THE UNIVERSITY OF NEWCASTLE AUSTRALIA

FACULTY OF ENGINEERING AND BUILT ENVIRONMENT

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# OPERATING SYSTEMS

## Week 6

Much of the material on these slides comes from the recommended textbook by William Stallings

## Announcement

### Weekly program

**Midterm**

- ❑ Week 8 : TBA
- ❑ Syllabus: Up to Real-time Scheduling (Lecture and Workshop)
- ❑ Venue: TBA
- ❑ Time: TBA

## Detailed content

### Weekly program

- ✓ Week 1 – Operating System Overview
- ✓ Week 2 – Processes and Threads
- ✓ Week 3 – Scheduling
- ✓ Week 4 – Real-time System Scheduling and Multiprocessor Scheduling
- ✓ Week 5 – Concurrency: Mutual Exclusion and Synchronization
- ❑ **Week 6 – Concurrency: Deadlock and Starvation**
- ❑ Week 7 – Memory Management
- ❑ Week 8 – Disk and I/O Scheduling
- ❑ Week 9 – File Management
- ❑ Week 10 – Real-world Operating Systems: Embedded and Security
- ❑ Week 11 – Real-world Operating Systems: Distributed Operating Systems
- ❑ Week 12 – Revision of the course
- ❑ Week 13 – Extra revision (if needed)

## Key Concepts From Last Lecture

- Semaphore is a special purpose signaling variable that can be operated using two primitives: `semSignal` and `semWait`
- Two types: general semaphore and binary semaphore – essentially have the same expressive power
- Semaphores can be implemented in software or with support from hardware
- Semaphores are powerful and felxible tools for enforcing mutual exclusion but difficult to manage and handle
  - Programmers are responsible to ensure mutual exclusion and synchronization

## Key Concepts From Last Lecture

- Monitors provide equivalent functionality of semaphores but easier to use
  - Monitor itself ensures mutual exclusion and programmers are responsible to ensure synchronization
- Solution to two classic problems
  - Producer/Consumer problem
  - Readers/Writers problem

## Week 06 Lecture Outline

**Concurrency: Mutual Exclusion, Deadlock and Starvation**

- ❑ Software Approaches to mutual exclusion
- ❑ Dekker’s Algorithm
- ❑ Peterson’s Algorithm
- ❑ Deadlock
- ❑ Principles of Deadlock
- ❑ Consumable and Reusable Resources
- ❑ Conditions for Deadlock
- ❑ Deadlock Prevention
- ❑ Deadlock Avoidance
- ❑ Deadlock Detection
- ❑ Dining Philosopher Problem

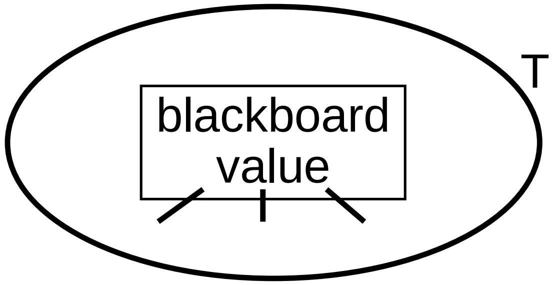
Videos to watch before lecture

## Mutual Exclusion: Software Approach

- Software approaches can be implemented for concurrent processes
  - Executing on single processor or multiple processor
  - Assumes elementary mutual exclusion at memory access level
  - No other support in hardware, OS or programming language is assumed

## Mutual Exclusion: Software Approach

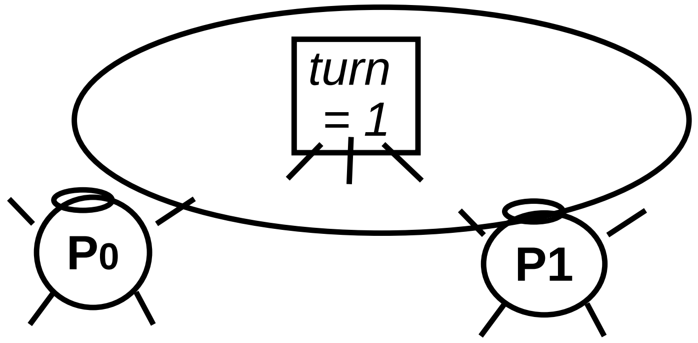
- In any case, we can assume that the hardware provides elementary mutual exclusion for memory accesses.
  - Simultaneous access to the same location in main memory is prevented by the hardware.
  - Requests are serialised and granted in an unspecified order.



The elementary hardware protection is modelled by the **protocol igloo**: the entrance and interior of the igloo are small enough that at most **one person can enter** or **be in** the igloo at a time.

The igloo contains a **blackboard** for writing a message (usually a single value).

## Software approach: Attempt 1



- A process Pi that wants to execute its critical section first enters the igloo and checks the blackboard.
- If process Pi finds the value i, then it leaves the igloo and goes critical.
- If not, then Pi repeats the entry and check until the blackboard shows i.
- When it finishes the critical section, it returns to the igloo and writes the number of the other process.
- **Mutual exclusion** is guaranteed.

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 0*

```
process  P0
begin
  while turn !=0
           do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
           do  <nothing>;
    <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 0*

```
process  P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 0*

```
process  P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 1*

```
process  P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process $P_i$
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 1*

```
process $P_1$
begin
  while turn !=1
          do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
process $P_0$
begin
  while turn !=0
          do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 1*

```
process  P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process  $P_i$
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 0*

```
process  $P_1$
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
process  $P_0$
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 0*

```
process  P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 1*

```
process  P0
begin
  while turn !=0
           do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
           do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 1*

```
process P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 1*

```
process  P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

```
process  P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

```
global var turn:0..1;

process  Pi
begin
  while turn !=i do  <nothing>;
  <critical section>
  turn := 1-i
end.
```

*Turn = 1*

```
process  P1
begin
  while turn !=1
            do  <nothing>;
  <critical section>
  turn := 1-1
end.
```

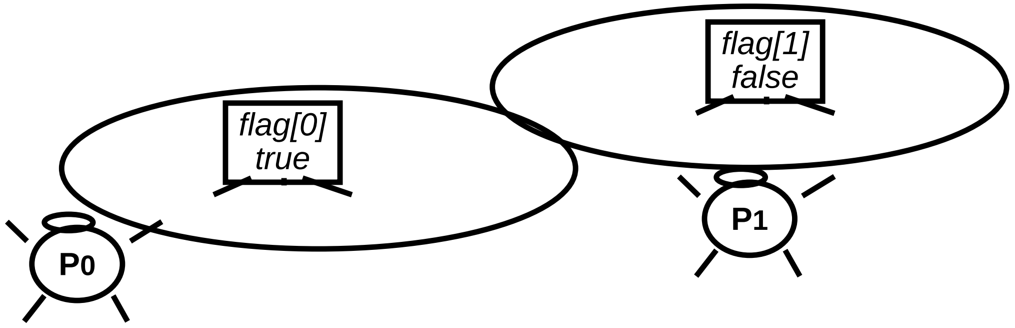
```
process  P0
begin
  while turn !=0
            do  <nothing>;
  <critical section>
turn := 1-0
end.
```

## Software approach: Attempt 1

**Problems:**

- The procedure is “**busy-waiting**”, that is, the thwarted process can do nothing productive while it waits, yet it **keeps the CPU active** by continually checking.
- Pace of execution is **limited to the slower process**, because the executions must strictly alternate.
- **It does NOT prevent starvation**, because one process may fail, permanently blocking the other.

## Software approach: Attempt 2



```
var flag  : array[0..1] of Boolean;

process  Pi
  while flag[1-i] do  <nothing>;
  flag[i]:=true;
  <critical section>
  flag[i]:=false;
```

- Each process should have its own key to its critical section, rather than rely on others as in last attempt.
- Process Pi is in its critical section if and only if we have flag[i] = true.
- Each process can **check the other** blackboard, but it can **update only its own** blackboard.

```
var flag  : array[0..1] of Boolean;

process  Pi
  while flag[1-i] do  <nothing>;
  flag[i]:=true;
  <critical section>
  <critical section>
  flag[i]:=false;
```

```
process  P0
  while flag[1] do
            <nothing>;
  flag[0]:=true;
  <critical section>
  <critical section>
flag[0]:=false;
```

```
process  P1
  while flag[0] do
            <nothing>;
  flag[1]:=true;
  <critical section>
  <critical section>
flag[1]:=false;
```

*flag[0] = true*

*flag[1] = false*

# Software approach: Attempt 2

Problem:

1. This method **does not guarantee mutual exclusion**. It is not independent of relative speeds of process execution.
    1. P0 executes **while** and finds flag[1]=false.
    2. P1 executes **while** and finds flag[0]=false.
    3. P0 sets flag[0]:=true  and goes critical.
    4. P1 sets flag[1]:=true  and goes critical.

2. If one process fails outside the critical section then the other process is not blocked but if a process fails inside its critical section then the other process is permanently blocked.

## Software approach: Attempt 3

- Attempt 2 failed because one process could change its state (flag)
  - after the other process has checked it,
  - before it enters its critical section.
- We can fix this by changing state **before** checking the other's flag.

```
var flag  : array[0..1] of Boolean;

process  Pi
  flag[i]:=true;
  while flag[1-i] do  <nothing>
  <critical section>
  flag[i]:=false;
```

- This enforces mutual exclusion.

```
var flag  : array[0..1] of Boolean;

process  Pi
  flag[i]:=true;
  while flag[1-i] do  <nothing>
  <critical section>
  <critical section>
  flag[i]:=false;
```

```
process  P0
  flag[0]:=true;
  while flag[1] do
            <nothing>
  <critical section>
 <critical section>
  flag[0]:=false;
```

```
process  P1
  flag[1]:=true;
  while flag[0] do
            <nothing>
  <critical section>
 <critical section>
  flag[1]:=false;
```

*flag[0] = true*

*flag[1] = true*

# Software approach: Attempt 3

**Problem**

- It does **not prevent deadlock**: both processes may set their flags to *true* and be caught on the *while* statement before either enters the critical section. Both processes would then think that the other was in the critical region, when neither are!

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## Software approach: Attempt 4

- Attempt 3 fails because **a process sets its state without knowing the state of the other process**.
- Thus we change the procedure so that **each process gives the other some time to jump ahead of it**, i.e. it "backs off", or defers to the other process.

```
flag[i]:=true
while flag[1-i] do
  begin
    flag[i]:=false;
    <delay for a short time>
    flag[i]:=true
  end
<critical section>
flag[i]:=false
```

- **Mutual exclusion** is enforced.

