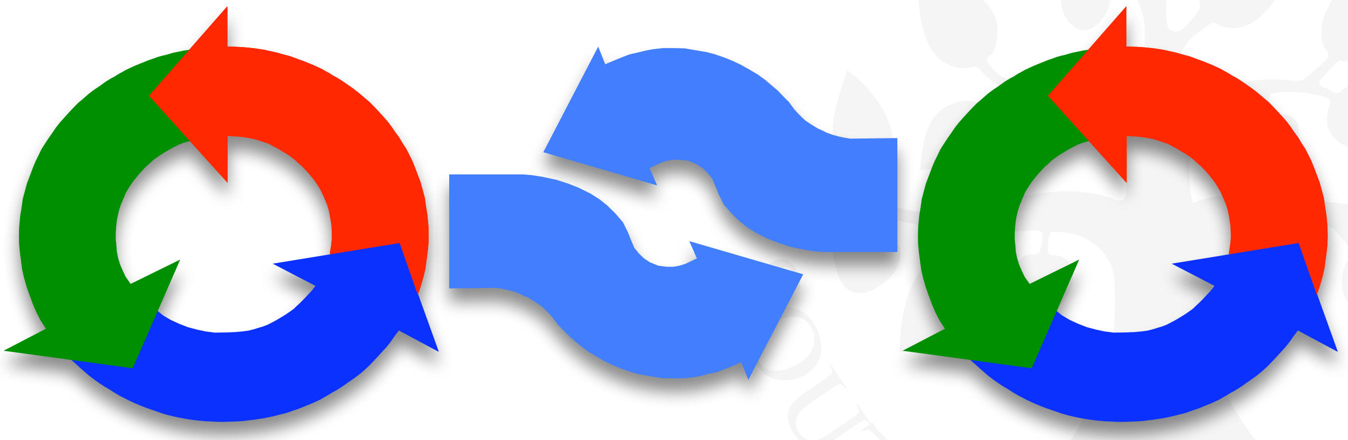
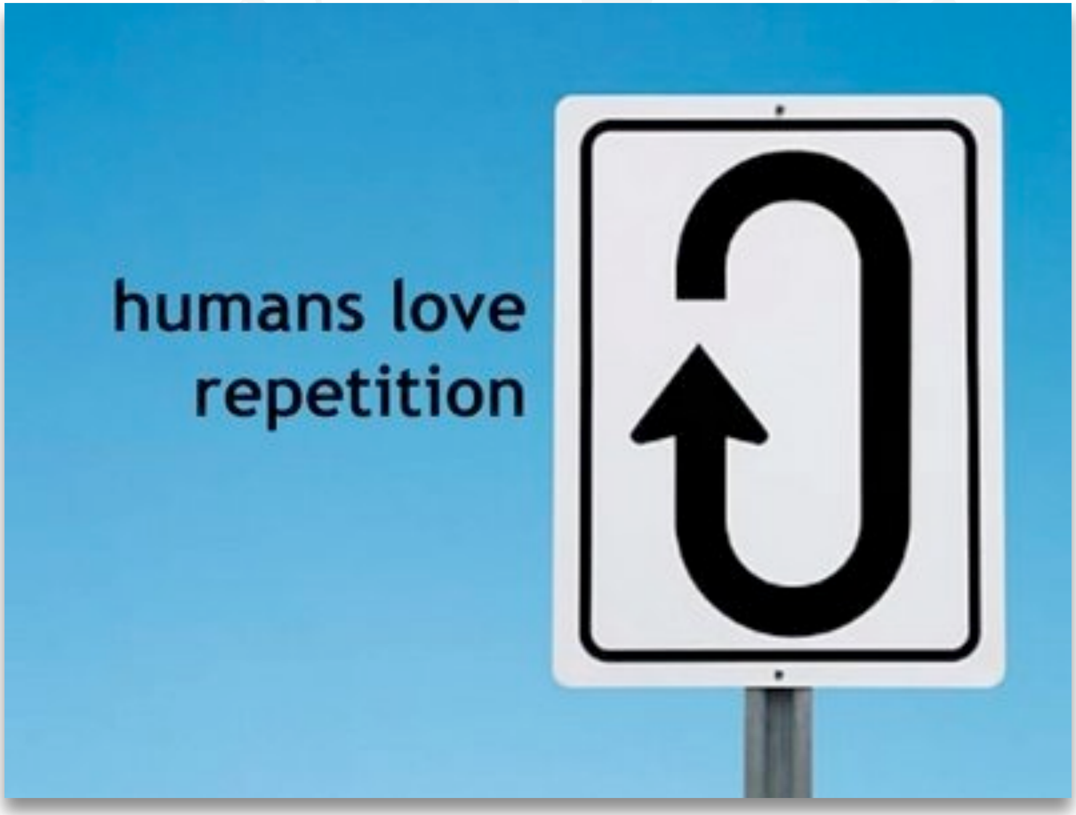
UNIVERSITY OF SOUTHERN DENMARK

Deadlock



But First: Repetition

Monitors and Condition Synchronisation



Monitors & Condition Synchronisation

Monitors & Condition Synchronisation

Concepts: monitors:

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

Monitors & Condition Synchronisation

University of Southern Denmark

Concepts: monitors:

encapsulated data + access procedures +

mutual exclusion + condition synchronisation +

single access procedure active in the monitor

nested monitors

Monitors & Condition Synchronisation

Concepts: monitors:

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

nested monitors

Models: guarded actions

Monitors & Condition Synchronisation

Concepts: monitors:

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

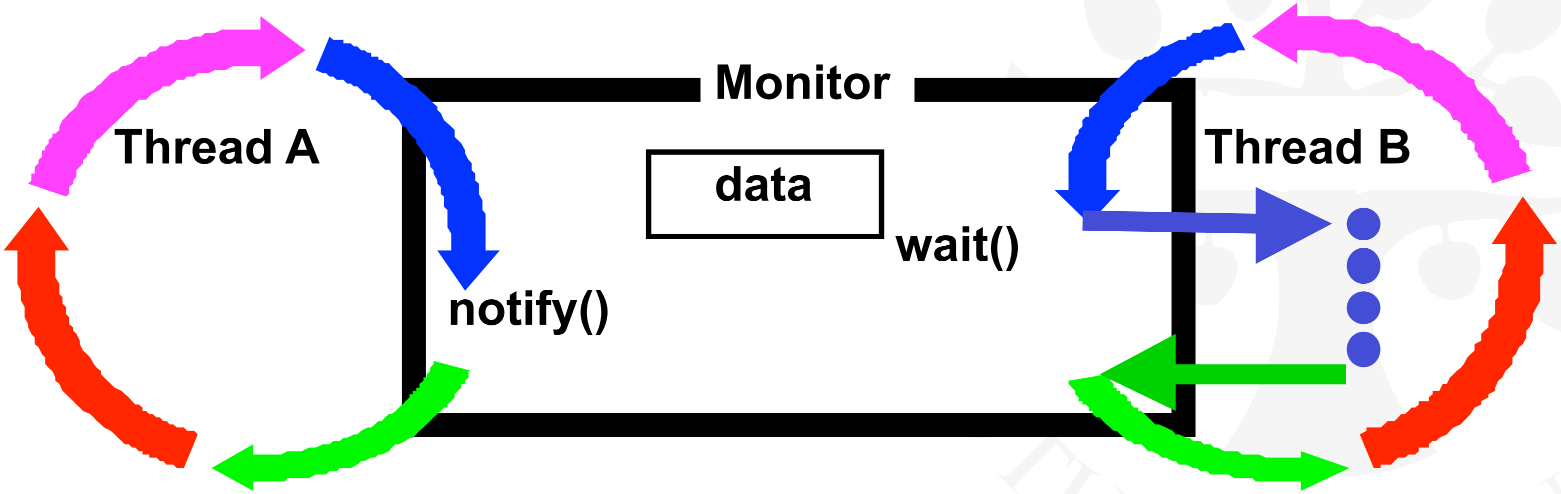
nested monitors

Models: guarded actions

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

Wait(), Notify(), And NotifyAll()

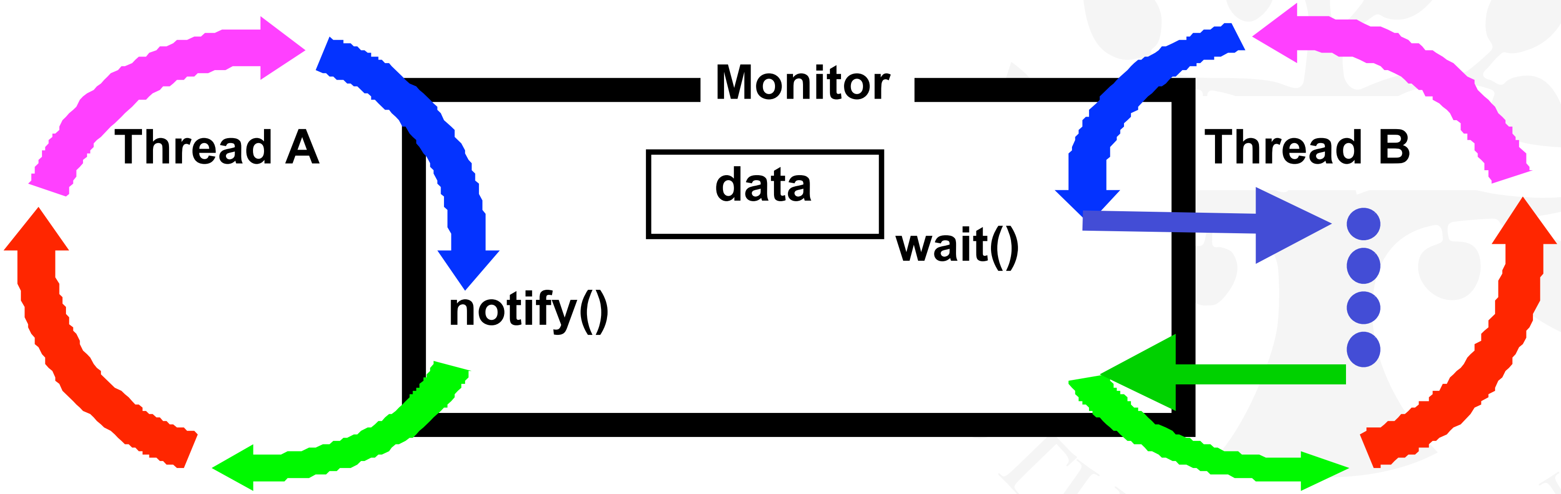

```
public final void wait() throws InterruptedException;
```



Wait(), Notify(), And NotifyAll()


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

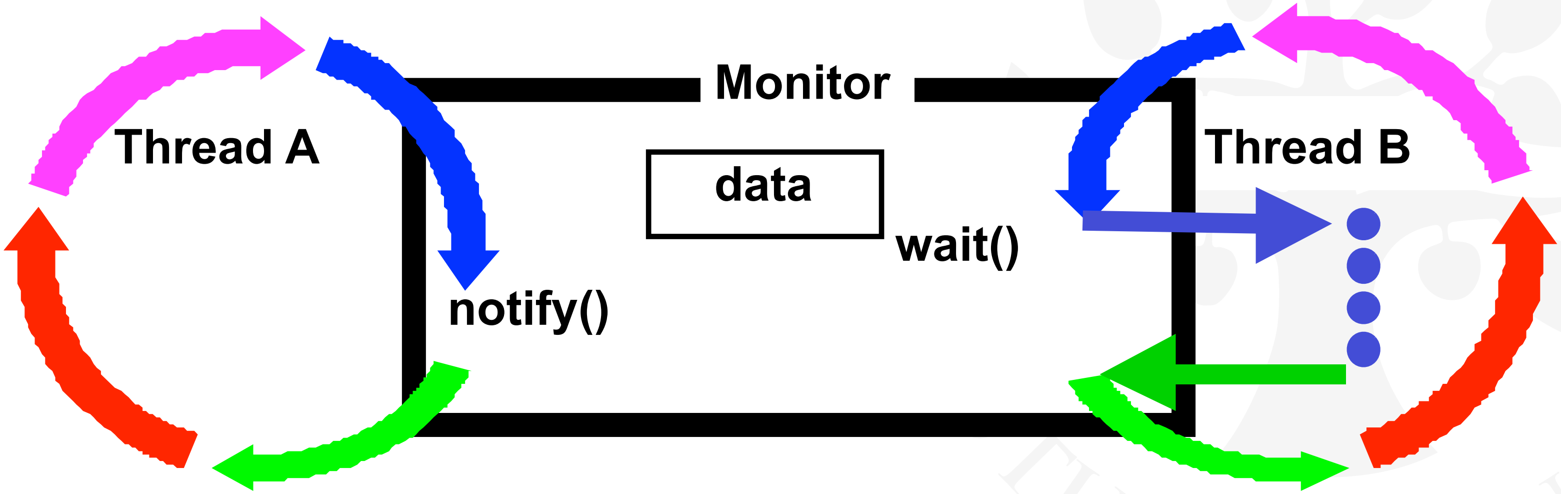
Wait() causes the thread to **exit** the monitor, permitting other threads to **enter** the monitor



Wait(), Notify(), And NotifyAll()


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

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




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

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

Condition Synchronisation (in Java)

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

Condition Synchronisation (in Java)


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

```
class CarParkControl {
```

Condition Synchronisation (in Java)

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

```
class CarParkControl {
    protected int spaces, capacity;
```

Condition Synchronisation (in Java)


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

```
class CarParkControl {
    protected int spaces, capacity;

    synchronized void arrive()
                   throws Int'Exc' {
```

Condition Synchronisation (in Java)


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

```
class CarParkControl {
    protected int spaces, capacity;

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

Condition Synchronisation (in Java)

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

```
class CarParkControl {
    protected int spaces, capacity;

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

Condition Synchronisation (in Java)


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

```
class CarParkControl {
    protected int spaces, capacity;

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

Condition Synchronisation (in Java)


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


```
class CarParkControl {
    protected int spaces, capacity;

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

Condition Synchronisation (in Java)


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

```
class CarParkControl {
    protected int spaces, capacity;

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

    synchronized void depart()
```

Condition Synchronisation (in Java)

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


```
class CarParkControl {
    protected int spaces, capacity;

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

    synchronized void depart()
                throws Int'Exc' {
```

Condition Synchronisation (in Java)


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

```
class CarParkControl {
    protected int spaces, capacity;

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

    synchronized void depart()
                 throws Int'Exc' {
        while (!(spaces<capacity)) wait();
```

Condition Synchronisation (in Java)


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


```
class CarParkControl {
    protected int spaces, capacity;

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

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

Condition Synchronisation (in Java)


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


```
class CarParkControl {
    protected int spaces, capacity;

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

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

Condition Synchronisation (in Java)


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


```
class CarParkControl {
    protected int spaces, capacity;

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

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

notify() instead of notifyAll() ?
1. Uniform waiters - everybody waits on the same condition
2. One-in, one-out

What goes wrong with notify and 8xDepartures, 5xArrivals?

Semaphores

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

Semaphores

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

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

Semaphores

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

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

