait();
        queue[in] = o;
        count++;
        in = (in+1) % SIZE;
        notifyAll();
    }
```

if(count == 1)

Can we use notify()?



Similarly for get()

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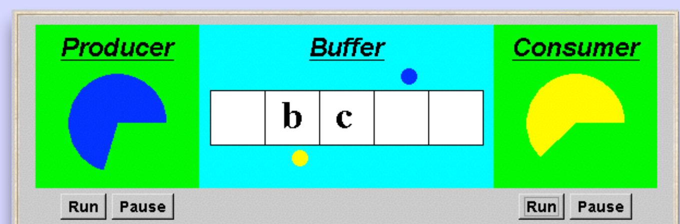
```
BUFFER(SIZE=5) = COUNT[0],
COUNT[count:0..SIZE] =
        (when (count<SIZE) put -> COUNT[count+1]
        |when (count>0)    get -> COUNT[count-1]).
```

```
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;
     }
```




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

Producer Process

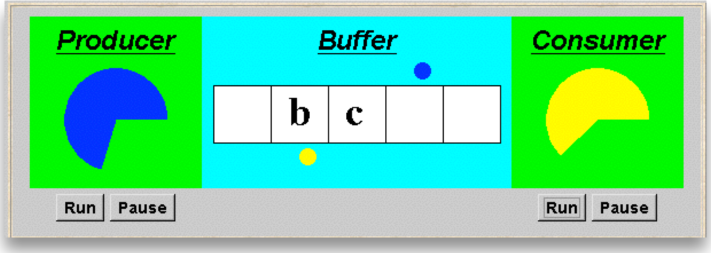
```
PRODUCER = (put->PRODUCER).
```

```
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 _) {}
    }
}
```

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

The Nested Monitor Problem

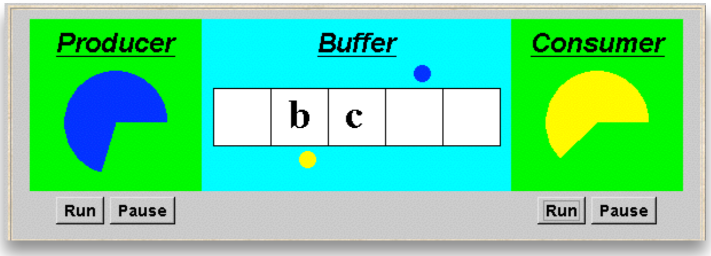
5.4 Nested Monitors (Semaphores)



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:

```
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




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

synchronized public E get() throws Int'Exc' {
    full.down();
    E o = queue[out];
    queue[out] = null;
    count--;
    out = (out+1) % SIZE;
    empty.up();
    return o;
}
```

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

full is decremented by a **get**, which is blocked if full is zero, i.e., if the buffer is empty.

Does this behave as desired?

Nested Monitors Model

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

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

CONSUMER = (get -> CONSUMER).

SEMAPHORE(N=0) = SEMA[N],
SEMA[v:Int]    = (when(v>0) down -> SEMA[v-1]
                 |          up   -> SEMA[v+1]).

BUFFER = (put -> empty.down -> full.up  -> BUFFER
         |get -> full.down  -> empty.up -> BUFFER).

||BOUNDEDBUFFER =
     ( PRODUCER || BUFFER || CONSUMER
                || empty:SEMAPHORE(5)
                || full:SEMAPHORE(0) ).
```

Does this behave as desired?

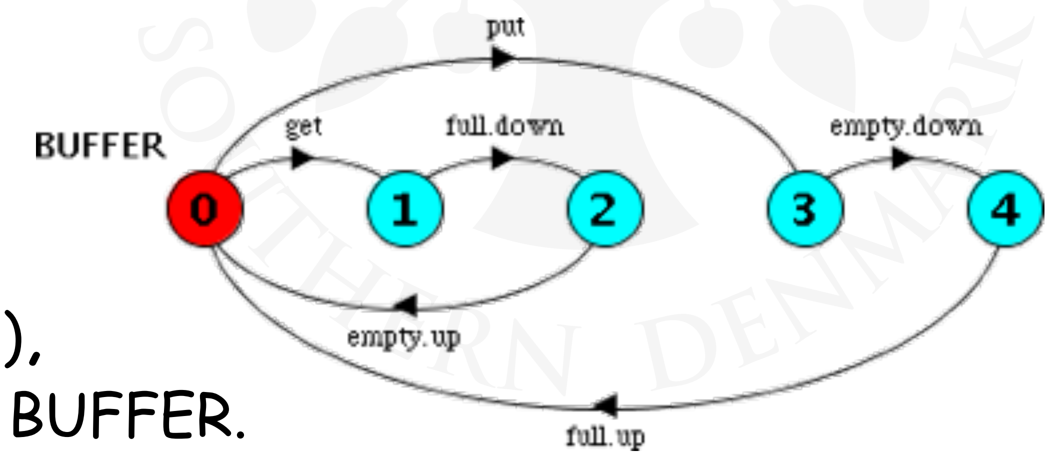
Nested Monitors

LTSA analysis predicts a **DEADLOCK**:

```
Composing
  potential DEADLOCK
...
Trace to DEADLOCK:
      get
```

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

Looking at BUFFER:
After **get** the next action is
full.down (blocks).