# Software approach: Attempt 4

```
flag[i]:=true
while flag[1-i] do
  begin
    flag[i]:=false;
    <delay for a short time>
    flag[i]:=true
  end
<critical section>
flag[i]:=false
```

- **Problem**
  - P0 sets flag[0]:=true
  - P1 sets flag[1]:=true
  - P0 checks flag[1]
  - P1 checks flag[0]
  - P0 sets flag[0]:=false
  - P1 sets flag[1]:=false
  - P0 sets flag[0]:=true
  - P1 sets flag[1]:=true
  - . . . .

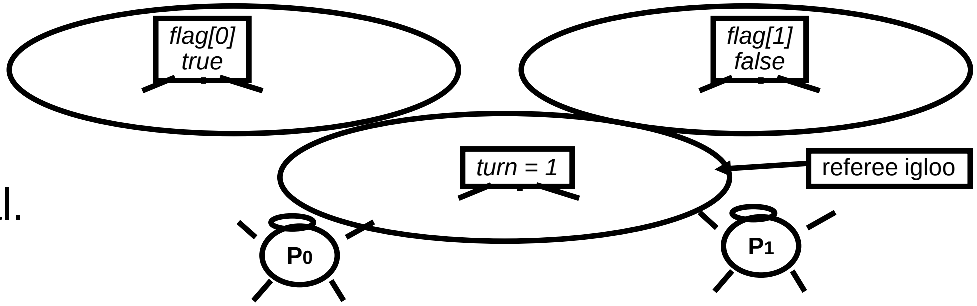
This is **livelock**.

Although it seems **unlikely**, it is a **possible** scenario, and can easily happen in practice.

Alteration in relative speed of the 2 processes will break the cycle.

## Correct S/W approach: Dekker's Algorithm

We to give the processes **the right to insist** that they can enter their critical sections. The processes can take **turns** to insist.



- Suppose that P0 wants to go critical.
  - it sets its own flag  to true.
  - it checks the flag of P1:
    - if P1's flag is false, then P0 goes critical.
    - if P1's flag  is true, then it checks the referee
      - if turn = 0, then P0 has the right to insist on taking a turn, and it checks P1's flag again.
      - if turn = 1, then P0 sets its flag to false, waits for its turn, resets its flag and goes critical.
  - after finishing its critical section, P0 sets turn = 1 and its flag to false transferring the right to insist to P1.

# Dekker's Algorithm

```
var flag: array[0..1] of Boolean;
      turn:0..1;
```

```
main program
begin
  flag[0]:=false;
  flag[1]:=false;
  turn:=1;
  parbegin
    P0;
    P1
  parend
end
```

```
process  P0
begin
  repeat
    flag[0]:=true;
    while flag[1] do
              if turn=1 then
                begin
                flag[0]:=false;
                while turn=1 do <nothing>
                flag[0]:=true
                end;
    <critical section>
    turn:=1;
    flag[0]:=false;
    <remainder of the process>
  forever
end;
```

```
process  P1
begin
  repeat
    flag[1]:=true;
    while flag[0] do
              if turn=0 then
                begin
                flag[1]:=false;
                while turn=0 do <nothing>
                flag[1]:=true
                end;
    <critical section>
    turn:=0;
    flag[1]:=false;
    <remainder of the process>
  forever
end;
```

# Dekker’s Algorithm

- Dekker’s Algorithm solves the mutual exclusion but with a rather complicated program that is difficult to follow and whose correctness is difficult to prove

- Peterson (1981) provided a simple elegant solution.

# Peterson's Algorithm

- **Mutual exclusion is enforced**:
- **Deadlock is prevented**:

```
var flag: array[0..1] of Boolean;
      turn:0..1;
```

```
procedure  P0;
begin
  repeat
    flag[0]:=true;
    turn:=1;
    while flag[1] and turn=1 do <nothing>
    <critical section>
    flag[0]:=false;
    <remainder>
  forever
end
```

```
procedure  P1;
begin
  repeat
    flag[1]:=true;
    turn:=0;
    while flag[0] and turn=0 do  <nothing>
    <critical section>
    flag[1]:=false;
    <remainder>
  forever
end
```

# Peterson's Algorithm

- **Mutual exclusion is enforced**: Suppose that P0 wants to enter its critical section. First, it sets flag[0] to true; then it is impossible for P1 to enter its critical section. If P1 is already in its critical section, then flag[1] must be true, and so P0 cannot get to its critical section.

- **Deadlock is prevented**: Suppose that both P0 and P1 are blocked; this can only occur indefinitely if both are in the **while** loops. But the conditions on these **while** loops are inconsistent: it is not possible to have turn=1 and turn=0 at the same time.

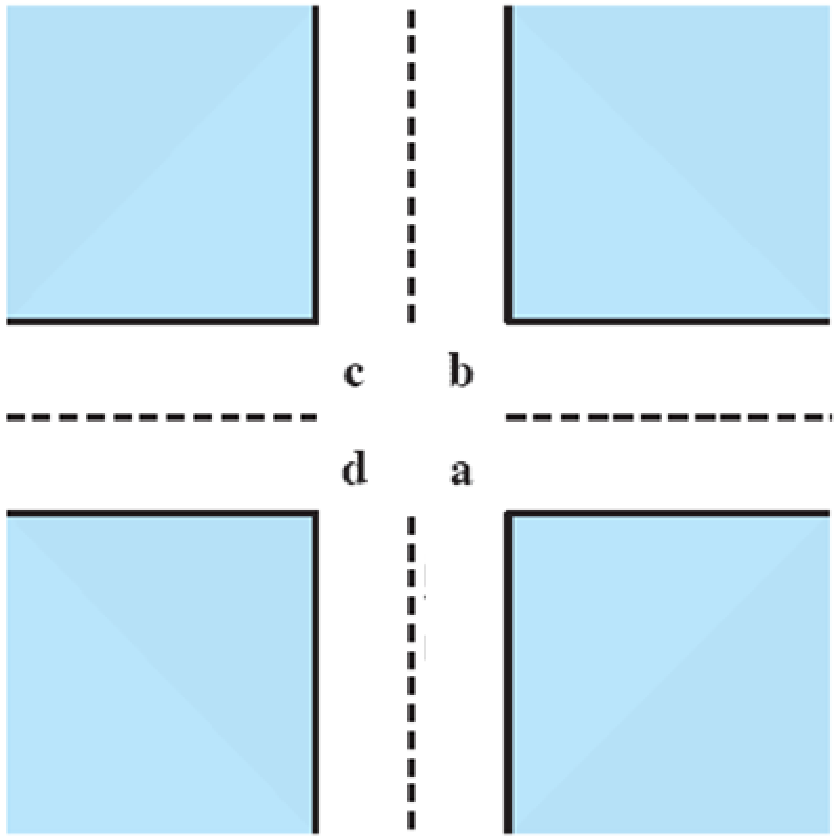
## Summary

- Software approaches to mutual exclusion does not assume any support from hardware, OS or programming language
  - Except that no simultaneous access to the same location in main memory is possible.
- Dekker’s algorithm/Peterson algorithms
  - Can ensure mutual exclusion and freedom from deadlock and freedom from starvation
  - Employs busy waiting

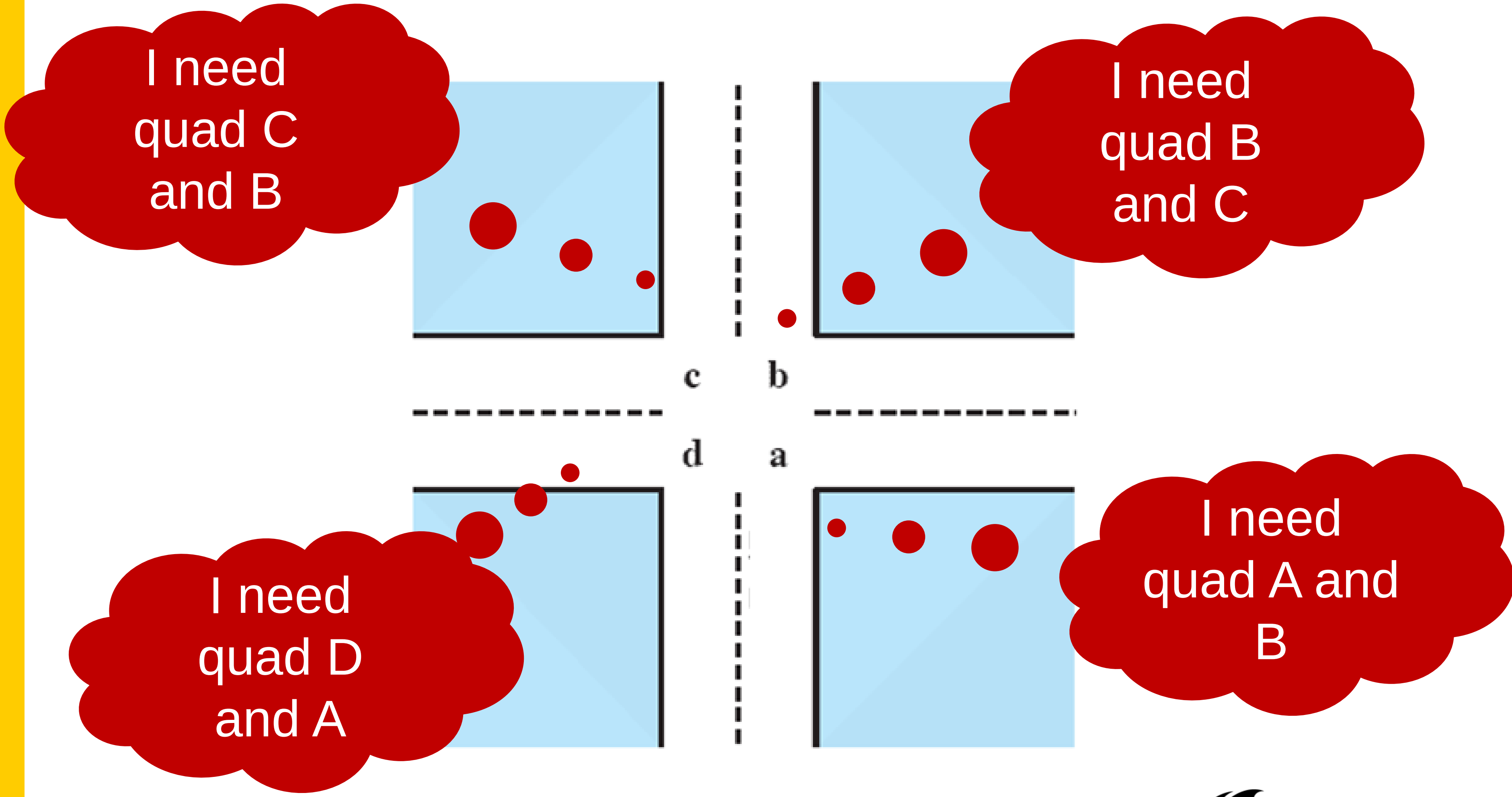
## Deadlock

- The permanent blocking of a set of processes that either compete for system resources or communicate with each other
- A set of processes is deadlocked when each process in the set is blocked awaiting an event that can only be triggered by another blocked process in the set
- Permanent – none of the events is ever triggered
- No efficient solution