```
sem.down(); // decrement (block if counter = 0)
```

Semaphores

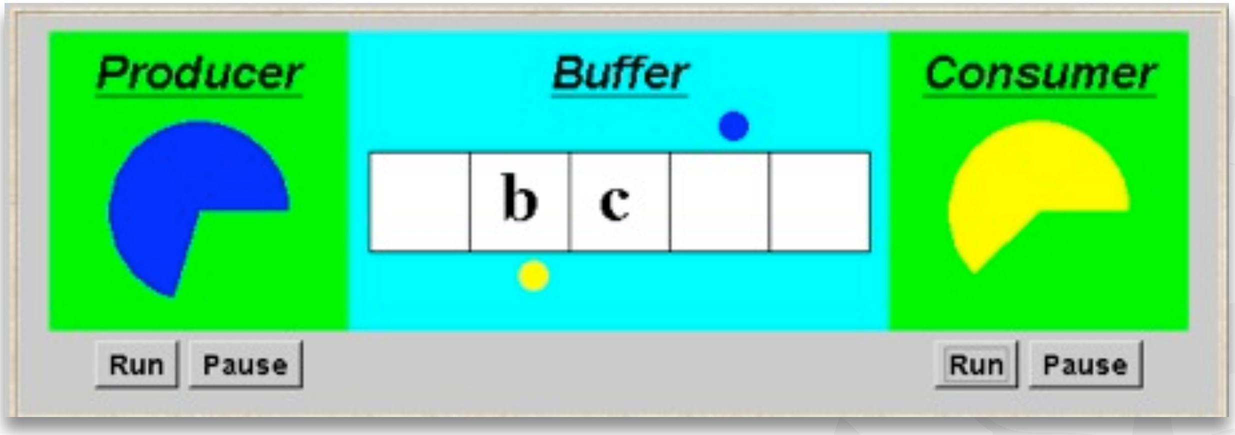
Semaphores are widely used for dealing with inter-process synchronisation in operating systems.

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

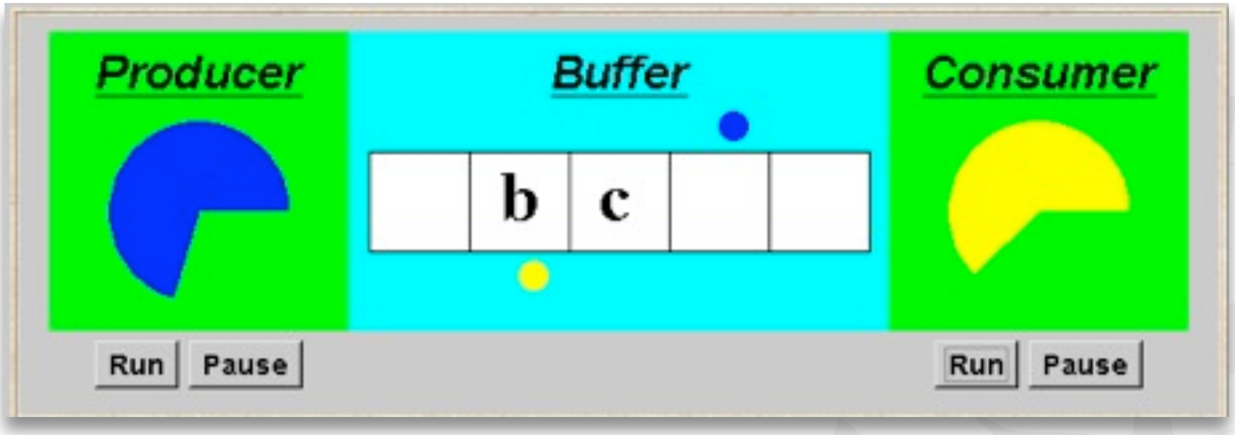
```
sem.down(); // decrement (block if counter = 0)
```

```
sem.up(); // increment counter (allowing one blocked thread to pass)
```

Nested Monitors - Bounded Buffer Model



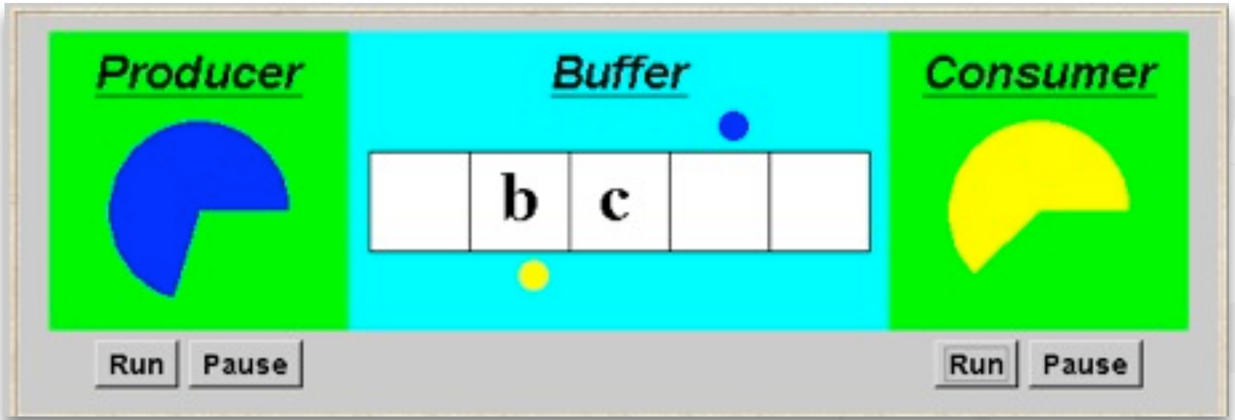
Nested Monitors - Bounded Buffer Model



LTSA's (analyse safety) predicts a possible DEADLOCK:

```
Composing
  potential DEADLOCK
  States Composed: 28 Transitions: 32 in 60ms
  Trace to DEADLOCK:
    get
```

Nested Monitors - Bounded Buffer Model



LTSA's (analyse safety) predicts a possible DEADLOCK:

```
Composing
  potential DEADLOCK
  States Composed: 28 Transitions: 32 in 60ms
  Trace to DEADLOCK:
    get
```

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

Deadlock

Deadlock

Deadlock

Concepts: system deadlock (no further progress)

Deadlock

Concepts: system deadlock (no further progress)
4 necessary & sufficient conditions

Deadlock

Concepts: system deadlock (no further progress)

4 necessary & sufficient conditions

Models: deadlock - no eligible actions

Deadlock

University of Southern Denmark

Concepts:	system deadlock (no further progress) 4 necessary & sufficient conditions
Models:	deadlock - no eligible actions
Practice:	blocked threads

Deadlock

UNIVERSITY OF SOUTHERN DENMARK

Concepts:	system deadlock (no further progress) 4 necessary & sufficient conditions
Models:	deadlock - no eligible actions
Practice:	blocked threads

Aim: **deadlock avoidance** - to design systems where deadlock cannot occur.

Necessary & Sufficient Conditions

Necessary condition:

Sufficient condition:

Necessary & sufficient condition:

Necessary & Sufficient Conditions

Necessary condition:

P *necessary* for Q:
$P \Leftarrow Q$

Sufficient condition:

Necessary & sufficient condition:

Necessary & Sufficient Conditions

Necessary condition:

P *necessary* for Q:
$P \Leftarrow Q$

Sufficient condition:

P *sufficient* for Q:
$P \Rightarrow Q$

Necessary & sufficient condition:

Necessary & Sufficient Conditions

Necessary condition:

P *necessary* for Q:
$P \Leftarrow Q$

Sufficient condition:

P *sufficient* for Q:
$P \Rightarrow Q$

Necessary & sufficient condition:

P *necessary* & *sufficient* for Q:
$(P \Leftarrow Q) \wedge (P \Rightarrow Q) \quad \equiv \quad P \Leftrightarrow Q$

Necessary & Sufficient Conditions

Necessary condition:

P *necessary* for Q:
$P \Leftarrow Q$

Sufficient condition:

P *sufficient* for Q:
$P \Rightarrow Q$

Necessary & sufficient condition:

P *necessary* & *sufficient* for Q:
$(P \Leftarrow Q) \wedge (P \Rightarrow Q) \quad \equiv \quad P \Leftrightarrow Q$

P: The sun is shining

Q: I get sunlight on my beer

Necessary & Sufficient Conditions

Necessary condition:

P *necessary* for Q:
$P \Leftarrow Q$

Sufficient condition:

P *sufficient* for Q:
$P \Rightarrow Q$

Necessary & sufficient condition:

P *necessary* & *sufficient* for Q:
$(P \Leftarrow Q) \wedge (P \Rightarrow Q) \quad \equiv \quad P \Leftrightarrow Q$

P: The sun is shining
Q: I get sunlight on my beer

$P \Leftarrow Q$ only.

Necessary & Sufficient Conditions

Necessary condition:

P *necessary* for Q:
$P \Leftarrow Q$

Sufficient condition:

P *sufficient* for Q:
$P \Rightarrow Q$

Necessary & sufficient condition:

P *necessary* & *sufficient* for Q:
$(P \Leftarrow Q) \wedge (P \Rightarrow Q) \quad \equiv \quad P \Leftrightarrow Q$

P: The sun is shining
Q: I get sunlight on my beer

$P \Leftarrow Q$ only.

Deadlock: 4 Necessary And Sufficient Conditions

Deadlock: 4 Necessary And Sufficient Conditions

University of Southern Denmark

1. **Mutual exclusion condition** (aka. “Serially reusable resources”):

Deadlock: 4 Necessary And Sufficient Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

Deadlock: 4 Necessary And Sufficient Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

Deadlock: 4 Necessary And Sufficient Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

Deadlock: 4 Necessary And Sufficient Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

3. **No preemption condition:**

Deadlock: 4 Necessary And Sufficient Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

3. **No preemption condition:**

   once acquired by a process, resources cannot be "pre-empted" (forcibly withdrawn) but are only released voluntarily.

Deadlock: 4 Necessary And Sufficient Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

3. **No preemption condition:**

   once acquired by a process, resources cannot be "pre-empted" (forcibly withdrawn) but are only released voluntarily.

4. **Circular-wait condition** (aka. "Wait-for cycle"):

Deadlock: 4 Necessary And Sufficient Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

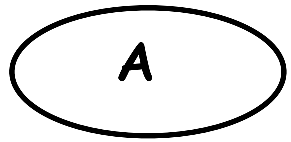
3. **No preemption condition:**

   once acquired by a process, resources cannot be "pre-empted" (forcibly withdrawn) but are only released voluntarily.

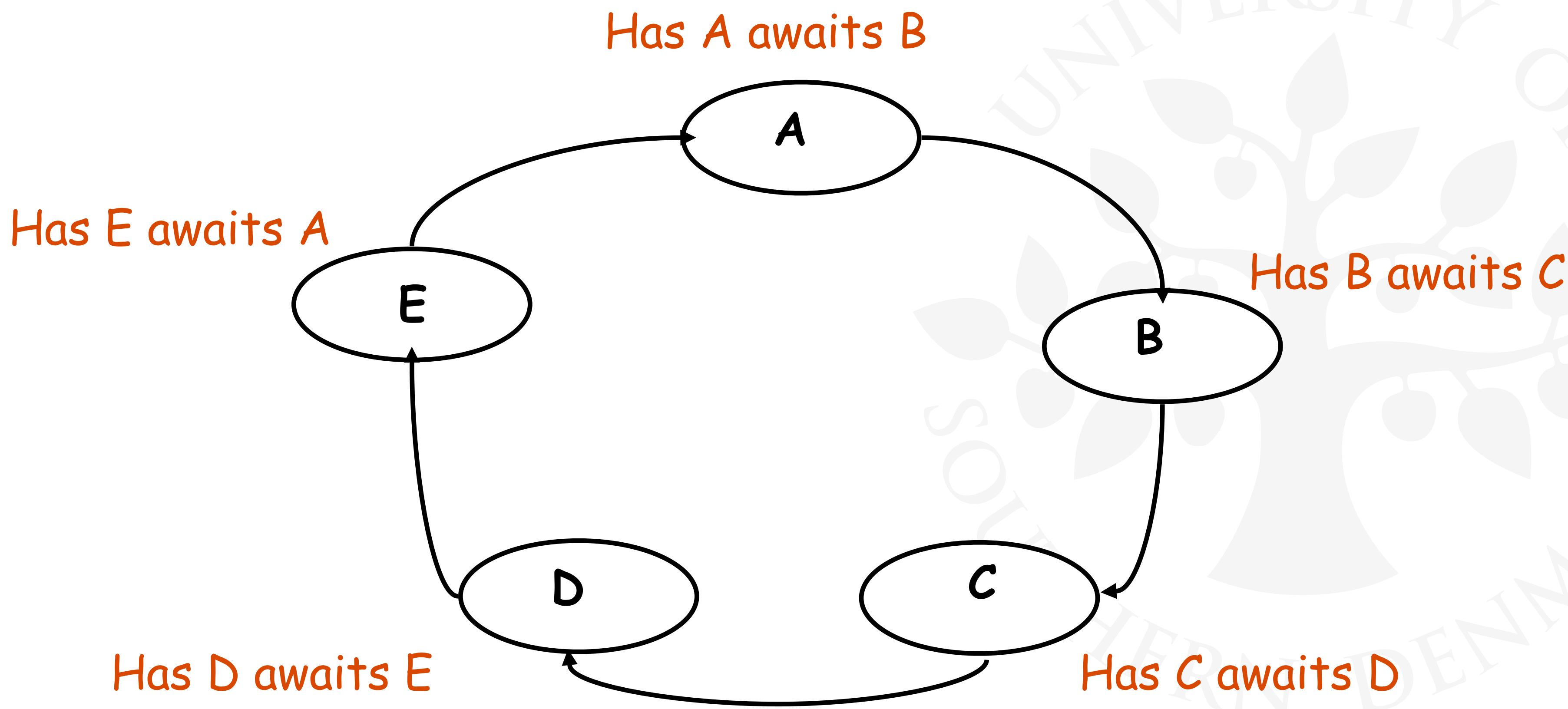
4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

Wait-For Cycle



Wait-For Cycle



6.1 Deadlock Analysis - Primitive Processes

6.1 Deadlock Analysis - Primitive Processes

- **Deadlocked state** is one with no outgoing transitions

6.1 Deadlock Analysis - Primitive Processes

- **Deadlocked state** is one with no outgoing transitions
- In FSP: (modelled by) the `STOP` process

6.1 Deadlock Analysis - Primitive Processes

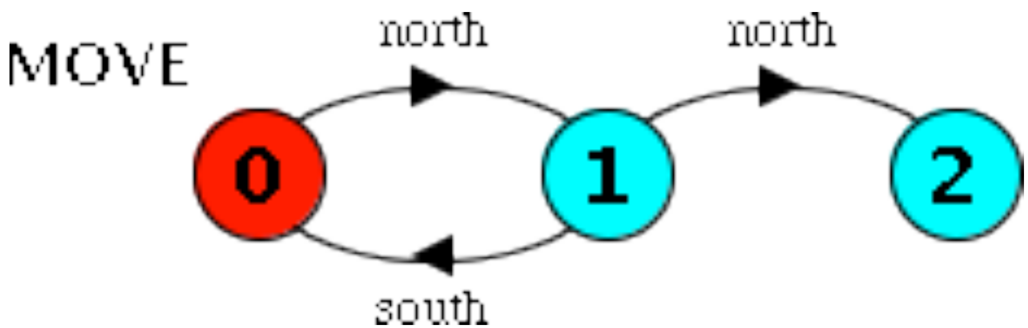
- **Deadlocked state** is one with no outgoing transitions
- In FSP: (modelled by) the **STOP** process