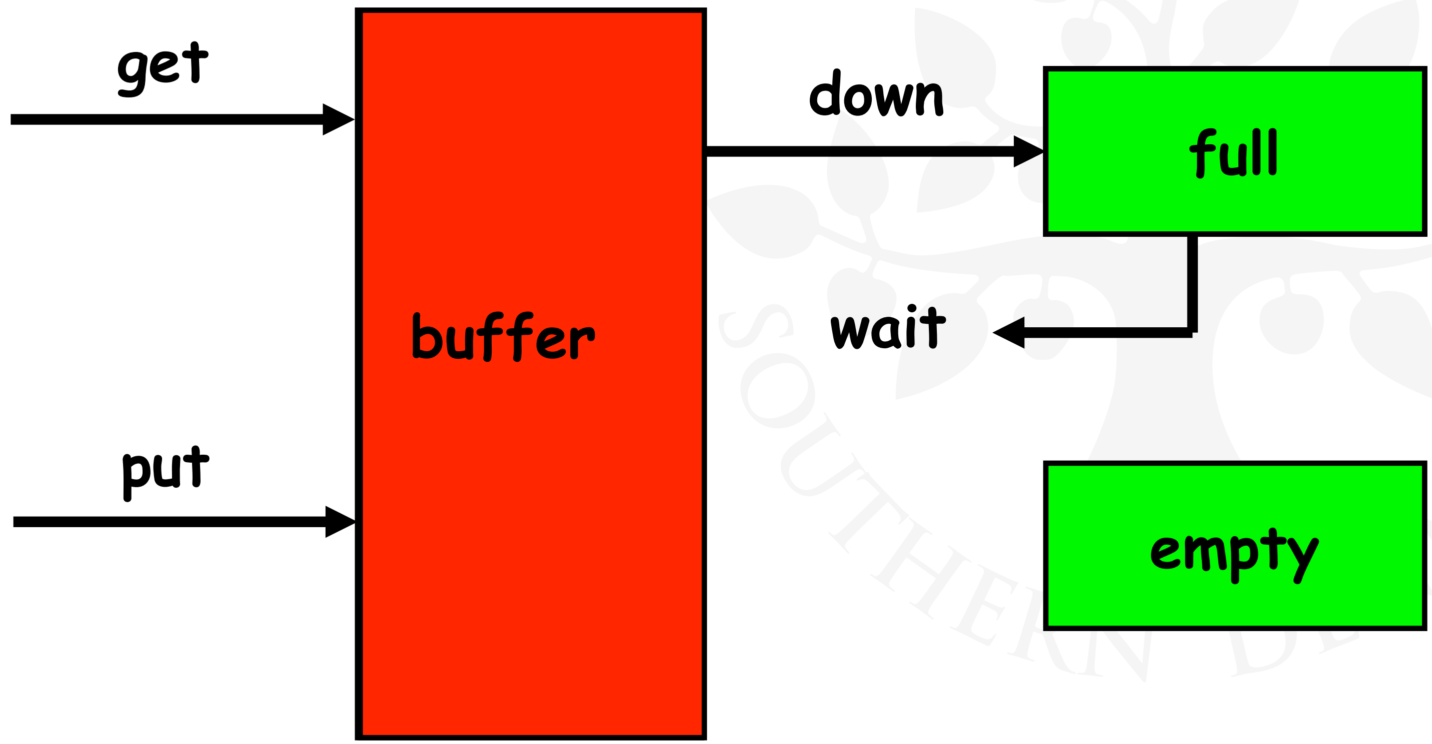


We cannot do **put** (and unblock full),
since we have the "semaphore" for BUFFER.

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

Nested Monitor Problem

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



Nested Monitors - Revised Bounded Buffer Program

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

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

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

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.

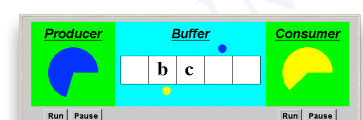
Nested Monitors
- Revised Bounded Buffer Model

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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An invariant for a monitor is an assertion concerning the variables it encapsulates. This assertion must hold whenever there is no thread executing inside the monitor, i.e., on thread **entry** to and **exit** from a monitor .

INV(CarParkControl):		$0 \le spaces \le CAPACITY$
INV(Semaphore):		$0 \le value$
INV(Buffer):		$0 \le count \le SIZE$
	and	$0 \le in < SIZE$
	and	$0 \le out < SIZE$
	and	$in = (out + count) \% SIZE$

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 +
single access procedure active in the monitor

nested monitors ("nested monitor problem")

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