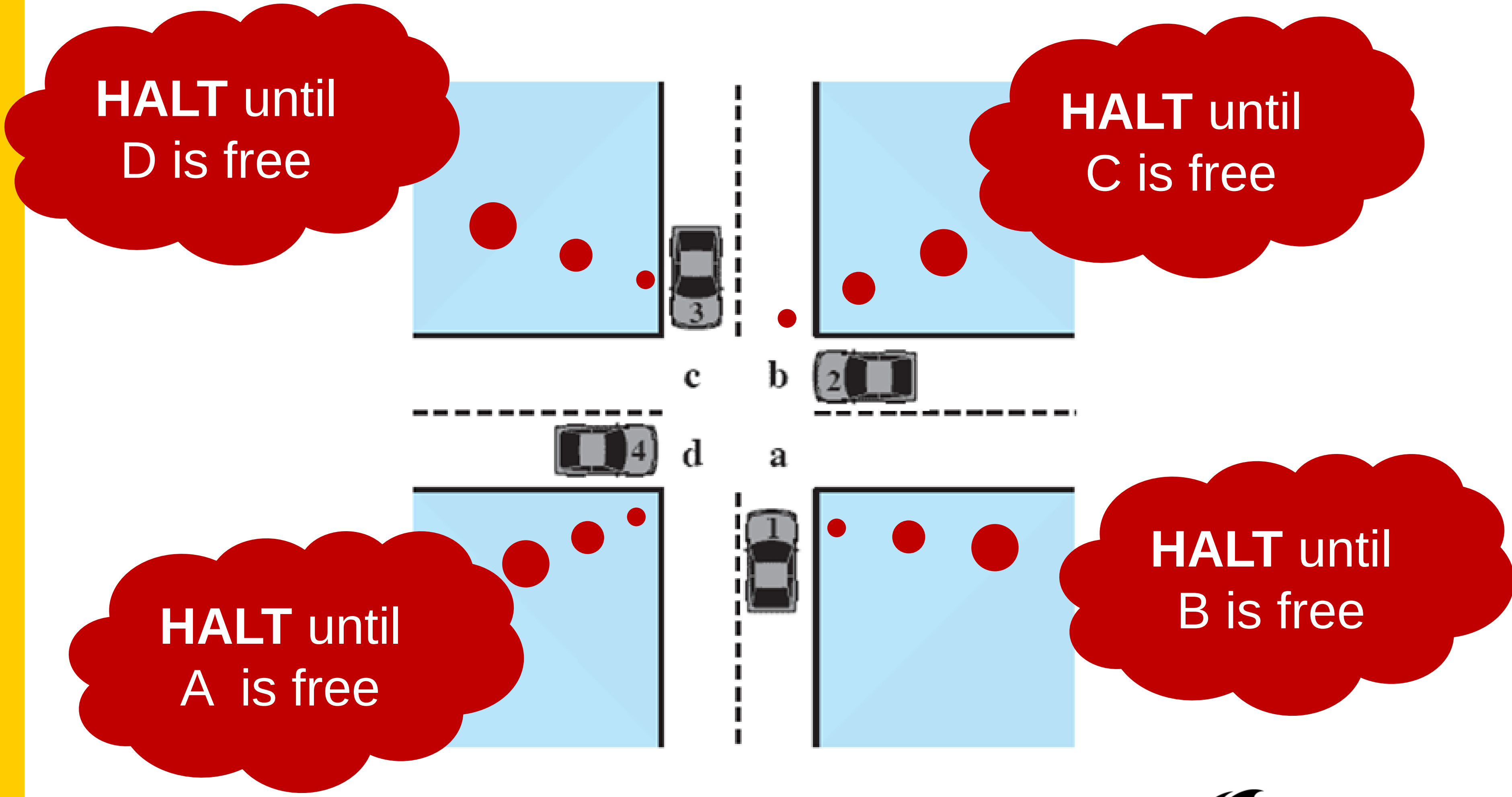
## Potential Deadlock



## Potential Deadlock



## Actual Deadlock

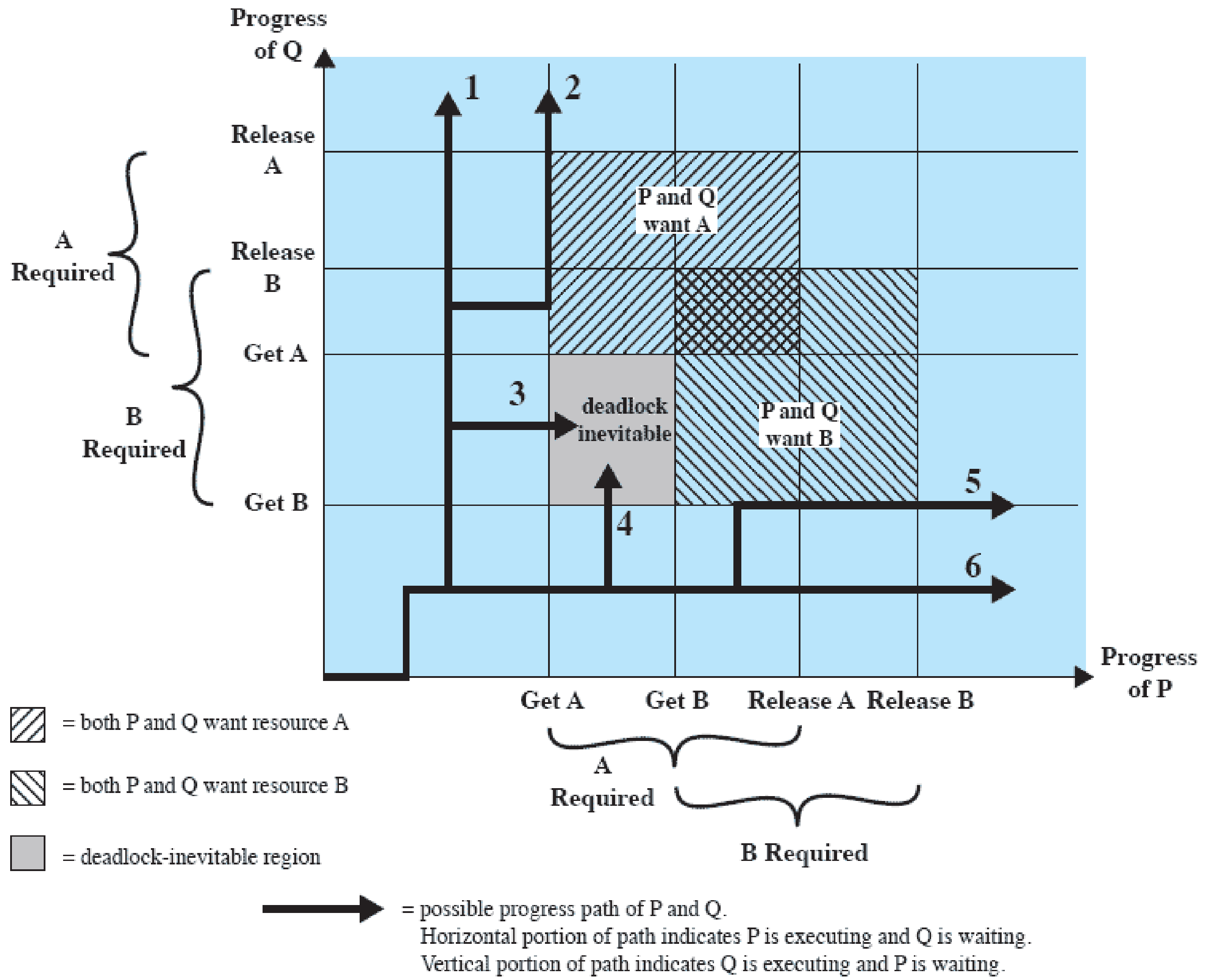


## Process deadlock

- Consider two processes

| Process P | Process Q |
|---|---|
| …. | …. |
| Get A | Get B |
| …. | …. |
| Get B | Get A |
| …. | …. |
| Release A | Release B |
| …. | …. |
| Release B | Release A |
| …. | …. |

## Joint Process Diagram



▨ = both P and Q want resource A

▧ = both P and Q want resource B

⬜ = deadlock-inevitable region

→ = possible progress path of P and Q.
Horizontal portion of path indicates P is executing and Q is waiting.
Vertical portion of path indicates Q is executing and P is waiting.

**Figure 6.2 Example of Deadlock**

## Process deadlock

- How about?

| Process P | Process Q |
|---|---|
| …. | …. |
| Get A | Get B |
| …. | …. |
| Release A | Get A |
| …. | …. |
| Get B | Release B |
| …. | …. |
| Release B | Release A |
| …. | …. |