```
MOVE = (north->(south->MOVE|north->STOP)).
```

6.1 Deadlock Analysis - Primitive Processes

- **Deadlocked state** is one with no outgoing transitions
- In FSP: (modelled by) the **STOP** process

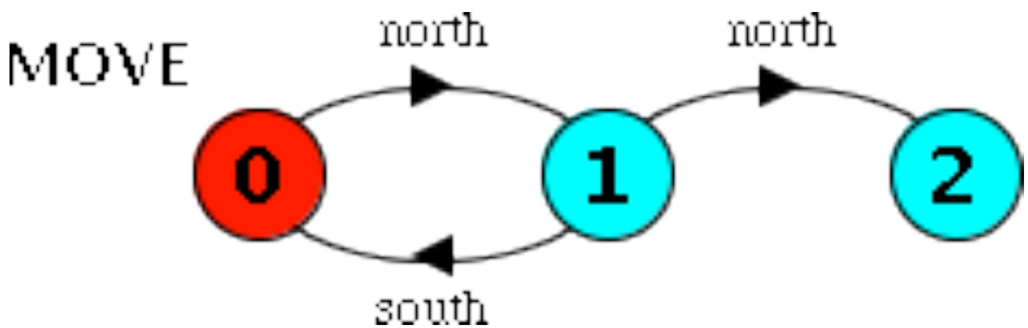
```
MOVE = (north->(south->MOVE|north->STOP)).
```



6.1 Deadlock Analysis - Primitive Processes

- **Deadlocked state** is one with no outgoing transitions
- In FSP: (modelled by) the **STOP** process

```
MOVE = (north->(south->MOVE|north->STOP)).
```

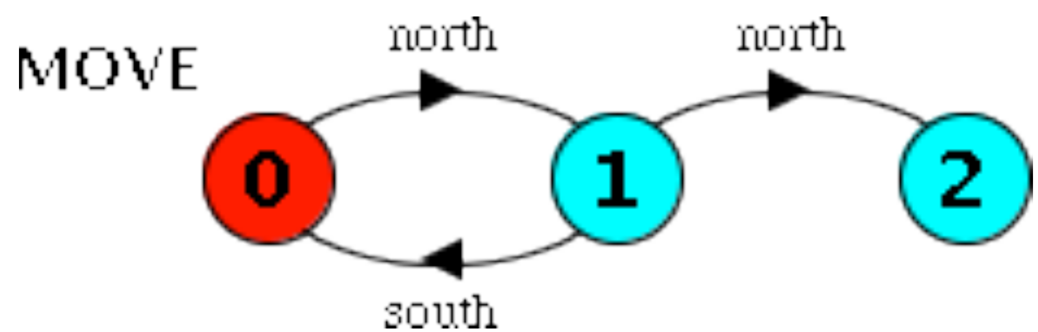


- Analysis using **LTSA**:

6.1 Deadlock Analysis - Primitive Processes

- **Deadlocked state** is one with no outgoing transitions
- In FSP: (modelled by) the **STOP** process

```
MOVE = (north->(south->MOVE|north->STOP)).
```



- Analysis using **LTSA**:

Shortest path to DEADLOCK:

```
Trace to DEADLOCK:
    north
    north
```

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```

```
RESOURCE = (get-> put-> RESOURCE).
```

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```

```
RESOURCE = (get-> put-> RESOURCE).

P = (printer.get-> scanner.get-> copy-> printer.put-> scanner.put-> P).
```

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

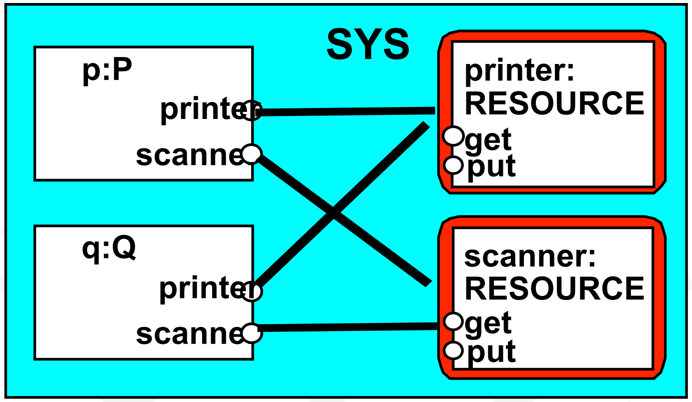
```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```

```
RESOURCE = (get-> put-> RESOURCE).

P = (printer.get-> scanner.get-> copy-> printer.put-> scanner.put-> P).

Q = (scanner.get-> printer.get-> copy-> scanner.put-> printer.put-> Q).
```

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```

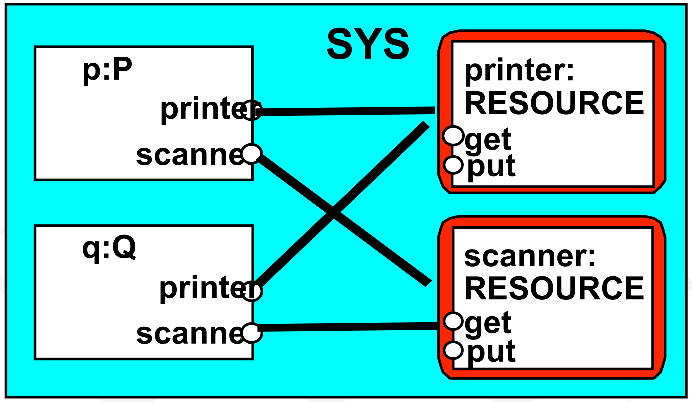



```
RESOURCE = (get-> put-> RESOURCE).

P = (printer.get-> scanner.get-> copy-> printer.put-> scanner.put-> P).

Q = (scanner.get-> printer.get-> copy-> scanner.put-> printer.put-> Q).

||SYS = (p:P || q:Q || {p,q}::printer:RESOURCE ||
{p,q}::scanner:RESOURCE).
```

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```



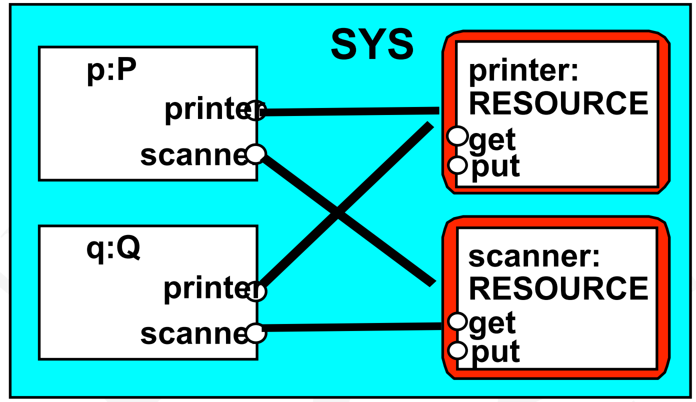

```
RESOURCE = (get-> put-> RESOURCE).

P = (printer.get-> scanner.get-> copy-> printer.put-> scanner.put-> P).

Q = (scanner.get-> printer.get-> copy-> scanner.put-> printer.put-> Q).

||SYS = (p:P || q:Q || {p,q}::printer:RESOURCE ||
{p,q}::scanner:RESOURCE).
```

Deadlock trace?

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```




```
RESOURCE = (get-> put-> RESOURCE).

P = (printer.get-> scanner.get-> copy-> printer.put->                .

Q = (scanner.get-> printer.get-> copy-> scanner.put-> printer.put-> Q).

||SYS = (p:P || q:Q || {p,q}::printer:RESOURCE ||
{p,q}::scanner:RESOURCE).
```

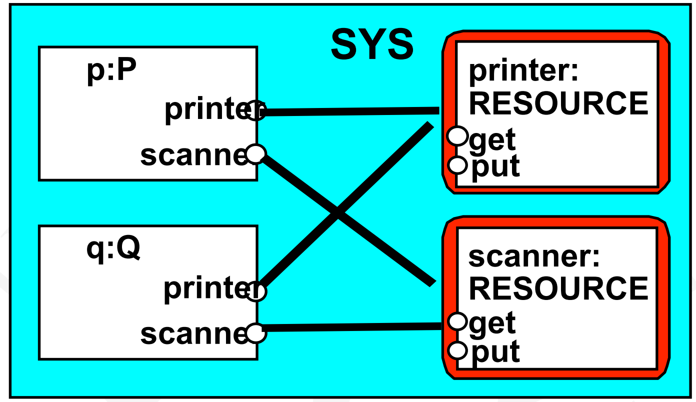
```
Trace to DEADLOCK:
  p.printer.get
  q.scanner.get
```

Deadlock trace?

Deadlock Analysis - Parallel Composition

- In practice, deadlock arises from parallel composition of interacting processes.

```
P = (x -> y -> P).
Q = (y -> x -> Q).
||D = (P || Q).
```




```
RESOURCE = (get-> put-> RESOURCE).

P = (printer.get-> scanner.get-> copy-> printer.put->                .

Q = (scanner.get-> printer.get-> copy-> scanner.put-> printer.put-> Q).

||SYS = (p:P || q:Q || {p,q}::printer:RESOURCE ||
{p,q}::scanner:RESOURCE).
```

```
Trace to DEADLOCK:
  p.printer.get
  q.scanner.get
```

Deadlock trace?

Avoidance...

Recall The 4 Conditions

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

3. **No preemption condition:**

   once acquired by a process, resources cannot be "pre-empted" (forcibly withdrawn) but are only released voluntarily.

4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

Deadlock Analysis – Avoidance (#1 ?)

UNIVERSITY OF SOUTHERN DENMARK

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

Deadlock Analysis – Avoidance (#1 ?)

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

- Ideas?

Deadlock Analysis – Avoidance (#1 ?)

University of Southern Denmark

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

- Ideas?
  - ...avoid shared resources (used under mutual exclusion)

Deadlock Analysis – Avoidance (#1 ?)

UNIVERSITY OF SOUTHERN DENMARK

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

- Ideas?
  - ...avoid shared resources (used under mutual exclusion)
- No shared resources (buy **two** printers and **two** scanners)

Deadlock Analysis – Avoidance (#1 ?)

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

- Ideas?
  - ...avoid shared resources (used under mutual exclusion)

- No shared resources (buy **two** printers and **two** scanners)

Deadlock?

Deadlock Analysis – Avoidance (#1 ?)

UNIVERSITY OF SOUTHERN DENMARK

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

- Ideas?
  - ...avoid shared resources (used under mutual exclusion)
- No shared resources (buy **two** printers and **two** scanners)

Deadlock? ☺

Deadlock Analysis – Avoidance (#1 ?)

University of Southern Denmark

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

- Ideas?
  - ...avoid shared resources (used under mutual exclusion)
- No shared resources (buy **two** printers and **two** scanners)

Deadlock? ☺ **Scalability?**

Deadlock Analysis – Avoidance (#1 ?)

1. **Mutual exclusion condition** (aka. "Serially reusable resources"):

   the processes involved share resources which they use under mutual exclusion.

- Ideas?
  - ...avoid shared resources (used under mutual exclusion)
- No shared resources (buy **two** printers and **two** scanners)

Deadlock? ☺ **Scalability?** ☹

Deadlock Analysis – Avoidance (#2 ?)

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

Deadlock Analysis – Avoidance (#2 ?)

2. **Hold-and-wait condition** (aka. “Incremental acquisition”):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** “mutex” lock for **both** scanner and printer:

Deadlock Analysis – Avoidance (#2 ?)

UNIVERSITY OF SOUTHERN DENMARK

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).
```

Deadlock Analysis – Avoidance (#2 ?)

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).
P = (scanner_printer.acquire->
```

Deadlock Analysis – Avoidance (#2 ?)

UNIVERSITY OF SOUTHERN DENMARK

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).

P = (scanner_printer.acquire->
       printer.get->
         scanner.get->
           copy->
         scanner.put->
       printer.put->
```

Deadlock Analysis – Avoidance (#2 ?)

University of Southern Denmark

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).

P = (scanner_printer.acquire->
       printer.get->
         scanner.get->
           copy->
         scanner.put->
       printer.put->
     scanner_printer.release-> P).
```

Deadlock Analysis – Avoidance (#2 ?)

University of Southern Denmark

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).

P = (scanner_printer.acquire->
       printer.get->
         scanner.get->
           copy->
         scanner.put->
       printer.put->
     scanner_printer.release-> P).
```

Deadlock?

Deadlock Analysis – Avoidance (#2 ?)

University of Southern Denmark

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).

P = (scanner_printer.acquire->
       printer.get->
         scanner.get->
           copy->
         scanner.put->
       printer.put->
     scanner_printer.release-> P).
```

Deadlock? ☺

Deadlock Analysis – Avoidance (#2 ?)

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).

P = (scanner_printer.acquire->
       printer.get->
          scanner.get->
             copy->
          scanner.put->
       printer.put->
     scanner_printer.release-> P).
```

Deadlock? ☺ Efficiency/Scalability?

Deadlock Analysis – Avoidance (#2 ?)

2. **Hold-and-wait condition** (aka. "Incremental acquisition"):

   processes hold on to resources already allocated to them while waiting to acquire additional resources.

- Only **one** "mutex" lock for **both** scanner and printer:

```
LOCK = (acquire-> release-> LOCK).

P = (scanner_printer.acquire->
       printer.get->
          scanner.get->
             copy->
          scanner.put->
       printer.put->
     scanner_printer.release-> P).
```

Deadlock? ☺ **Efficiency/Scalability?** ☹

Deadlock Analysis – Avoidance (#3 ?)

UNIVERSITY OF SOUTHERN DENMARK

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

Deadlock Analysis – Avoidance (#3 ?)

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

Deadlock Analysis – Avoidance (#3 ?)

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P            = (printer.get-> GETSCANNER),
```

Deadlock Analysis – Avoidance (#3 ?)

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P           = (printer.get-> GETSCANNER),
GETSCANNER = (scanner.get-> copy-> printer.put-> scanner.put-> P
```

Deadlock Analysis – Avoidance (#3 ?)

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P           = (printer.get-> GETSCANNER),
GETSCANNER = (scanner.get-> copy-> printer.put-> scanner.put-> P
             |timeout -> printer.put-> P).
```

Deadlock Analysis – Avoidance (#3 ?)

University of Southern Denmark

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P           = (printer.get-> GETSCANNER),
GETSCANNER = (scanner.get-> copy-> printer.put-> scanner.put-> P
             |timeout -> printer.put-> P).

Q           = (scanner.get-> GETPRINTER),
GETPRINTER = (printer.get-> copy-> printer.put-> scanner.put-> Q
             |timeout -> scanner.put-> Q).
```

Deadlock Analysis – Avoidance (#3 ?)

University of Southern Denmark

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P           = (printer.get-> GETSCANNER),
GETSCANNER = (scanner.get-> copy-> printer.put-> scanner.put-> P
               |timeout -> printer.put-> P).

Q           = (scanner.get-> GETPRINTER),
GETPRINTER = (printer.get-> copy-> printer.put-> scanner.put-> Q
               |timeout -> scanner.put-> Q).
```

Deadlock?

Deadlock Analysis – Avoidance (#3 ?)

University of Southern Denmark

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P           = (printer.get-> GETSCANNER),
GETSCANNER = (scanner.get-> copy-> printer.put-> scanner.put-> P
             |timeout -> printer.put-> P).

Q           = (scanner.get-> GETPRINTER),
GETPRINTER = (printer.get-> copy-> printer.put-> scanner.put-> Q
             |timeout -> scanner.put-> Q).
```

Deadlock? ☺

Deadlock Analysis – Avoidance (#3 ?)

University of Southern Denmark

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P           = (printer.get-> GETSCANNER),
GETSCANNER = (scanner.get-> copy-> printer.put-> scanner.put-> P
             |timeout -> printer.put-> P).

Q           = (scanner.get-> GETPRINTER),
GETPRINTER = (printer.get-> copy-> printer.put-> scanner.put-> Q
             |timeout -> scanner.put-> Q).
```

Deadlock? ☺ **Progress?**

Deadlock Analysis – Avoidance (#3 ?)

University of Southern Denmark

3. No pre-emption condition:

once acquired by a process, resources cannot be pre-empted (forcibly withdrawn) but are only released voluntarily.

- Force release (e.g., through timeout or arbiter):

```
P           = (printer.get-> GETSCANNER),
GETSCANNER = (scanner.get-> copy-> printer.put-> scanner.put-> P
              |timeout -> printer.put-> P).

Q           = (scanner.get-> GETPRINTER),
GETPRINTER = (printer.get-> copy-> printer.put-> scanner.put-> Q
              |timeout -> scanner.put-> Q).
```

Deadlock? ☺ Progress? ☹

Deadlock Analysis – Avoidance (#4 ?)

4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

Deadlock Analysis – Avoidance (#4 ?)

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

Deadlock Analysis – Avoidance (#4 ?)

4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
```

Deadlock Analysis – Avoidance (#4 ?)

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
       scanner.get->
```

Deadlock Analysis – Avoidance (#4 ?)

4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
        scanner.get->
          copy-> printer.put-> scanner.put-> P).
```

Deadlock Analysis – Avoidance (#4 ?)

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
        scanner.get->
          copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
```

Deadlock Analysis – Avoidance (#4 ?)

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
        scanner.get->
          copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
        scanner.get->
```

Deadlock Analysis – Avoidance (#4 ?)

UNIVERSITY OF SOUTHERN DENMARK

4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
        scanner.get->
          copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
        scanner.get->
          copy-> printer.put-> scanner.put-> Q).
```

Deadlock Analysis – Avoidance (#4 ?)

UNIVERSITY OF SOUTHERN DENMARK

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
        scanner.get->
          copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
        scanner.get->
          copy-> printer.put-> scanner.put-> Q).
```

Deadlock?

Deadlock Analysis – Avoidance (#4 ?)

UNIVERSITY OF SOUTHERN DENMARK

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> Q).
```

Deadlock? ☺

Deadlock Analysis – Avoidance (#4 ?)

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> Q).
```

Deadlock? ☺ Scalability/Progress/...?

Deadlock Analysis – Avoidance (#4 ?)

University of Southern Denmark

4. Circular-wait condition (aka. "Wait-for cycle"):

a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> Q).
```

Deadlock? ☺ **Scalability/Progress/…?** ☺

Deadlock Analysis – Avoidance (#4 ?)

4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> Q).
```

Deadlock? ☺ **Scalability/Progress/…?** ☺

General solution: "sort" resource acquisitions

Deadlock Analysis – Avoidance (#4 ?)

4. **Circular-wait condition** (aka. "Wait-for cycle"):

   a circular chain (or cycle) of processes exists such that each process holds a resource which its successor in the cycle is waiting to acquire.

- Acquire resources in the same order:

```
P = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> P).

Q = (printer.get->
       scanner.get->
         copy-> printer.put-> scanner.put-> Q).
```

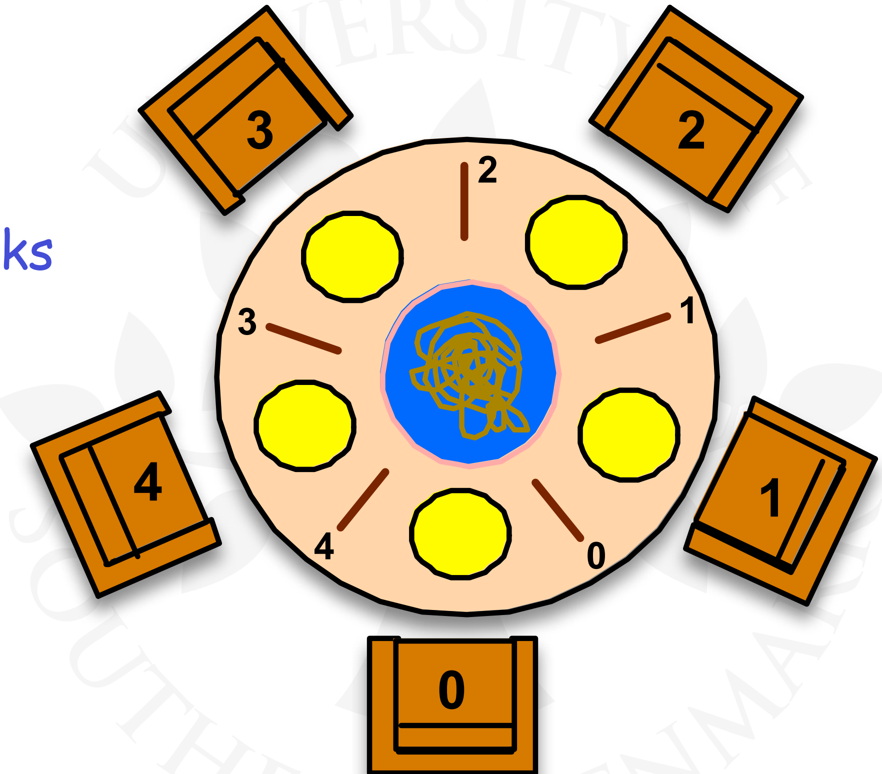
Deadlock? ☺ Scalability/Progress/…? ☺

General solution: "sort" resource acquisitions

BUT Sort by... ...what?

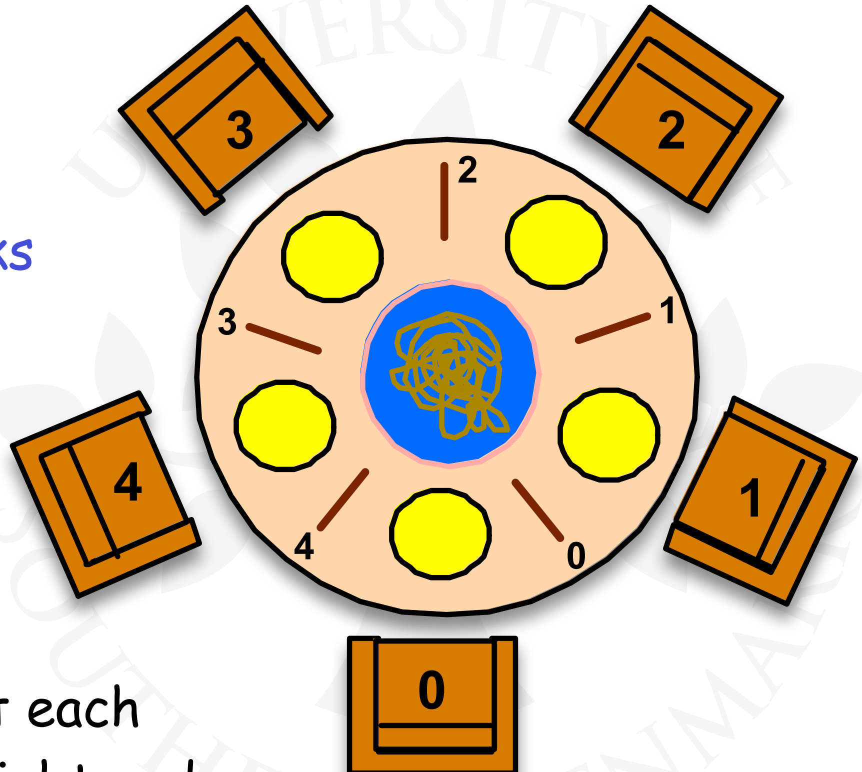
6.2 Dining Philosophers

Five philosophers sit around a circular table. Each philosopher spends his life alternately thinking and eating. In the centre of the table is a large bowl of spaghetti. A philosopher needs two forks to eat a helping of spaghetti.



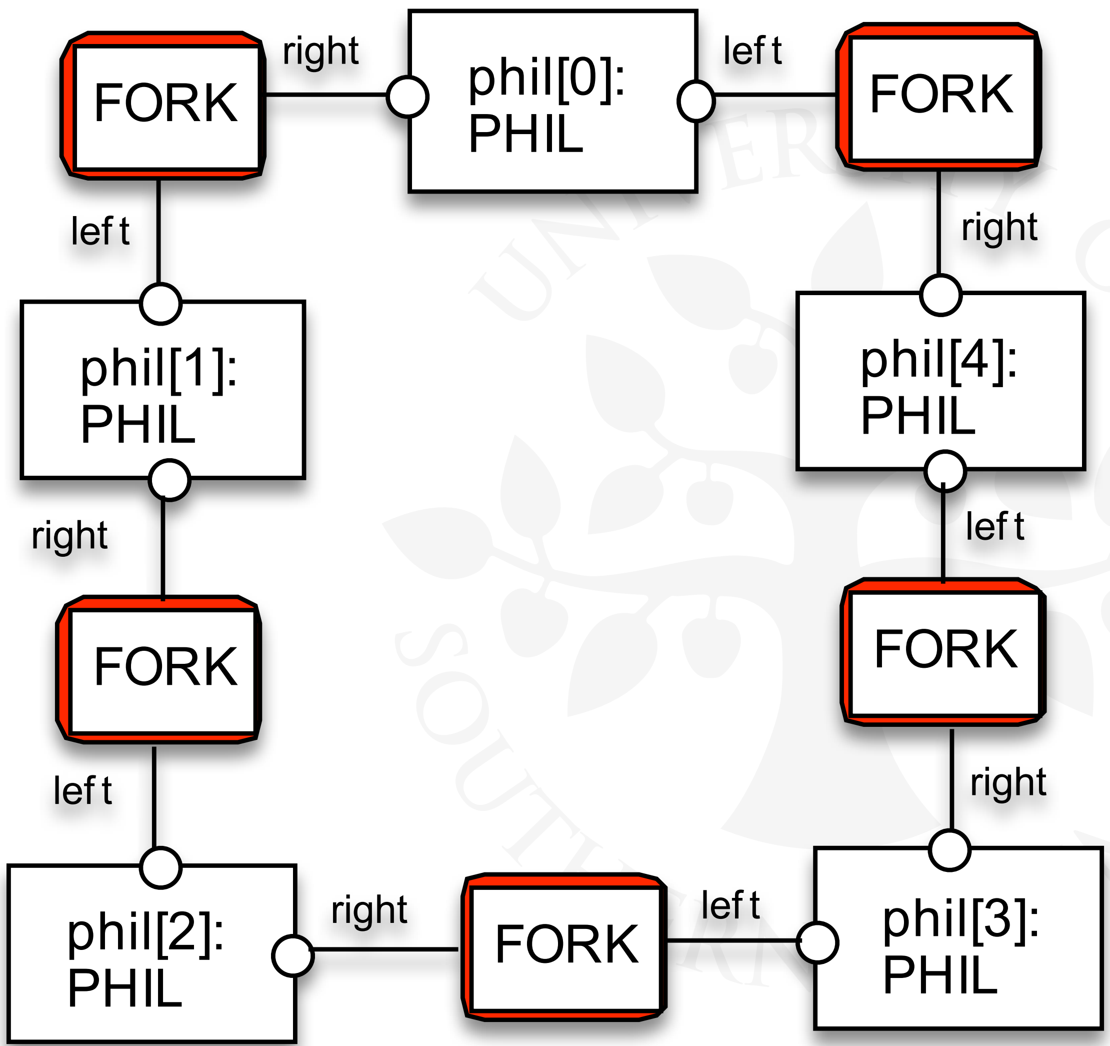
6.2 Dining Philosophers

Five philosophers sit around a circular table. Each philosopher spends his life alternately thinking and eating. In the centre of the table is a large bowl of spaghetti. A philosopher needs two forks to eat a helping of spaghetti.



One fork is placed between each pair of philosophers and they agree that each will only use the fork to his immediate right and left.

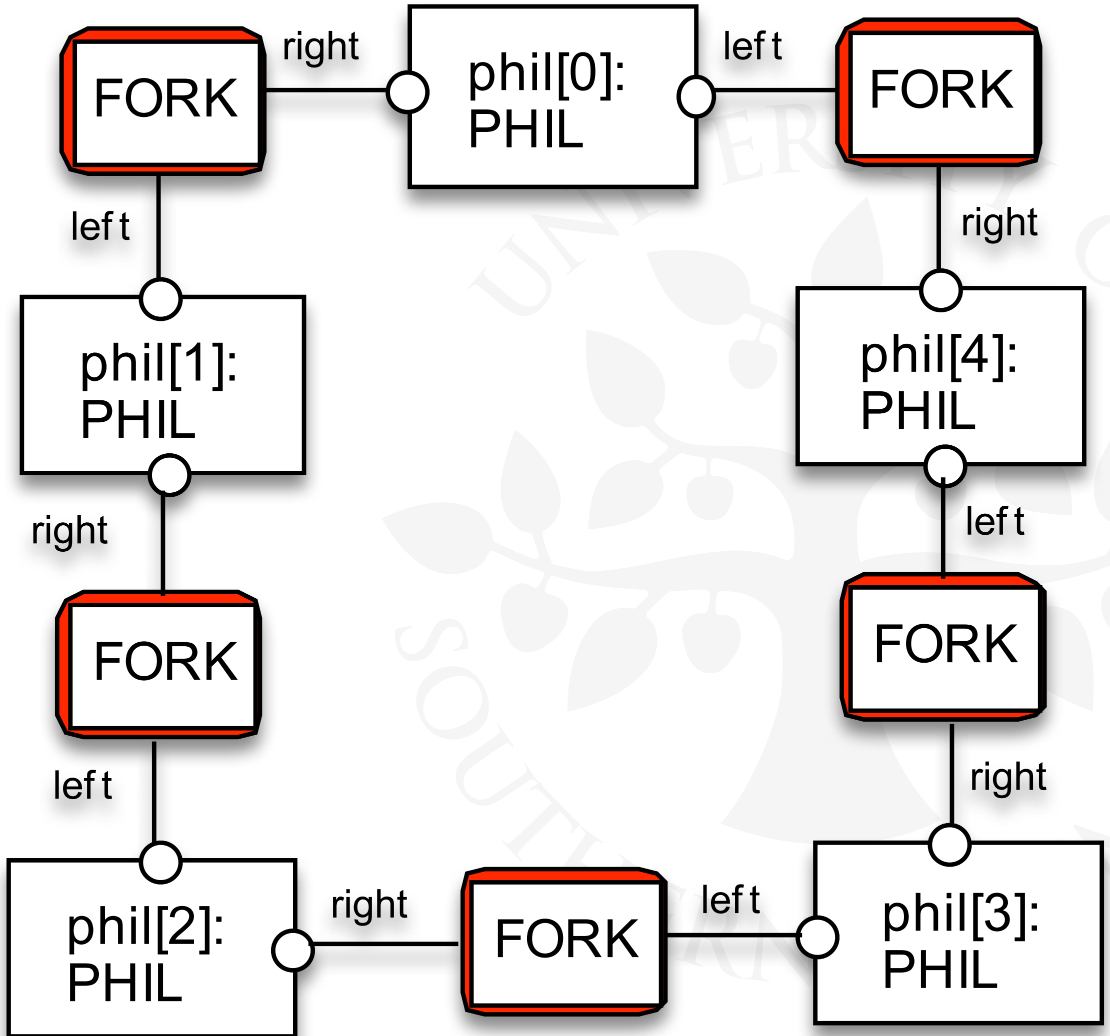
Dining Philosophers - Model Structure Diagram



Dining Philosophers - Model Structure Diagram

University of Southern Denmark

Each **FORK** is a shared resource with actions **get** and **put**.

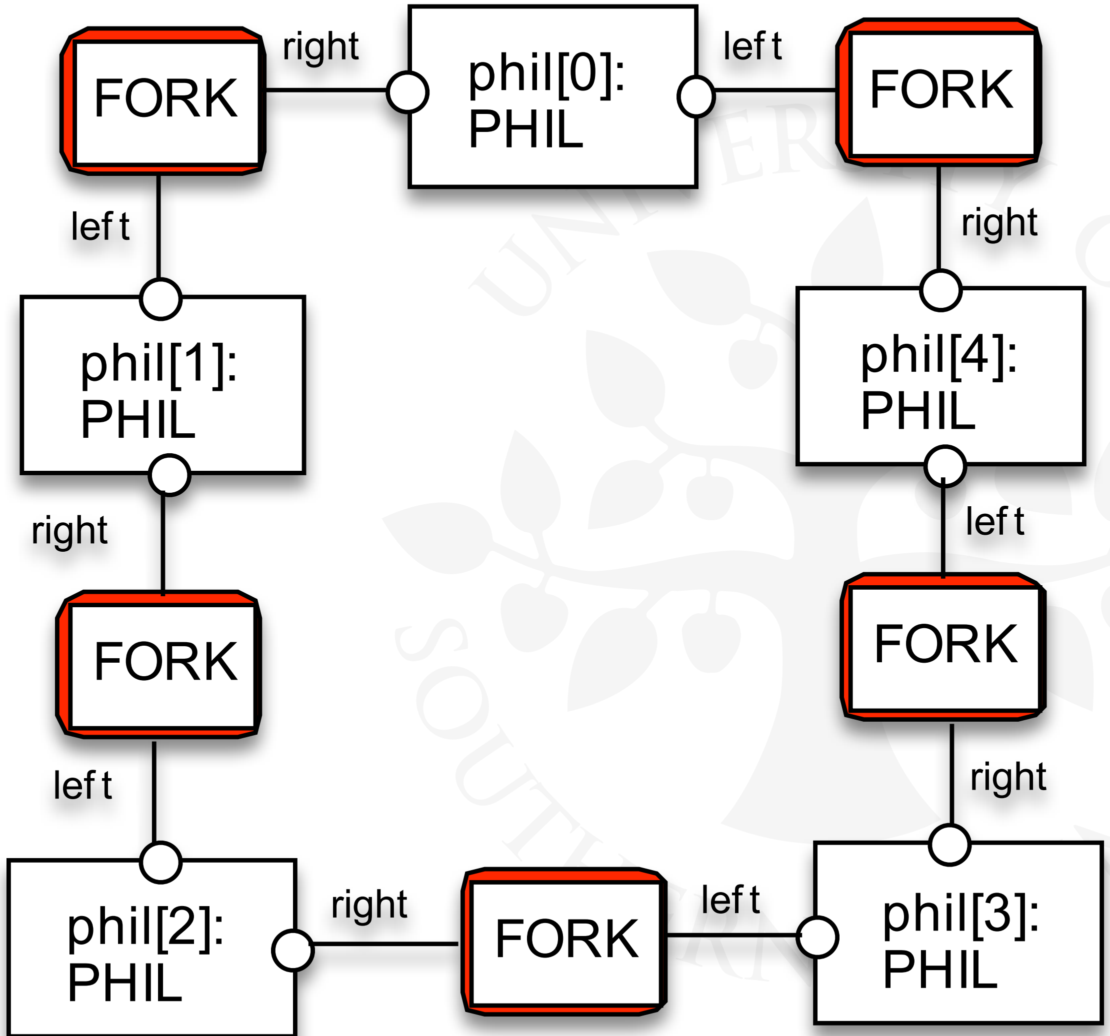


Dining Philosophers - Model Structure Diagram

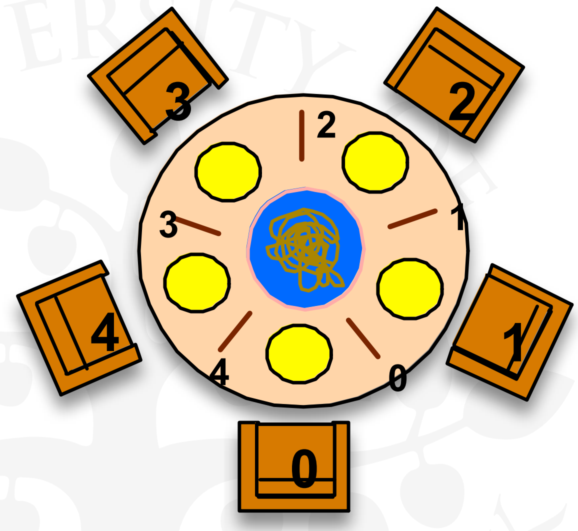
University of Southern Denmark

Each **FORK** is a shared resource with actions **get** and **put**.

When hungry, each **PHIL** must first get his right and left forks before he can start eating.

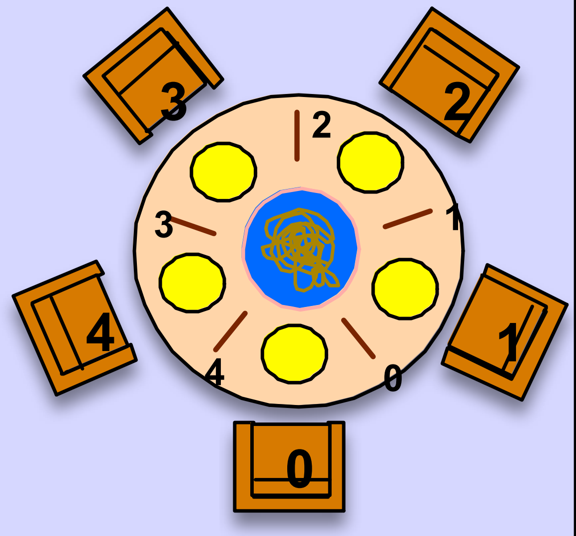


Dining Philosophers - Model



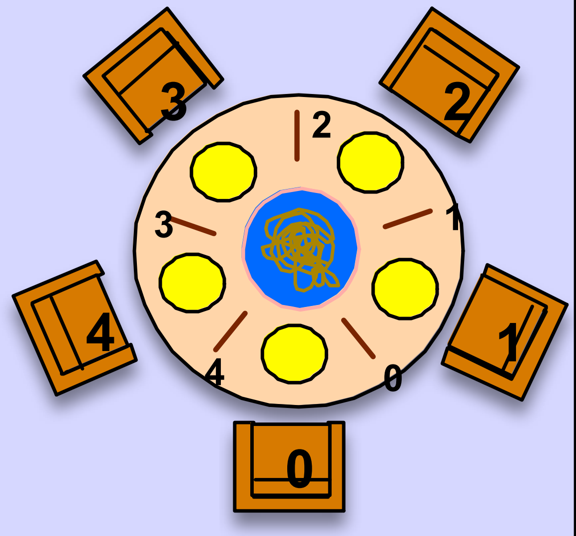
Dining Philosophers - Model