## No Deadlock example

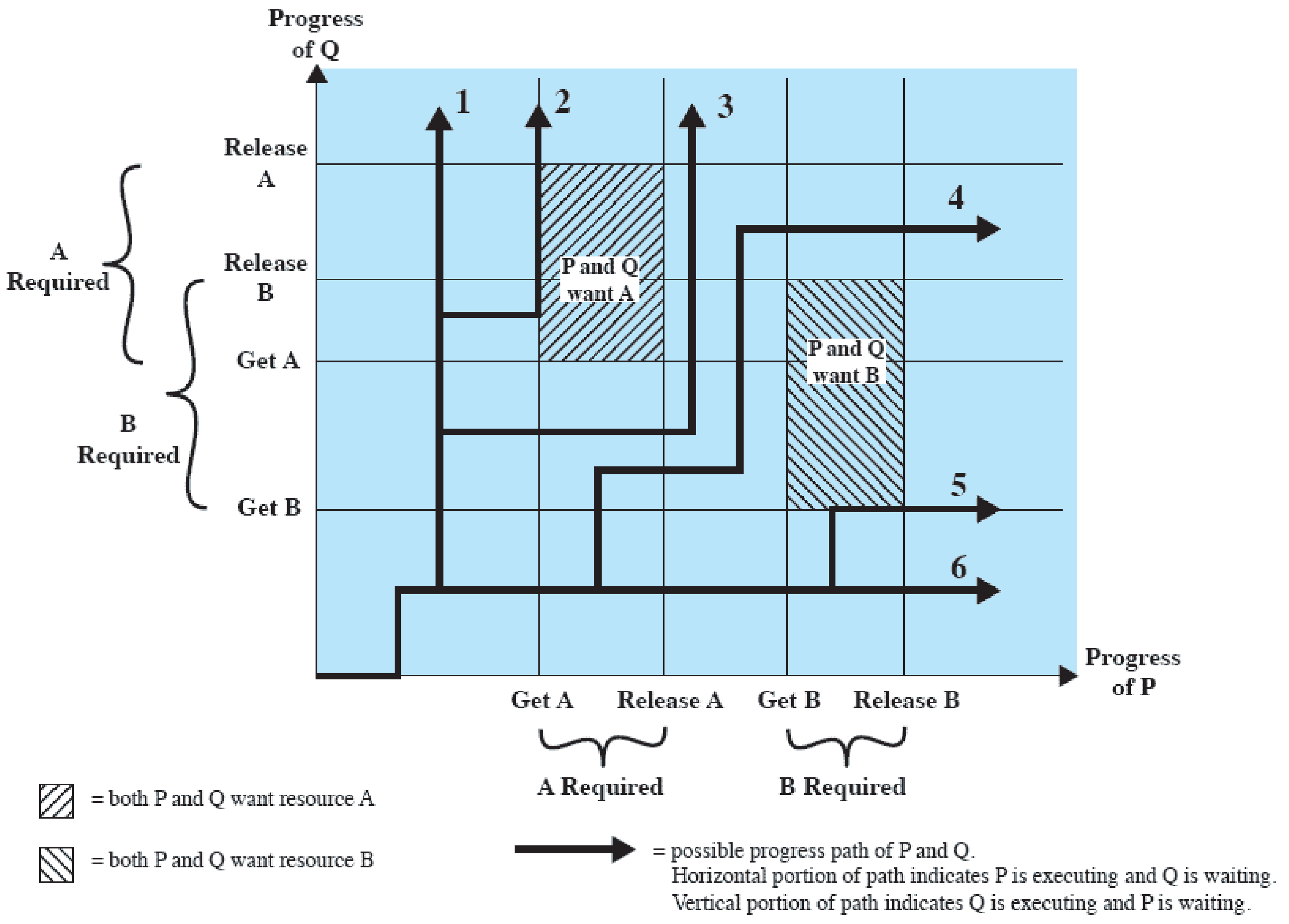

Progress of Q
Release A
Release B
Get A
Get B
A Required
B Required
1
2
3
4
5
6
P and Q want A
P and Q want B
Progress of P
Get A
Release A
Get B
Release B
A Required
B Required
▨ = both P and Q want resource A
▧ = both P and Q want resource B
= possible progress path of P and Q.
Horizontal portion of path indicates P is executing and Q is waiting.
Vertical portion of path indicates Q is executing and P is waiting.

Figure 6.3 Example of No Deadlock [BACO03]

## Resource Categories

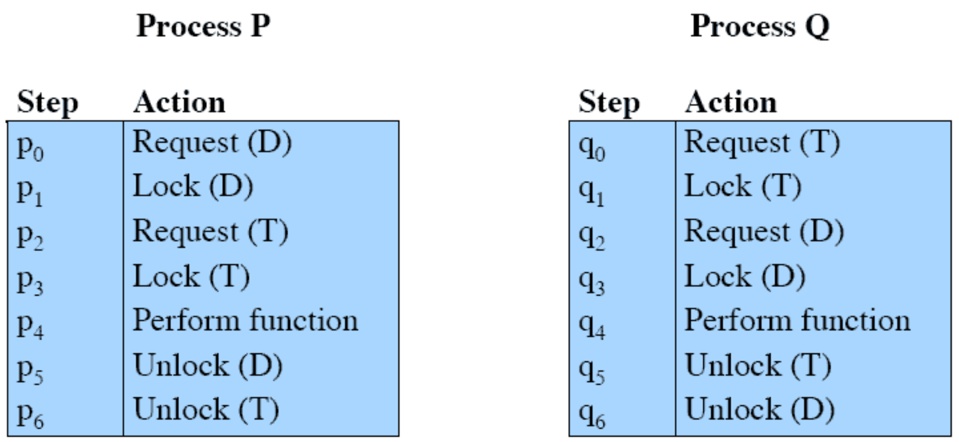
### Reusable

- can be safely used by only one process at a time and is not depleted by that use
  - processors, I/O channels, main and secondary memory, devices, and data structures such as files, databases, and semaphores

### Consumable

- one that can be created (produced) and destroyed (consumed)
  - interrupts, signals, messages, and information in I/O buffers

## Reusable resource example 1



**Process P**

| Step | Action |
|---|---|
| $p_0$ | Request (D) |
| $p_1$ | Lock (D) |
| $p_2$ | Request (T) |
| $p_3$ | Lock (T) |
| $p_4$ | Perform function |
| $p_5$ | Unlock (D) |
| $p_6$ | Unlock (T) |

**Process Q**

| Step | Action |
|---|---|
| $q_0$ | Request (T) |
| $q_1$ | Lock (T) |
| $q_2$ | Request (D) |
| $q_3$ | Lock (D) |
| $q_4$ | Perform function |
| $q_5$ | Unlock (T) |
| $q_6$ | Unlock (D) |

**Figure 6.4 Example of Two Processes Competing for Reusable Resources**

- Deadlock if execution order is : p0, p1, q0, q1, p2, q2
- Such deadlocks do occur, and the cause is often embedded in complex program logic, making detection difficult.
- One strategy is to impose system design constraints concerning the order in which resources can be requested.

## Reusable example 2: Memory request

- Space is available for allocation of 200 Kbytes, and the following sequence of events occur:

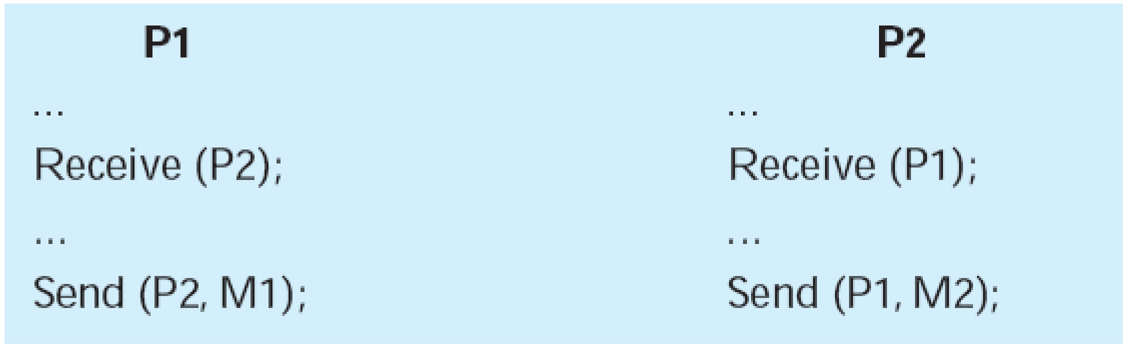
```
P1
. . .
Request 80 Kbytes;
. . .
Request 60 Kbytes;
```

```
P2
. . .
Request 70 Kbytes;
. . .
Request 80 Kbytes;
```

- Deadlock occurs if both processes progress to their second request

## Consumable resource deadlock

- Consider a  pair of processes, in which each process attempts to receive a message from the other process and then send a message to the other process:



```
        P1                              P2
...                             ...
Receive (P2);                   Receive (P1);
...                             ...
Send (P2, M1);                  Send (P1, M2);
```

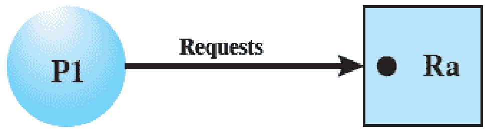
- Deadlock occurs if the Receive is blocking

# Resource Allocation Graphs

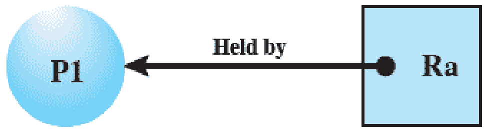
- **The resource allocation** graph is a directed graph that depicts a state of the system of resources and processes, with each process and each resource represented by a node.

- A graph edge directed from a process to a resource indicates a resource that has been requested by the process but not yet granted.
  - Within a resource node, a dot is shown for each instance of that resource.
  - Examples of resource types that may have multiple instances are I/O devices that are allocated by a resource management module in the OS.

- A graph edge directed from a reusable resource node dot to a process indicates a request that has been granted
  - The process has been assigned one unit of that resource. A graph edge directed from a consumable resource node dot to a process indicates that the process is the producer of that resource.