```
const N = 5
```



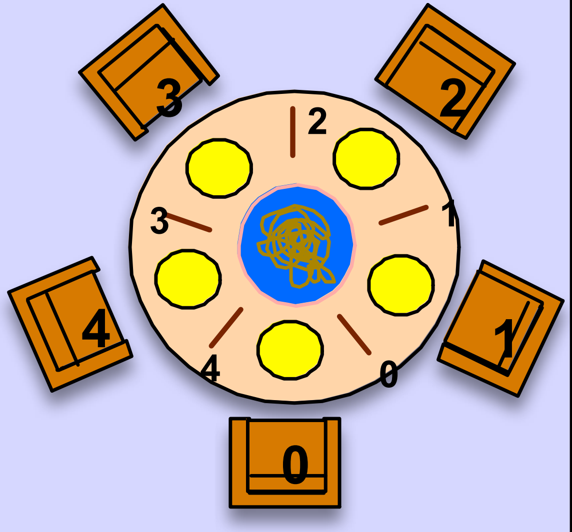
Dining Philosophers - Model

```
const N = 5

FORK = (get-> put-> FORK).
```



Dining Philosophers - Model

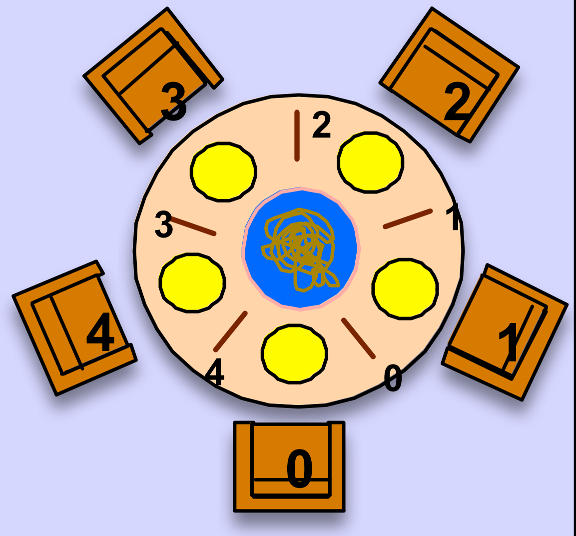

```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit        ->
```



Dining Philosophers - Model

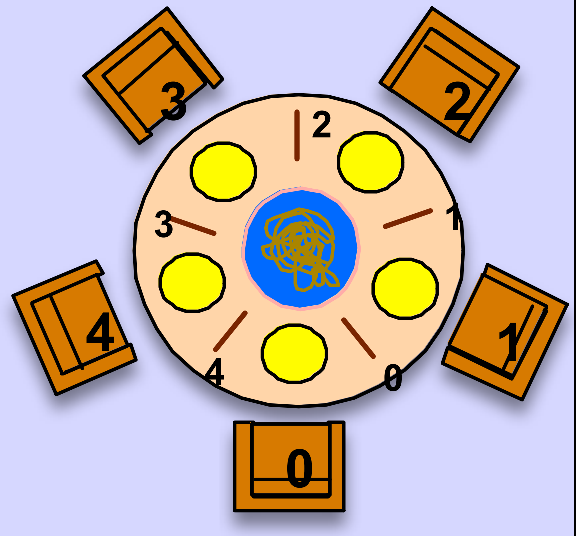
UNIVERSITY OF SOUTHERN DENMARK

```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
          right.get ->
            left.get  ->
```



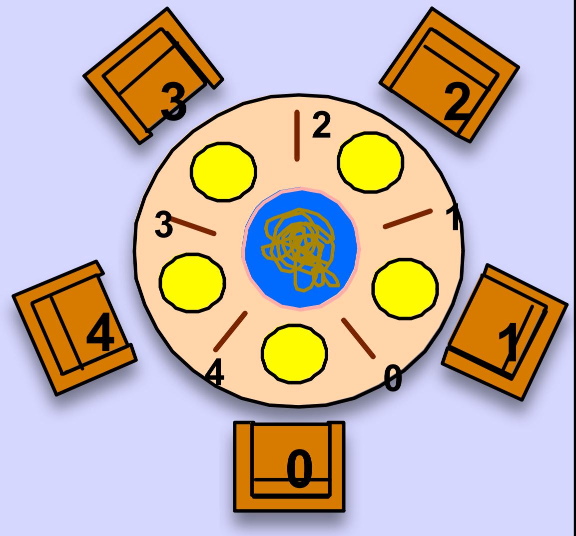
Dining Philosophers - Model


```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
          right.get ->
            left.get  ->
              eat        ->
```



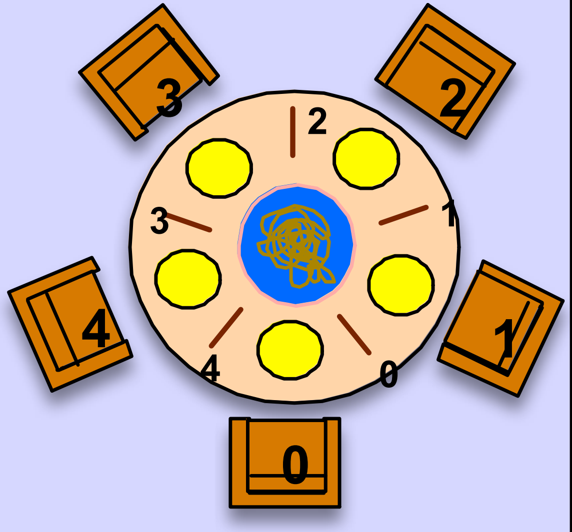
Dining Philosophers - Model

```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit           ->
          right.get ->
            left.get  ->
              eat          ->
                left.put  ->
```



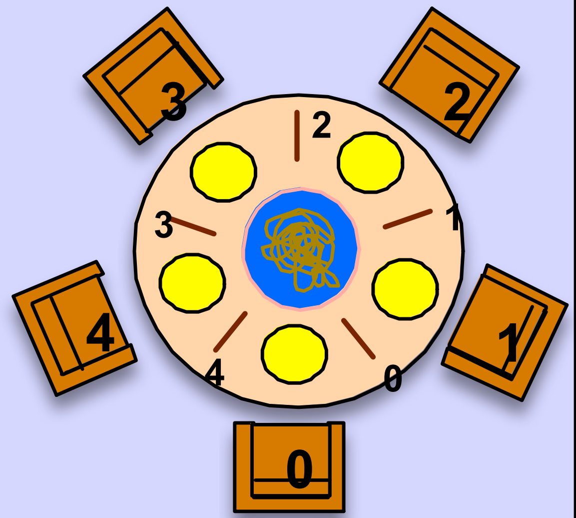
Dining Philosophers - Model