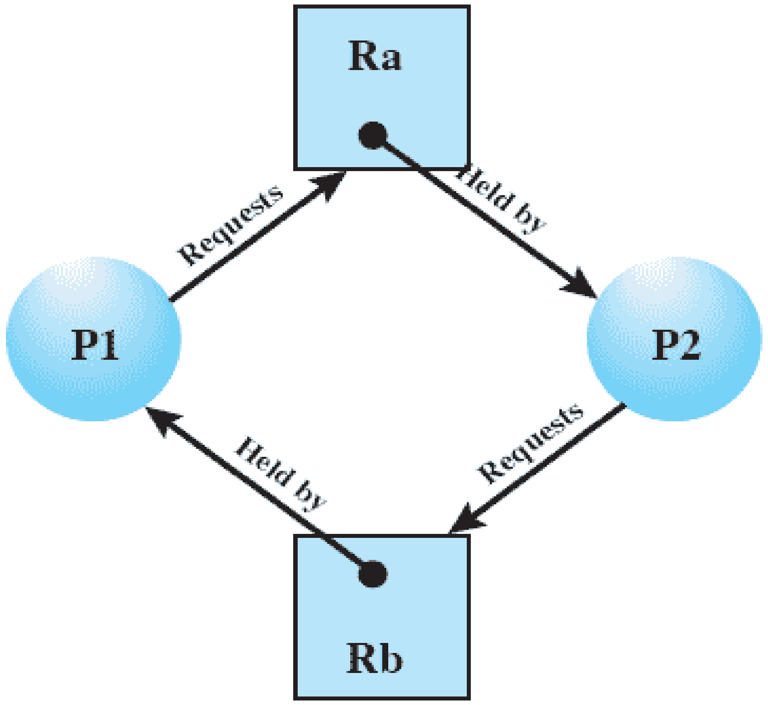


(a) Resouce is requested

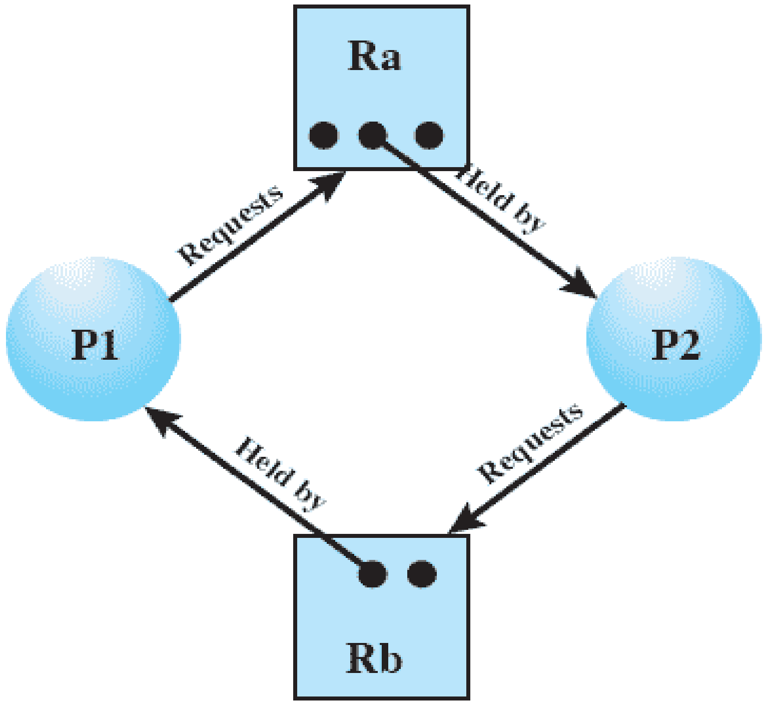


(b) Resource is held

# Resource Allocation Graphs



(c) Circular wait



(d) No deadlock

# Circular chain deadlock

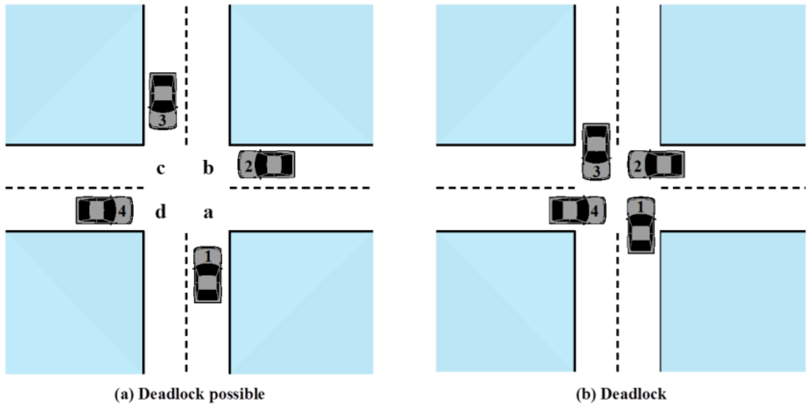


Figure 6.1 Illustration of Deadlock

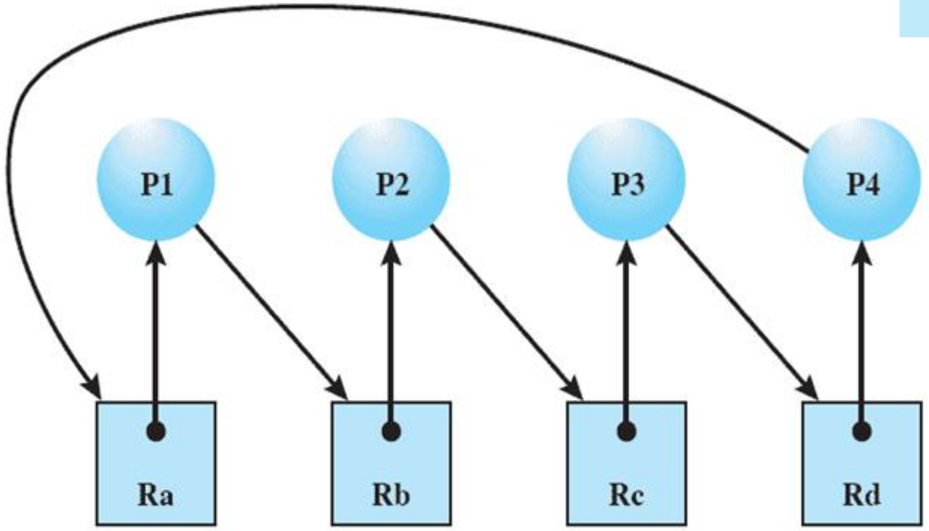


Figure 6.6 Resource Allocation Graph for Figure 6.1b

## Conditions for Deadlock

| Mutual Exclusion | Hold-and-Wait | No Pre-emption | Circular Wait |
|---|---|---|---|
| • only one process may use a resource at a time | • a process may hold allocated resources while awaiting assignment of others | • no resource can be forcibly removed from a process holding it | • a closed chain of processes exists, such that each process holds at least one resource needed by the next process in the chain |

## Conditions for Deadlock

| Mutual Exclusion | Hold-and-Wait | No Pre-emption |
|---|---|---|
| • only one process may use a resource at a time | • a process may hold allocated resources while awaiting assignment of others | • no resource can be forcibly removed from a process holding it |

- These conditions are quite desirable?
- The first three conditions are necessary but not sufficient for a deadlock to exist

# Conditions for Deadlock

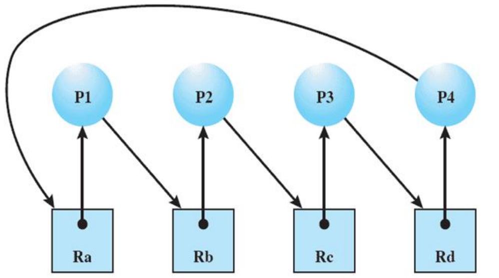


Figure 6.6 Resource Allocation Graph for Figure 6.1b

| Mutual Exclusion | Hold-and-Wait | No Pre-emption | Circular Wait |
|---|---|---|---|
| • only one process may use a resource at a time | • a process may hold allocated resources while awaiting assignment of others | • no resource can be forcibly removed from a process holding it | • a closed chain of processes exists, such that each process holds at least one resource needed by the next process in the chain |

- “Circular Wait” is actually a potential consequence of the first three conditions
- The unresolvable circular wait is in fact the definition of deadlock

# Dealing with deadlock

- **Prevent deadlock**
  - Adopt a policy that eliminates one of the conditions (conditions 1 through 4).
- **Avoid deadlock**
  - Make the appropriate dynamic choices based on the current state of resource allocation.
- **Detect** the presence of deadlock
  - When conditions 1 through 4 hold and take action to recover.

# Deadlock prevention strategy

- Design a system in such a way that the possibility of deadlock is excluded.

- Two main methods:
  - Indirect method
    - Prevent the occurrence of one of the three necessary conditions listed previously (items 1 through 3).
  - Direct method
    - Prevent the occurrence of a circular wait (item 4).

## Deadlock condition prevention

- **Mutual Exclusion:**
  - In general this can not be disallowed
  - If access to a resource requires mutual exclusion then it must be supported by the OS

- **Hold and Wait:**
  - Require that a process request all of its required resources at one time and blocking the process until all requests can be granted simultaneously
  - Inefficient
    - Process may be held up for a long time
    - Resources underutilized

## Deadlock condition prevention

- **No Preemption**
  - If a process holding certain resources is denied a further request, that process must release its original resources and request them again
  - OR OS may preempt the second process and require it to release its resources
  - Practical when resources state can be easily saved and restored later
- **Circular Wait**
  - Define a linear ordering of resource types
  - If a process has been allocated resources of type $R_i$ then it may subsequently request resource $R_j$ if $i < j$.

## Deadlock avoidance

- A decision is made dynamically whether the current resource allocation request will, if granted, potentially lead to a deadlock.
- Deadlock avoidance thus requires knowledge of future process resource requests.

## Two approaches to deadlock avoidance

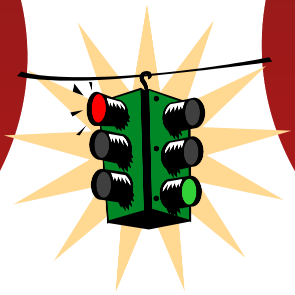
Deadlock Avoidance

**Resource Allocation Denial**

- Do not grant an incremental resource request to a process if this allocation might lead to deadlock

**Process Initiation Denial**

- Do not start a process if its demands might lead to deadlock



## Resource Allocation Denial

- Referred to as the **banker's algorithm**

- Consider a system with a fixed number of processes and a fixed number of resources. At any time a process may have zero or more resources allocated to it.

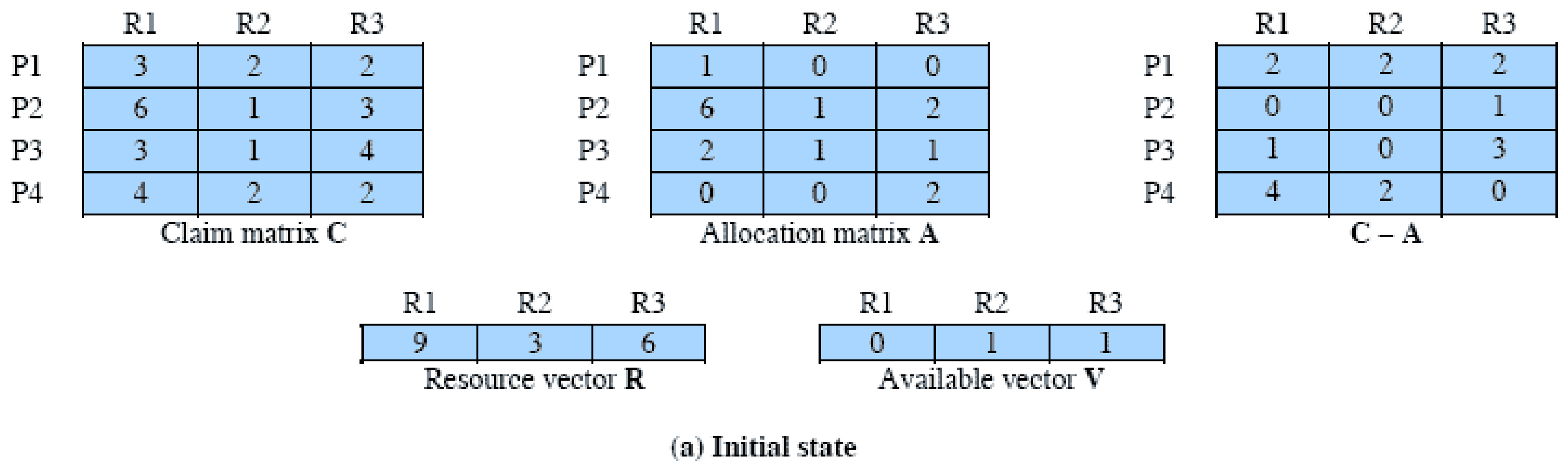
- **State** of the system reflects the current allocation of resources to processes
  - Two vectors, Resource and Available, and
  - Two matrices, Claim and Allocation

- **Safe state** is one in which there is at least one sequence of resource allocations to processes that does not result in a deadlock (i.e., all of the processes can be run to completion).