```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
          right.get ->
            left.get  ->
              eat        ->
                left.put  ->
                  right.put ->
```



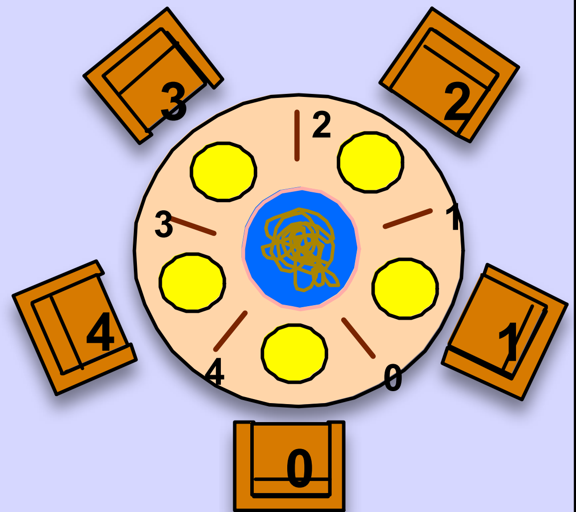
Dining Philosophers - Model

```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
          right.get ->
            left.get  ->
              eat        ->
                left.put  ->
                  right.put ->
                    arise     -> PHIL).
```



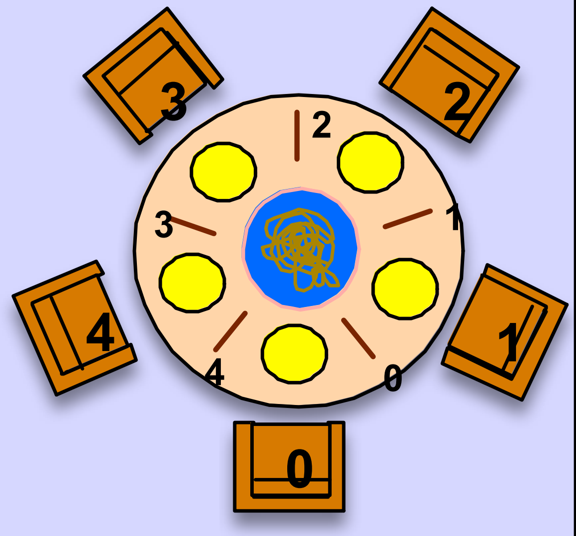
Dining Philosophers - Model


```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit        ->
          right.get ->
            left.get  ->
              eat        ->
                left.put  ->
                  right.put ->
                    arise      -> PHIL).



||DINING_PHILOSOPHERS =
```



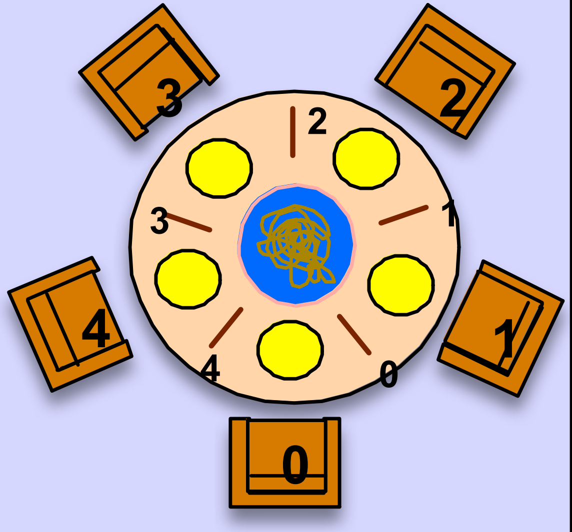
Dining Philosophers - Model


```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
          right.get ->
            left.get  ->
              eat         ->
                left.put  ->
                  right.put ->
                    arise      -> PHIL).


||DINING_PHILOSOPHERS =

   forall [i:0..N-1] (phil[i]:PHIL ||
```



Dining Philosophers - Model

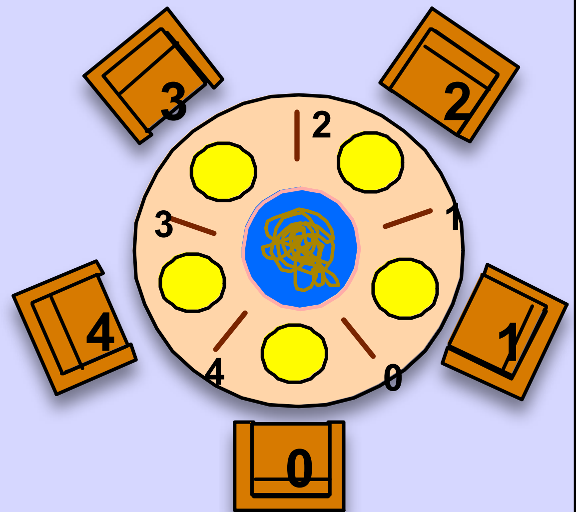

```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
            right.get ->
              left.get  ->
                eat         ->
                  left.put  ->
                    right.put ->
                      arise      -> PHIL).


||DINING_PHILOSOPHERS =

   forall [i:0..N-1] (phil[i]:PHIL ||

                                                        FORK).
```



Dining Philosophers - Model

University of Southern Denmark

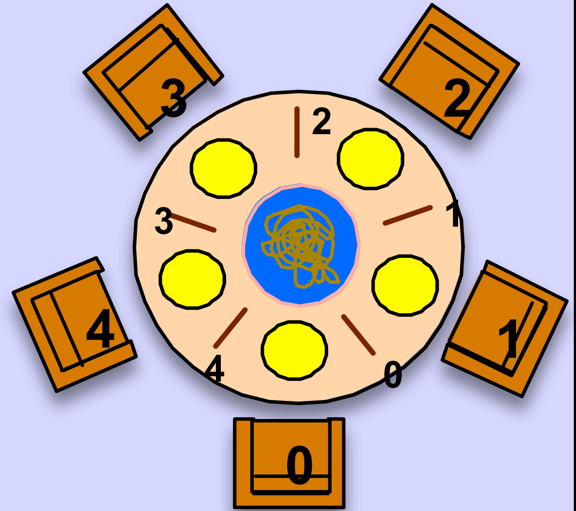
```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
          right.get ->
            left.get  ->
              eat        ->
                left.put  ->
                  right.put ->
                    arise     -> PHIL).


||DINING_PHILOSOPHERS =

   forall [i:0..N-1] (phil[i]:PHIL ||

           { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```



Dining Philosophers - Model

University of Southern Denmark

```
const N = 5

FORK = (get-> put-> FORK).

PHIL = (sit          ->
          right.get ->
            left.get  ->
              eat          ->
                left.put  ->
                  right.put ->
                    arise      -> PHIL).

||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
            { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```



Can this system deadlock?

Dining Philosophers - Model Analysis

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
  phil.1.right.get
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
  phil.1.right.get
  phil.2.sit
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
  phil.1.right.get
  phil.2.sit
  phil.2.right.get
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
   phil.0.sit
   phil.0.right.get
   phil.1.sit
   phil.1.right.get
   phil.2.sit
   phil.2.right.get
   phil.3.sit
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
  phil.1.right.get
  phil.2.sit
  phil.2.right.get
  phil.3.sit
  phil.3.right.get
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
  phil.1.right.get
  phil.2.sit
  phil.2.right.get
  phil.3.sit
  phil.3.right.get
  phil.4.sit
```

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
  phil.1.right.get
  phil.2.sit
  phil.2.right.get
  phil.3.sit
  phil.3.right.get
  phil.4.sit
  phil.4.right.get
```

Dining Philosophers - Model Analysis


```
Trace to DEADLOCK:
   phil.0.sit
   phil.0.right.get
   phil.1.sit
   phil.1.right.get
   phil.2.sit
   phil.2.right.get
   phil.3.sit
   phil.3.right.get
   phil.4.sit
   phil.4.right.get
```

This is the situation where all the philosophers become hungry at the same time, sit down at the table and each philosopher picks up the fork to his right.

Dining Philosophers - Model Analysis

```
Trace to DEADLOCK:
  phil.0.sit
  phil.0.right.get
  phil.1.sit
  phil.1.right.get
  phil.2.sit
  phil.2.right.get
  phil.3.sit
  phil.3.right.get
  phil.4.sit
  phil.4.right.get
```

This is the situation where all the philosophers become hungry at the same time, sit down at the table and each philosopher picks up the fork to his right.

The system can make no further progress since each philosopher is waiting for a left fork held by his neighbour (i.e., a **wait-for cycle** exists)!

Dining Philosophers

Dining Philosophers

Deadlock is easily detected in our model.

Dining Philosophers

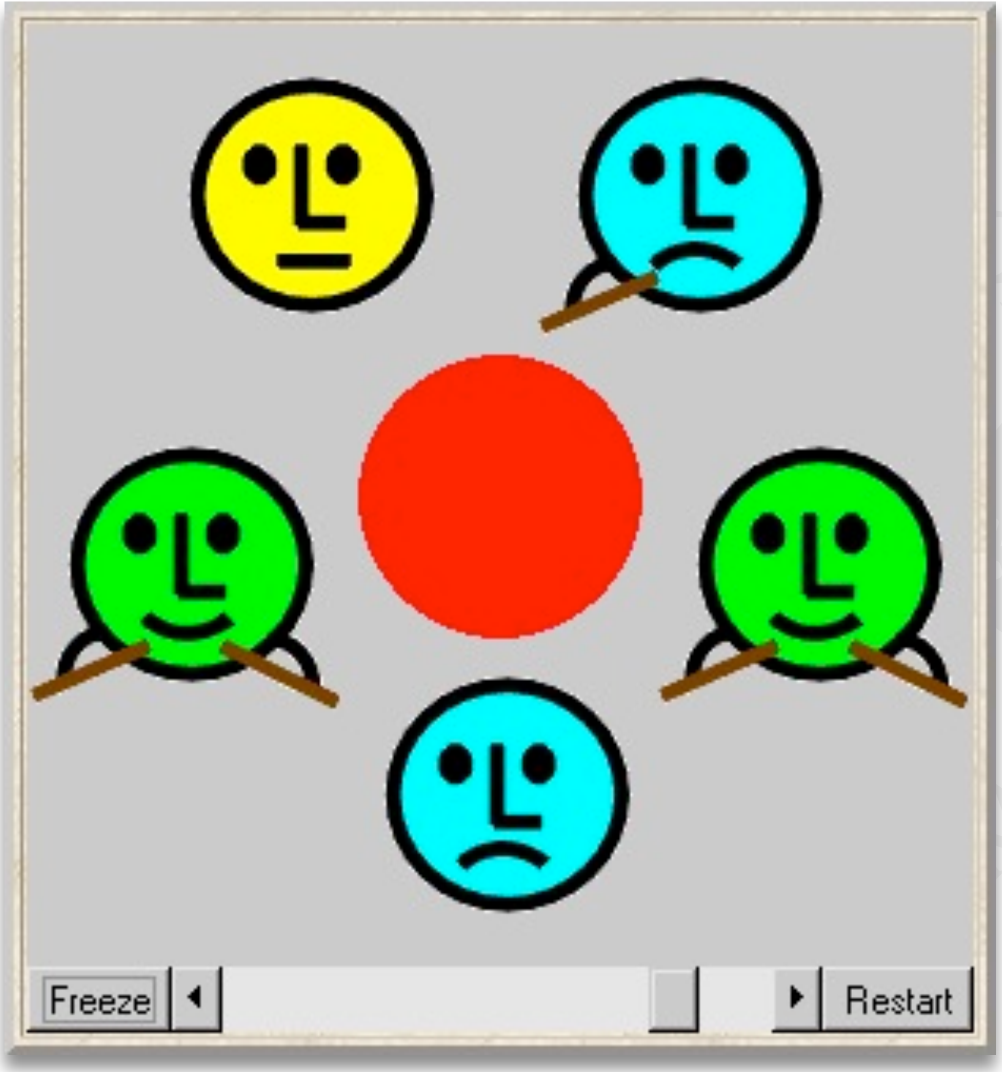
Deadlock is easily detected in our model.

How easy is it to detect a potential deadlock in an implementation?

Dining Philosophers

Deadlock is easily detected in our model.

How easy is it to detect a potential deadlock in an implementation?



Dining Philosophers - Implementation In Java

Dining Philosophers - Implementation In Java

- **Philosophers:**
  active entities
  (implement as
  threads)

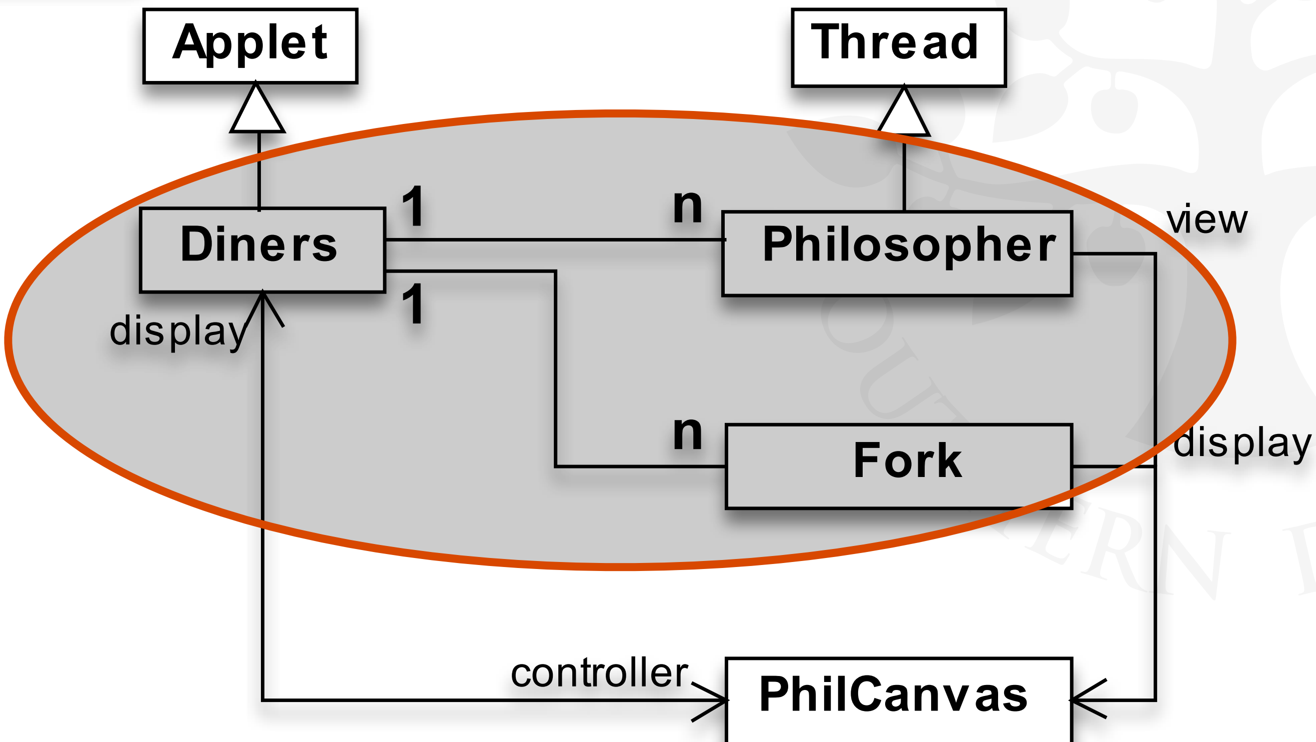
Dining Philosophers - Implementation In Java

- **Philosophers**: active entities (implement as threads)

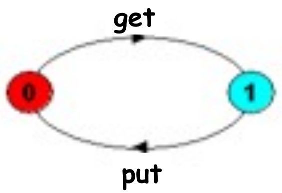
- **Forks**: shared passive entities (implement as monitors)

Dining Philosophers - Implementation In Java

- **Philosophers**: active entities (implement as threads)
- **Forks**: shared passive entities (implement as monitors)



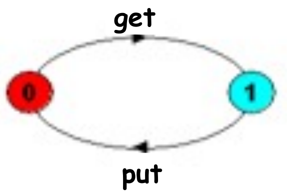
Dining Philosophers – Fork (Monitor)