- **Unsafe state** is a state that is not safe.

## Example state

- State of a system consisting of four processes and three resources
- Allocations have been made to the four processes
- But is it safe?



| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 3 | 2 | 2 |
| P2 | 6 | 1 | 3 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Claim matrix **C**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 1 | 0 | 0 |
| P2 | 6 | 1 | 2 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

Allocation matrix **A**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 2 | 2 |
| P2 | 0 | 0 | 1 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

**C – A**

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

Resource vector **R**

| R1 | R2 | R3 |
|---|---|---|
| 0 | 1 | 1 |

Available vector **V**

(a) **Initial state**

## Example state

- State of a system consisting of four processes and three resources
- Allocations have been made to the four processes
- But is it safe? **P2 requests 1 R3**

$$\boxed{C_{ij} - A_{ij} \le V_j \text{ for all } j}$$

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 3 | 2 | 2 |
| P2 | 6 | 1 | 3 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Claim matrix C

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 1 | 0 | 0 |
| P2 | 6 | 1 | 2 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

Allocation matrix A

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 2 | 2 |
| P2 | 0 | 0 | 1 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

C – A

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

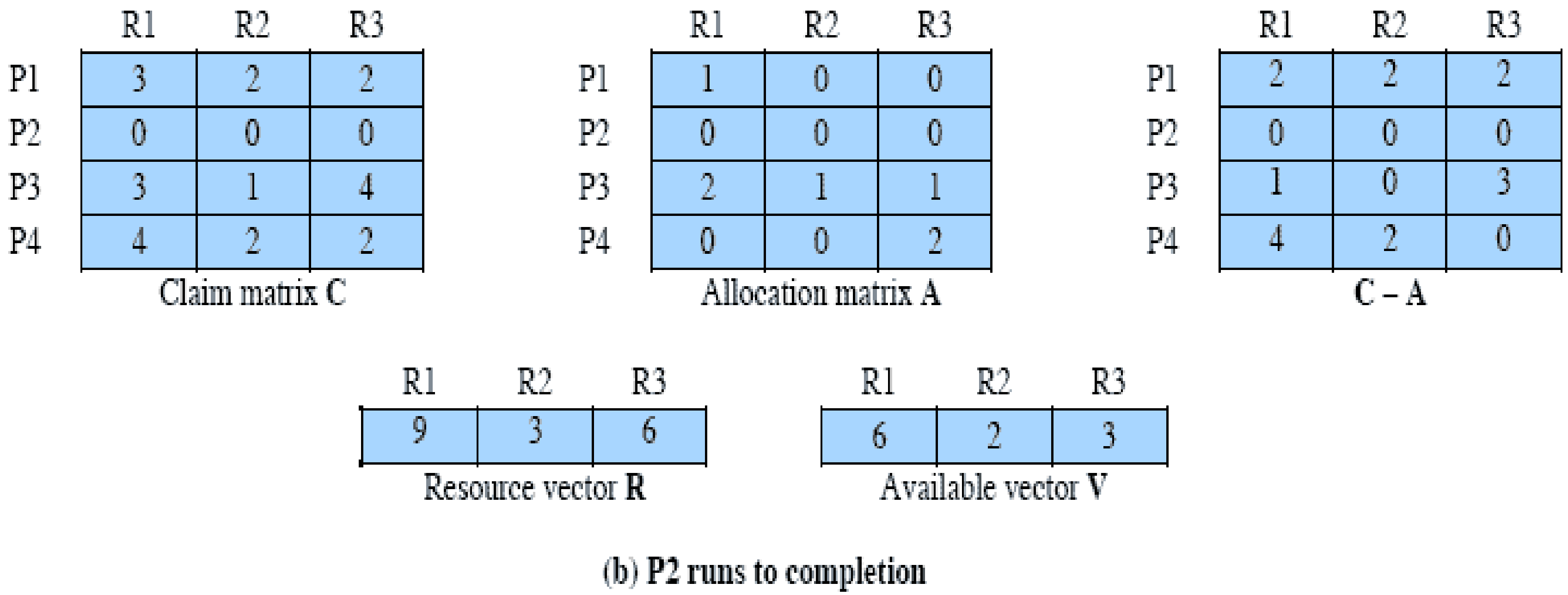
Resource vector R

| R1 | R2 | R3 |
|---|---|---|
| 0 | 1 | 1 |

Available vector V

(a) Initial state

# P2 runs to completion



Claim matrix C

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 3 | 2 | 2 |
| P2 | 0 | 0 | 0 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Allocation matrix A

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 1 | 0 | 0 |
| P2 | 0 | 0 | 0 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

C – A

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 2 | 2 |
| P2 | 0 | 0 | 0 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

Resource vector R

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

Available vector V

| R1 | R2 | R3 |
|---|---|---|
| 6 | 2 | 3 |

(b) **P2 runs to completion**

## P1 runs to completion

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Claim matrix **C**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

Allocation matrix **A**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

**C – A**

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

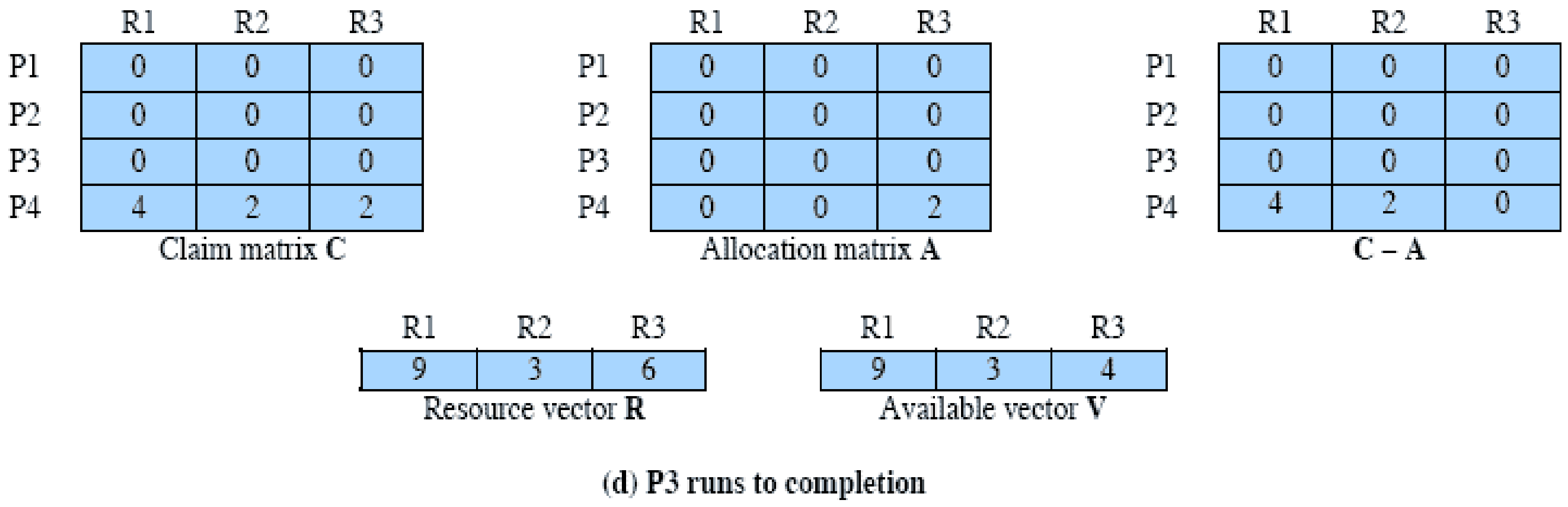
Resource vector **R**

| R1 | R2 | R3 |
|---|---|---|
| 7 | 2 | 3 |

Available vector **V**

(c) **P1 runs to completion**

# P3 runs to completion



|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 |
| P4 | 4 | 2 | 2 |

Claim matrix C

|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 |
| P4 | 0 | 0 | 2 |

Allocation matrix A

|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 0 | 0 | 0 |
| P2 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 |
| P4 | 4 | 2 | 0 |

C – A

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

Resource vector R

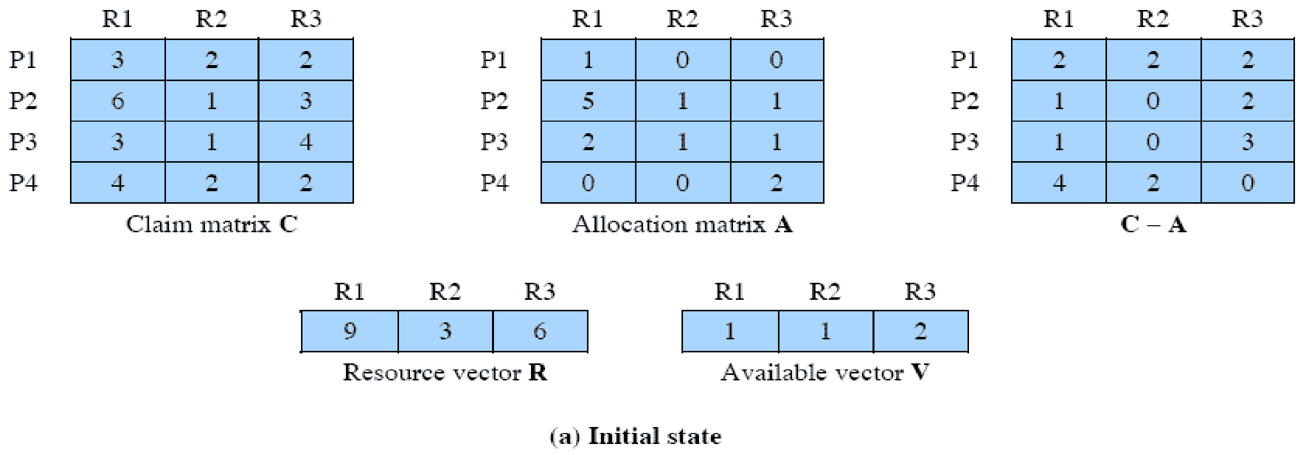
| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 4 |