```
FORK = (get->
        put->
        FORK).
```

Dining Philosophers – Fork (Monitor)

University of Southern Denmark



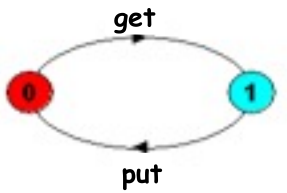

```
FORK = (get->
        put->
        FORK).
```

≡

```
FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
              |when (taken)  put-> FORK[FALSE]).
```

Dining Philosophers – Fork (Monitor)

Not needed
(if we always "get before put")



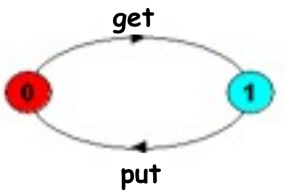

```
FORK = (get->
        put->
        FORK).
```

≡

```
FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
              |when (taken)  put-> FORK[FALSE]).
```

Dining Philosophers – Fork (Monitor)

Not needed
(if we always
"get before put")




```
FORK = (get->
        put->
        FORK).
```

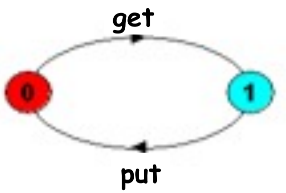
≡

```
FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
              |when (taken)  put-> FORK[FALSE]).
```

```
class Fork {
    private PhilCanvas display;
```

Dining Philosophers – Fork (Monitor)

Not needed (if we always "get before put")




```
FORK = (get->
        put->
        FORK).
```

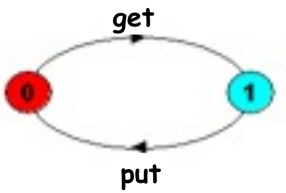
≡

```
FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
              |when (taken)  put-> FORK[FALSE]).
```

```
class Fork {
    private PhilCanvas display;
    private boolean taken = false;
```

taken encodes the state of the fork

Dining Philosophers – Fork (Monitor)




```
FORK = (get->
        put->
        FORK).
```

≡

```
FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
              |when (taken)  put-> FORK[FALSE]).
```

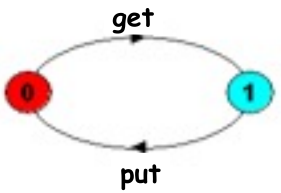
Not needed (if we always "get before put")

```
class Fork {
    private PhilCanvas display;
    private boolean taken = false;

    synchronized void get() throws Int'Exc' {
        while (taken) wait();              // cond. synch. (!)
        taken = true;
        display.setFork(identity, taken);
```

taken encodes the state of the fork

Dining Philosophers – Fork (Monitor)

Not needed (if we always "get before put")




```
FORK = (get->
        put->
        FORK).
```

≡

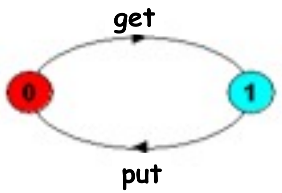
```
FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
              |when (taken)  put-> FORK[FALSE]).
```

```
class Fork {
    private PhilCanvas display;
    private boolean taken = false;

    synchronized void get() throws Int'Exc' {
        while (taken) wait();                // cond. synch. (!)
        taken = true;
        display.setFork(identity, taken);
    }

    synchronized void put() {
```

taken encodes the state of the fork

Dining Philosophers – Fork (Monitor)

Not needed
(if we always
"get before put")




```
FORK = (get->
        put->
        FORK).
```

≡

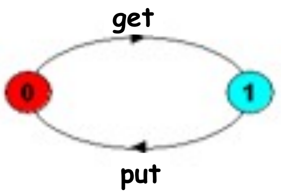
```
FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
              |when (taken)  put-> FORK[FALSE]).
```

```
class Fork {
    private PhilCanvas display;
    private boolean taken = false;

    synchronized void get() throws Int'Exc' {
        while (taken) wait();                // cond. synch. (!)
        taken = true;
        display.setFork(identity, taken);
    }

    synchronized void put() {
        taken = false;
```

taken encodes the state of the fork

Dining Philosophers – Fork (Monitor)

Not needed
(if we always
"get before put")




```
FORK = (get->
        put->
        FORK).
```

≡

FORK = (FORK[FALSE],
FORK[taken:B] (when (!taken) get-> FORK[TRUE]
|~~when (taken)~~ put-> FORK[FALSE]).

```
class Fork {
    private PhilCanvas display;
    private boolean taken = false;

    synchronized void get() throws Int'Exc' {
        while (taken) wait();              // cond. synch. (!)
        taken = true;
        display.setFork(identity, taken);
    }

    synchronized void put() {
        taken = false;
        display.setFork(identity, taken);
        notify();                          // cond. synch. (!)
}   }
```

taken encodes the state of the fork

Dining Philosophers – Philosopher (Thread)

```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

Dining Philosophers – Philosopher (Thread)


```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

```java
class Philosopher extends Thread {
    Fork left, right;
```

Dining Philosophers – Philosopher (Thread)


```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

```
class Philosopher extends Thread {
    Fork left, right;
    public void run() {
        try {
            while (true) {
```

Dining Philosophers – Philosopher (Thread)


```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

```
class Philosopher extends Thread {
    Fork left, right;
    public void run() {
        try {
            while (true) {
                view.setPhil(identity,view.SIT);
                sleep(controller.sitTime());
```

Dining Philosophers – Philosopher (Thread)


```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

```
class Philosopher extends Thread {
    Fork left, right;
    public void run() {
        try {
            while (true) {
                view.setPhil(identity,view.SIT);
                sleep(controller.sitTime());
                right.get();
                view.setPhil(identity,view.GOTRIGHT);
                sleep(500); // constant pause!
```

Dining Philosophers – Philosopher (Thread)

University of Southern Denmark

```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

```
class Philosopher extends Thread {
    Fork left, right;
    public void run() {
        try {
            while (true) {
                view.setPhil(identity,view.SIT);
                sleep(controller.sitTime());
                right.get();
                view.setPhil(identity,view.GOTRIGHT);
                sleep(500); // constant pause!
                left.get();
                view.setPhil(identity,view.EATING);
                sleep(controller.eatTime());
```

Dining Philosophers – Philosopher (Thread)

University of Southern Denmark

```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

```
class Philosopher extends Thread {
    Fork left, right;
    public void run() {
        try {
            while (true) {
                view.setPhil(identity,view.SIT);
                sleep(controller.sitTime());
                right.get();
                view.setPhil(identity,view.GOTRIGHT);
                sleep(500); // constant pause!
                left.get();
                view.setPhil(identity,view.EATING);
                sleep(controller.eatTime());
                left.put();
                right.put();
                view.setPhil(identity,view.ARISE);
                sleep(controller.ariseTime());
```

Dining Philosophers – Philosopher (Thread)


```
PHIL = (sit -> right.get -> left.get -> eat -> left.put ->  right.put -> arise -> PHIL).
```

```
class Philosopher extends Thread {
    Fork left, right;
    public void run() {
        try {
            while (true) {
                view.setPhil(identity,view.SIT);
                sleep(controller.sitTime());
                right.get();
                view.setPhil(identity,view.GOTRIGHT);
                sleep(500); // constant pause!
                left.get();
                view.setPhil(identity,view.EATING);
                sleep(controller.eatTime());
                left.put();
                right.put();
                view.setPhil(identity,view.ARISE);
                sleep(controller.ariseTime());
            }
        } catch (InterruptedException _) {}
}    }
```

Dining Philosophers – Main Applet

UNIVERSITY OF SOUTHERN DENMARK

```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                      { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

Dining Philosophers – Main Applet

```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                      { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

The applet's start() method creates (an array of) shared **Fork** monitors...:

Dining Philosophers – Main Applet

University of Southern Denmark

```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                       { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

The applet's start() method creates (an array of) shared **Fork** monitors...:

```
for (int i=0; i<N; i++) fork[i] = new Fork(display, i);
```

Dining Philosophers – Main Applet

```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                      { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

The applet's start() method creates (an array of) shared **Fork** monitors...:

```
for (int i=0; i<N; i++) fork[i] = new Fork(display, i);
```

...and (an array of) **Philosopher** threads (with refs to forks):

Dining Philosophers – Main Applet

University of Southern Denmark

```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                       { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

The applet's start() method creates (an array of) shared **Fork** monitors…:

```
for (int i=0; i<N; i++) fork[i] = new Fork(display, i);
```

…and (an array of) **Philosopher** threads (with refs to forks):

```
for (int i=0; i<N; i++)
    phil[i] =
        new Philosopher(this, i, fork[(i-1+N)%N], fork[i]);
```

Dining Philosophers – Main Applet


```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                     { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

The applet's start() method creates (an array of) shared **Fork** monitors…:

```
for (int i=0; i<N; i++) fork[i] = new Fork(display, i);
```

…and (an array of) **Philosopher** threads (with refs to forks):

```
for (int i=0; i<N; i++)
                                          left                right
    phil[i] =
        new Philosopher(this, i, fork[(i-1+N)%N], fork[i]);
```

Dining Philosophers – Main Applet

UNIVERSITY OF SOUTHERN DENMARK

```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                         { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

The applet's start() method creates (an array of) shared Fork monitors...:

```
for (int i=0; i<N; i++) fork[i] = new Fork(display, i);
```

...and (an array of) Philosopher threads (with refs to forks):

```
for (int i=0; i<N; i++)
    phil[i] =
        new Philosopher(this, i, fork[(i-1+N)%N], fork[i]);
```

left right

...and start all Philosopher threads:

Dining Philosophers – Main Applet

University of Southern Denmark

```
||DINING_PHILOSOPHERS =
   forall [i:0..N-1] (phil[i]:PHIL ||
                        { phil[i].left, phil[((i-1)+N)%N].right }::FORK).
```

The applet's start() method creates (an array of) shared **Fork** monitors...:

```
for (int i=0; i<N; i++) fork[i] = new Fork(display, i);
```

...and (an array of) **Philosopher** threads (with refs to forks):

```
for (int i=0; i<N; i++)                          left               right
     phil[i] =
          new Philosopher(this, i, fork[(i-1+N)%N], fork[i]);
```

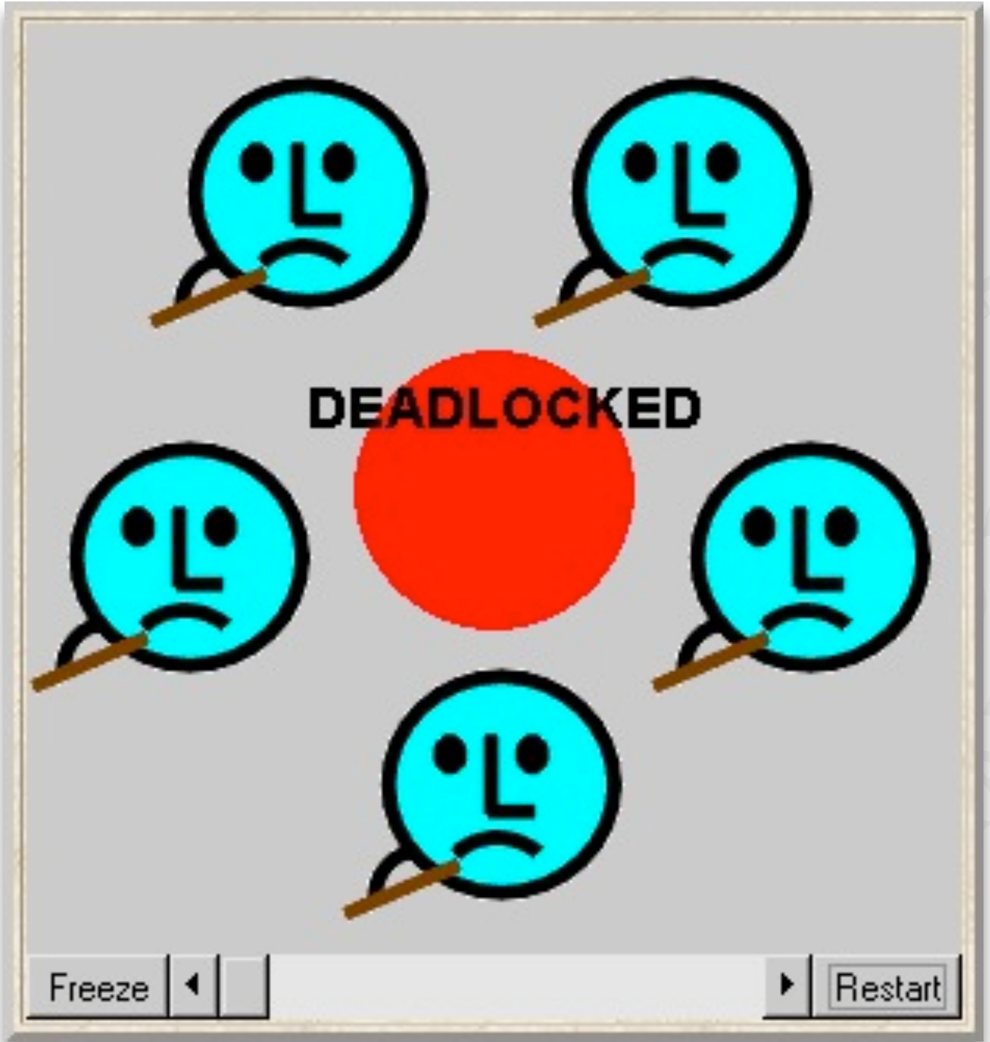
...and start all Philosopher threads:

```
for (int i=0; i<N; i++) phil[i].start();
```

Dining Philosophers

To ensure deadlock occurs eventually, the slider control may be moved to the left. This reduces the time each philosopher spends thinking and eating.

This "speedup" increases the **probability** of deadlock occurring.



Deadlock-free Philosophers

Deadlock can be avoided by ensuring that a wait-for cycle cannot exist.

Deadlock-free Philosophers

Deadlock can be avoided by ensuring that a wait-for cycle cannot exist.

How?

Deadlock-free Philosophers

Deadlock can be avoided by ensuring that a wait-for cycle cannot exist.

How?

Introduce an **asymmetry** into definition of philosophers.

Use the identity `'i'` of a philosopher to make even numbered philosophers get their left forks first, odd their right first.

Deadlock-free Philosophers

Deadlock can be avoided by ensuring that a wait-for cycle cannot exist.

How?

Introduce an **asymmetry** into definition of philosophers.

Use the identity `'i'` of a philosopher to make even numbered philosophers get their left forks first, odd their right first.

```
PHIL[i:0..N-1] =
   (when (i%2==0) sitdown-> left.get ->...-> PHIL
   |when (i%2==1) sitdown-> right.get->...-> PHIL).
```

Deadlock-free Philosophers

Deadlock can be avoided by ensuring that a wait-for cycle cannot exist.

How?

Introduce an **asymmetry** into definition of philosophers.

Use the identity `'i'` of a philosopher to make even numbered philosophers get their left forks first, odd their right first.

```
PHIL[i:0..N-1] =
   (when (i%2==0) sitdown-> left.get ->...-> PHIL
   |when (i%2==1) sitdown-> right.get->...-> PHIL).
```

How does this solution compare to the "sort-shared-acquisitions" idea?

Deadlock-free Philosophers

Deadlock can be avoided by ensuring that a wait-for cycle cannot exist.

How?

Introduce an **asymmetry** into definition of philosophers.

Use the identity 'i' of a philosopher to make even numbered philosophers get their left forks first, odd their right first.

```
PHIL[i:0..N-1] =
   (when (i%2==0) sitdown-> left.get ->...-> PHIL
   |when (i%2==1) sitdown-> right.get->...-> PHIL).
```

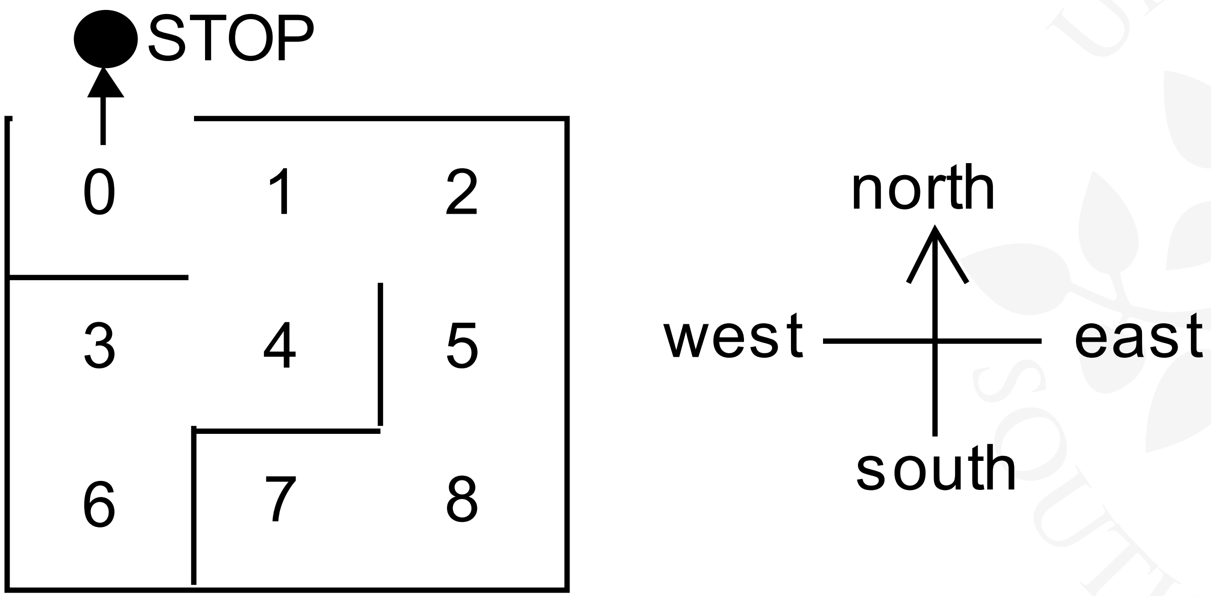
How does this solution compare to the "sort-shared-acquisitions" idea?

Other strategies?

1. Mutual exclusion condition
2. Hold-and-wait condition
3. No pre-emption condition
4. Circular-wait condition

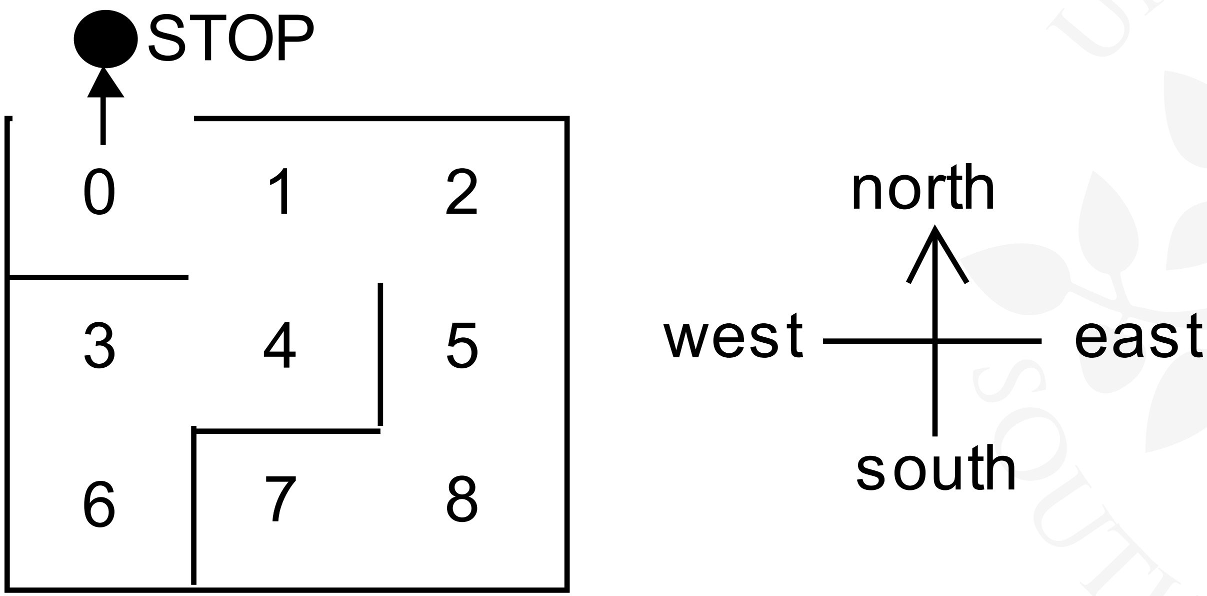
Maze Example - Shortest Path To "deadlock"

We can exploit the shortest path trace produced by the deadlock detection mechanism of **LTSA** to find the shortest path out of a maze to the **STOP** process!



Maze Example - Shortest Path To "deadlock"

We can exploit the shortest path trace produced by the deadlock detection mechanism of **LTSA** to find the shortest path out of a maze to the `STOP` process!

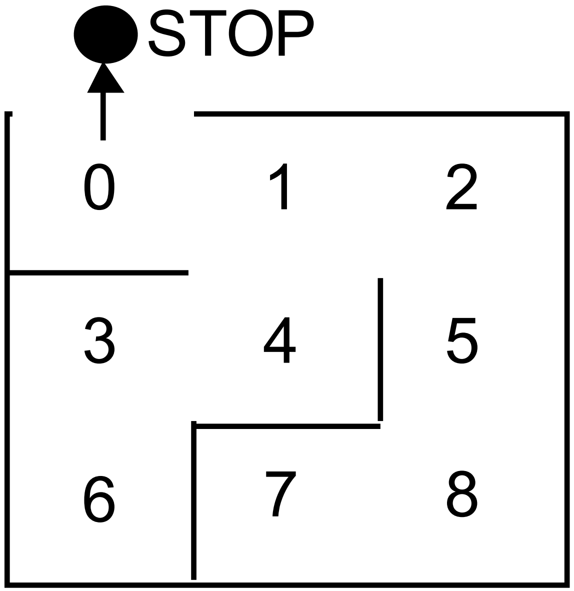


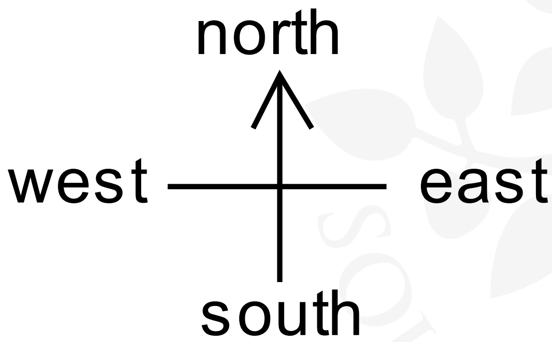
We first model the `MAZE`.

Each position is modelled by the moves that it permits. The `MAZE` parameter gives the starting position.

Maze Example - Shortest Path To “deadlock”

We can exploit the shortest path trace produced by the deadlock detection mechanism of **LTSA** to find the shortest path out of a maze to the `STOP` process!





We first model the `MAZE`.

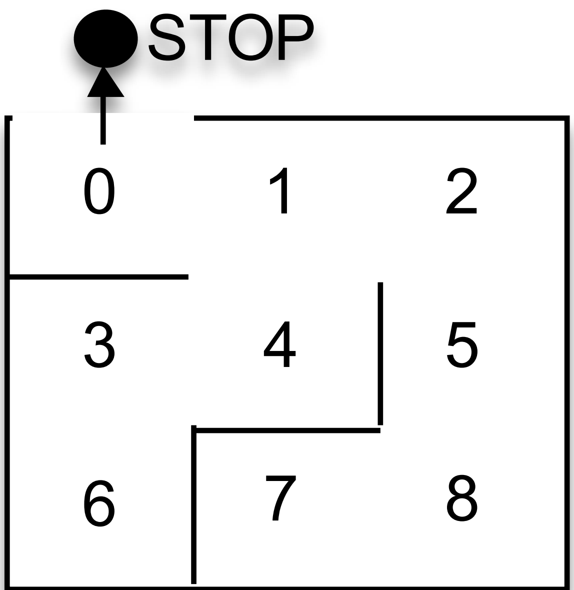
Each position is modelled by the moves that it permits. The `MAZE` parameter gives the starting position.

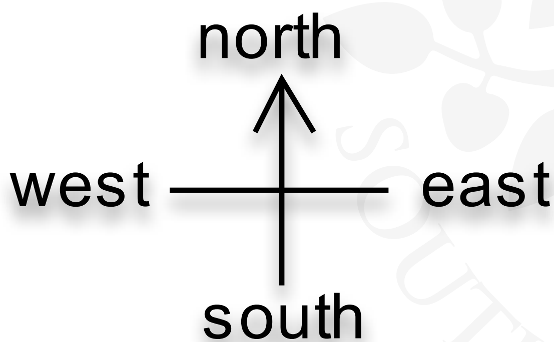
```
eg.  MAZE(Start=8) = P[Start],
     P[0] = (north->STOP|east->P[1]),...
```

Maze Example - Shortest Path To "deadlock"


```
||GETOUT = MAZE(7).
```

Shortest path escape trace from position 7 ?



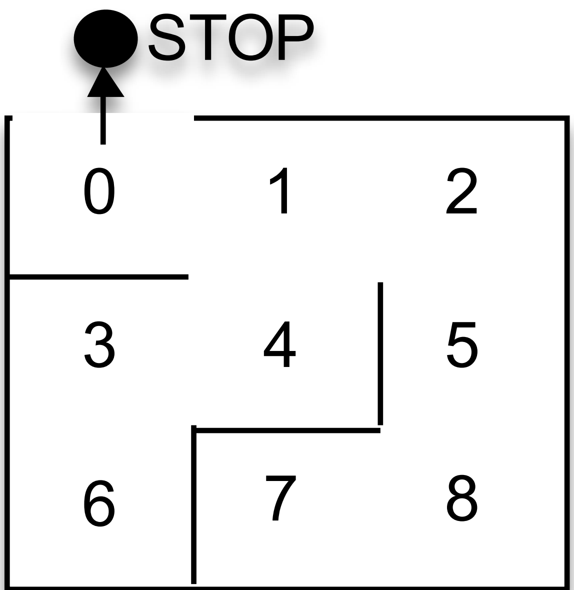


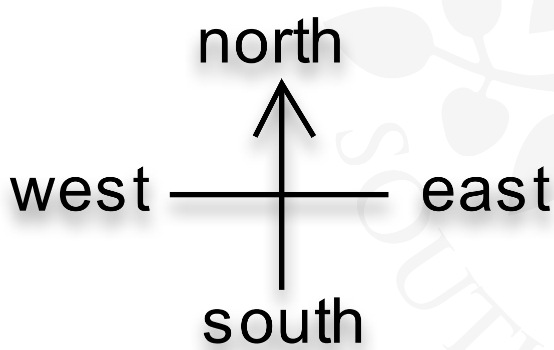

```
Trace to
DEADLOCK:
```

Maze Example - Shortest Path To "deadlock"


```
||GETOUT = MAZE(7).
```

Shortest path escape trace from position 7 ?






```
Trace to
DEADLOCK:

     east
     north
     north
     west
     west
     north
```

Summary

Summary

- Concepts

Summary

- Concepts
  - deadlock (no further progress)

Summary

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:

Summary

- **Concepts**
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition

Summary

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition
    2. Hold-and-wait condition

Summary

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition
    2. Hold-and-wait condition
    3. No pre-emption condition

Summary

Concepts

- deadlock (no further progress)
- 4x necessary and sufficient conditions:
  1. Mutual exclusion condition
  2. Hold-and-wait condition
  3. No pre-emption condition
  4. Circular-wait condition

Summary

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition
    2. Hold-and-wait condition
    3. No pre-emption condition
    4. Circular-wait condition
- Models

Summary

University of Southern Denmark

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition
    2. Hold-and-wait condition
    3. No pre-emption condition
    4. Circular-wait condition
- Models
  - no eligible actions (analysis gives shortest path trace)

Summary

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition
    2. Hold-and-wait condition
    3. No pre-emption condition
    4. Circular-wait condition
- Models
  - no eligible actions (analysis gives shortest path trace)
- Practice

Summary

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition
    2. Hold-and-wait condition
    3. No pre-emption condition
    4. Circular-wait condition
- Models
  - no eligible actions (analysis gives shortest path trace)
- Practice
  - blocked threads

Summary

- Concepts
  - deadlock (no further progress)
  - 4x necessary and sufficient conditions:
    1. Mutual exclusion condition
    2. Hold-and-wait condition
    3. No pre-emption condition
    4. Circular-wait condition

Aim - deadlock avoidance:

"Break at least one of the deadlock conditions".

- Models
  - no eligible actions (analysis gives shortest path trace)
- Practice
  - blocked threads