Available vector V

(d) P3 runs to completion

Thus, the state defined originally is a safe state

# Safe/Unsafe state?



| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 3 | 2 | 2 |
| P2 | 6 | 1 | 3 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Claim matrix **C**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 1 | 0 | 0 |
| P2 | 5 | 1 | 1 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

Allocation matrix **A**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 2 | 2 |
| P2 | 1 | 0 | 2 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

**C – A**

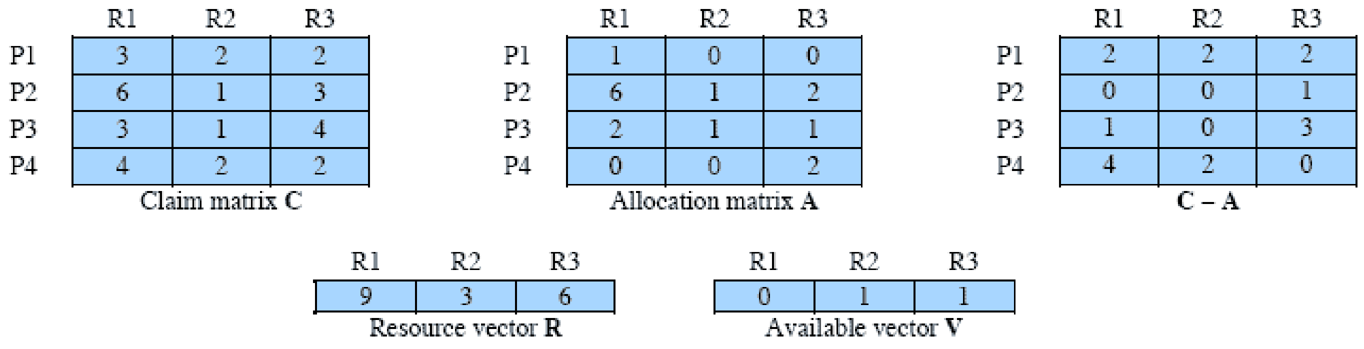
| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

Resource vector **R**

| R1 | R2 | R3 |
|---|---|---|
| 1 | 1 | 2 |

Available vector **V**

(a) **Initial state**



| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 3 | 2 | 2 |
| P2 | 6 | 1 | 3 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Claim matrix **C**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 1 | 0 | 0 |
| P2 | 6 | 1 | 2 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

Allocation matrix **A**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 2 | 2 |
| P2 | 0 | 0 | 1 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

**C – A**

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

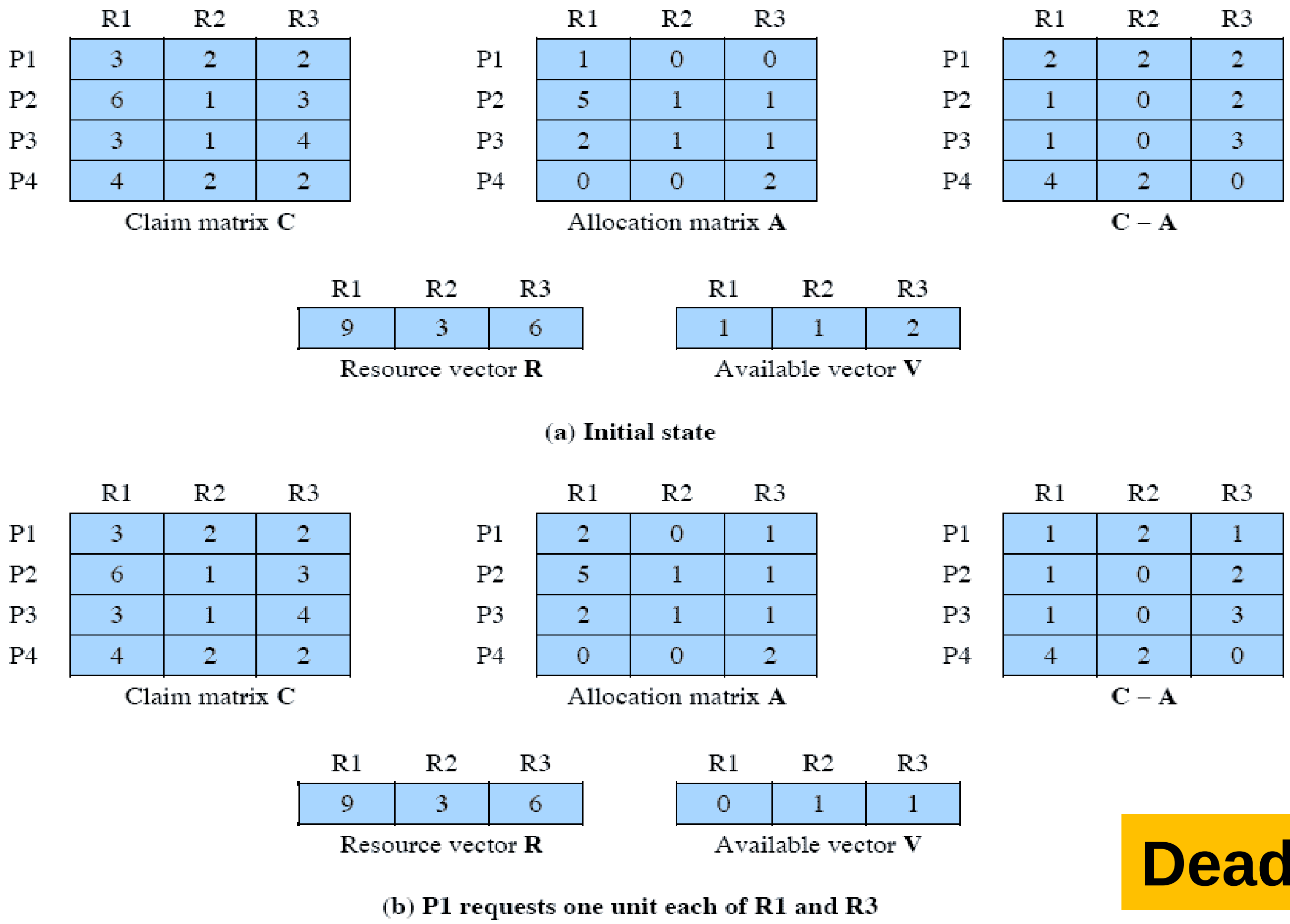
Resource vector **R**

| R1 | R2 | R3 |
|---|---|---|
| 0 | 1 | 1 |

Available vector **V**

**(b) P2 requests one unit or R1 and R3**

# Safe/Unsafe state?



|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 3 | 2 | 2 |
| P2 | 6 | 1 | 3 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Claim matrix **C**

|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 1 | 0 | 0 |
| P2 | 5 | 1 | 1 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

Allocation matrix **A**

|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 2 | 2 |
| P2 | 1 | 0 | 2 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

**C – A**

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

Resource vector **R**

| R1 | R2 | R3 |
|---|---|---|
| 1 | 1 | 2 |

Available vector **V**

(a) **Initial state**

|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 3 | 2 | 2 |
| P2 | 6 | 1 | 3 |
| P3 | 3 | 1 | 4 |
| P4 | 4 | 2 | 2 |

Claim matrix **C**

|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 0 | 1 |
| P2 | 5 | 1 | 1 |
| P3 | 2 | 1 | 1 |
| P4 | 0 | 0 | 2 |

Allocation matrix **A**

|  | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 1 | 2 | 1 |
| P2 | 1 | 0 | 2 |
| P3 | 1 | 0 | 3 |
| P4 | 4 | 2 | 0 |

**C – A**

| R1 | R2 | R3 |
|---|---|---|
| 9 | 3 | 6 |

Resource vector **R**

| R1 | R2 | R3 |
|---|---|---|
| 0 | 1 | 1 |

Available vector **V**

(b) **P1 requests one unit each of R1 and R3**

**Deadlocked?**

## Deadlock avoidance logic1

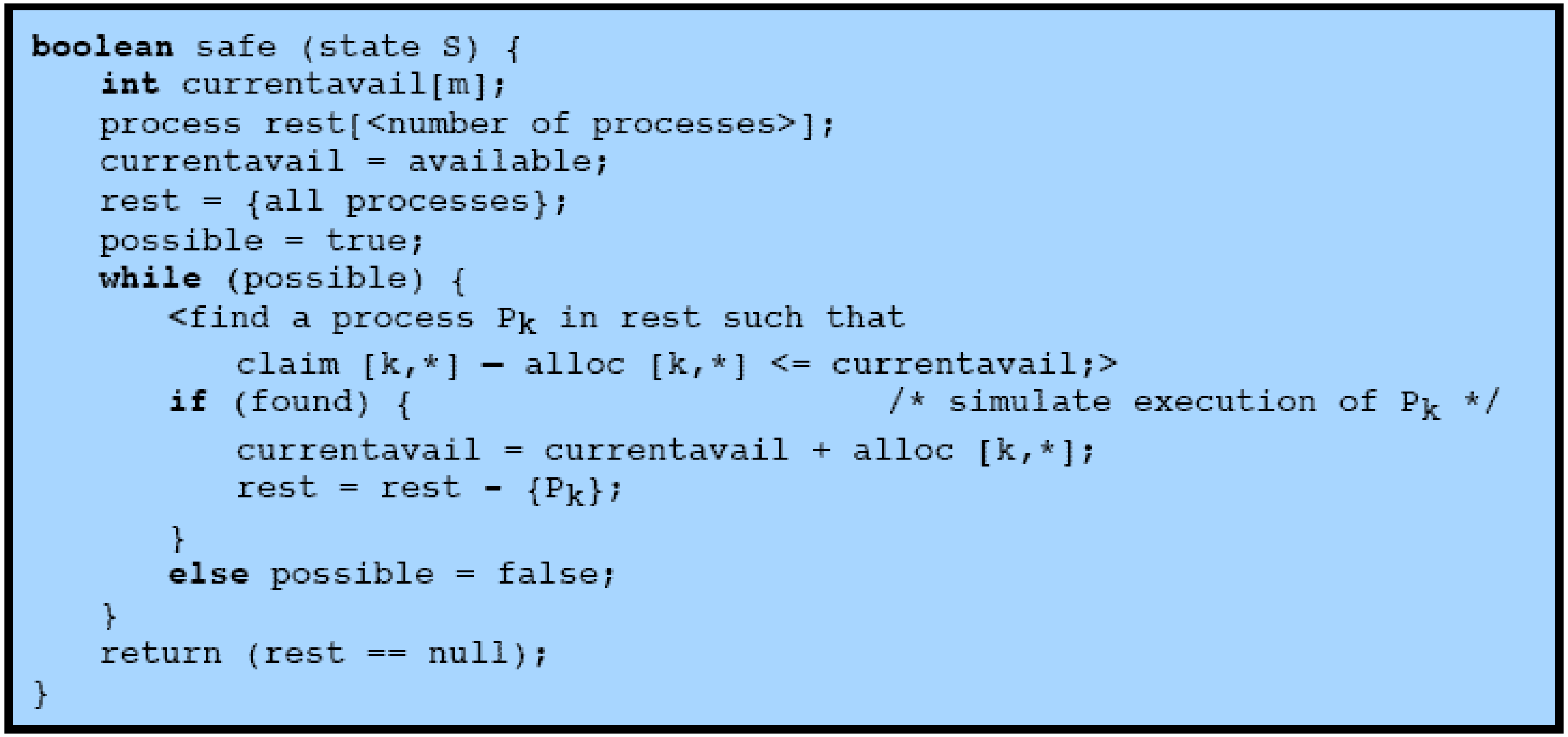
```
struct state {
        int resource[m];
        int available[m];
        int claim[n][m];
        int alloc[n][m];
}
```

(a) global data structures

```
if (alloc [i,*] + request [*] > claim [i,*])
     < error >;                              /* total request > claim*/
else if (request [*] > available [*])
     < suspend process >;
else {                                             /* simulate alloc */
     < define newstate by:
     alloc [i,*] = alloc [i,*] + request [*];
     available [*] = available [*] - request [*] >;
}
if (safe (newstate))
     < carry out allocation >;
else {
     < restore original state >;
     < suspend process >;
}
```

(b) resource alloc algorithm

# Deadlock avoidance logic2



```
boolean safe (state S) {
    int currentavail[m];
    process rest[<number of processes>];
    currentavail = available;
    rest = {all processes};
    possible = true;
    while (possible) {
        <find a process Pk in rest such that
            claim [k,*] – alloc [k,*] <= currentavail;>
        if (found) {                          /* simulate execution of Pk */
            currentavail = currentavail + alloc [k,*];
            rest = rest - {Pk};
        }
        else possible = false;
    }
    return (rest == null);
}
```

(c) test for safety algorithm (banker's algorithm)

Figure 6.9 Deadlock Avoidance Logic

## Deadlock avoidance

**Advantages**

- It is not necessary to preempt and rollback processes, as in deadlock detection
- Is less restrictive than deadlock prevention

**Restrictions**

- The maximum resource requirement for each process must be stated in advance
- The processes under consideration must be independent
  - the order in which they execute must be unconstrained by any synchronization requirements
- There must be a fixed number of resources to allocate.
- No process may exit while holding resources.

## Deadlock Detection

- Deadlock prevention strategies are very conservative
  - Limit access to resources by imposing restrictions on processes

- Deadlock detection strategies do the opposite
  - Resource requests are granted whenever possible

## Deadline detection algorithms

- A check for deadlock can be made as frequently as each resource request or, less frequently, depending on how likely it is for a deadlock to occur.

- Checking at each resource request
  - Advantages:
    1. It leads to early detection
    2. The algorithm is relatively simple because it is based on incremental changes to the state of the system.
  - Disadvantage
    - Frequent checks consume considerable processor time.

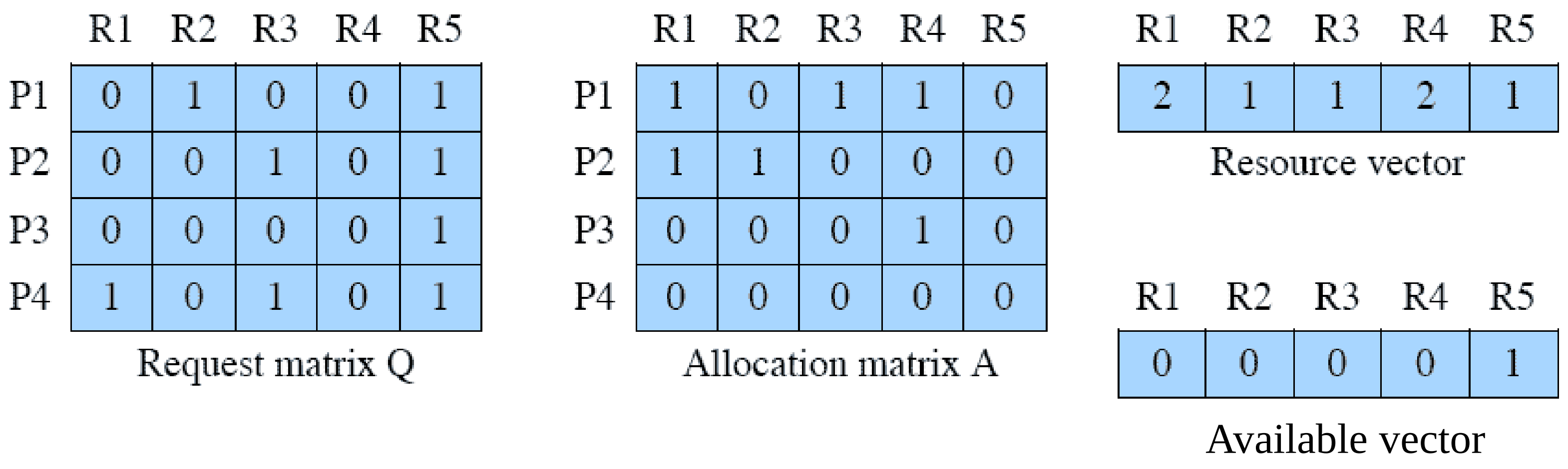
# Deadline detection algorithm

- Use an Allocation matrix (***A***) and Available vector (***V***)
- Also have a Request matrix (***Q***)

1. Mark any process with all 0s in Allocation matrix ***A***
2. Make temporary vector ***W*** = Availability vector ***V***
3. Find an index ***i*** *where*
   - $P_i$ is unmarked
   - *ith* row of ***Q*** (requests) <= *W* (available) [i.e. $Q_{ik} \leq W_k$ for $1 \leq k \leq m$ ]
   - If no such row is found then terminate
4. Mark $P_i$, add $A_i$ to *W* [i.e. $W_k = W_k + A_{ik}$ for $1 \leq k \leq m$ ]
5. Goto Step 3

- On termination, if there are unmarked processes, then there is deadlock.
- Unmarked processes are involved in deadlock

## Deadline detection algorithm example



|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 0 | 1 | 0 | 0 | 1 |
| P2 | 0 | 0 | 1 | 0 | 1 |
| P3 | 0 | 0 | 0 | 0 | 1 |
| P4 | 1 | 0 | 1 | 0 | 1 |

Request matrix Q

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 1 | 0 | 1 | 1 | 0 |
| P2 | 1 | 1 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 1 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 |

Allocation matrix A

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 2 | 1 | 1 | 2 | 1 |

Resource vector

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 |

Available vector

# Deadline detection algorithm example

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 0 | 1 | 0 | 0 | 1 |
| P2 | 0 | 0 | 1 | 0 | 1 |
| P3 | 0 | 0 | 0 | 0 | 1 |
| P4 | 1 | 0 | 1 | 0 | 1 |

Request matrix Q

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 1 | 0 | 1 | 1 | 0 |
| P2 | 1 | 1 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 1 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 |

Allocation matrix A

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 2 | 1 | 1 | 2 | 1 |

Resource vector

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 |

Available vector

1. Mark any process with all 0s in Allocation matrix ***A***

## Deadline detection algorithm example

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 0 | 1 | 0 | 0 | 1 |
| P2 | 0 | 0 | 1 | 0 | 1 |
| P3 | 0 | 0 | 0 | 0 | 1 |
| P4 | 1 | 0 | 1 | 0 | 1 |

Request matrix Q

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 1 | 0 | 1 | 1 | 0 |
| P2 | 1 | 1 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 1 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 |

Allocation matrix A

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 2 | 1 | 1 | 2 | 1 |

Resource vector

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 |

Available vector

2. Make temporary vector ***W*** = Availability vector ***V***

Initialise W = Available Vector

W = 0 0 0 0 1

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# Deadline detection algorithm example

|    | R1 | R2 | R3 | R4 | R5 |
|----|----|----|----|----|----|
| P1 | 0 | 1 | 0 | 0 | 1 |
| P2 | 0 | 0 | 1 | 0 | 1 |
| P3 | 0 | 0 | 0 | 0 | 1 |
| P4 | 1 | 0 | 1 | 0 | 1 |

Request matrix Q

|    | R1 | R2 | R3 | R4 | R5 |
|----|----|----|----|----|----|
| P1 | 1 | 0 | 1 | 1 | 0 |
| P2 | 1 | 1 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 1 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 |

Allocation matrix A

| R1 | R2 | R3 | R4 | R5 |
|----|----|----|----|----|
| 2 | 1 | 1 | 2 | 1 |

Resource vector

| R1 | R2 | R3 | R4 | R5 |
|----|----|----|----|----|
| 0 | 0 | 0 | 0 | 1 |

Available vector

W = 0 0 0 0 1

3. Find an index ***i*** *where*
   - ***$P_i$*** is unmarked
   - *ith* row of **Q** (requests) <= *W* (available) [i.e. $Q_{ik} \le W_k$ for $1 \le k \le m$ ]
   - If no such row is found then terminate

# Deadline detection algorithm example

| | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 0 | 1 | 0 | 0 | 1 |
| P2 | 0 | 0 | 1 | 0 | 1 |
| P3 | 0 | 0 | 0 | 0 | 1 |
| P4 | 1 | 0 | 1 | 0 | 1 |

Request matrix Q

| | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 1 | 0 | 1 | 1 | 0 |
| P2 | 1 | 1 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 1 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 |

Allocation matrix A

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 2 | 1 | 1 | 2 | 1 |

Resource vector

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 |

Available vector

W = 0 0 0 1 1

4. Mark $\boldsymbol{P_i}$, add $A_i$ to $W$ [i.e. $W_k = W_k + A_{ik}$ for $1 \le k \le m$ ]
5. Goto Step 3

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# Deadline detection algorithm example

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 0 | 1 | 0 | 0 | 1 |
| P2 | 0 | 0 | 1 | 0 | 1 |
| P3 | 0 | 0 | 0 | 0 | 1 |
| P4 | 1 | 0 | 1 | 0 | 1 |

Request matrix Q

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 1 | 0 | 1 | 1 | 0 |
| P2 | 1 | 1 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 1 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 |

Allocation matrix A

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 2 | 1 | 1 | 2 | 1 |

Resource vector

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 |

Allocation vector

W = 0 0 0 1 1

3. Find an index ***i*** *where*
   - ***P**$_i$* is unmarked
   - *ith* row of ***Q*** (requests) <= *W* (available) [i.e. $Q_{ik} \leq W_k$ for $1 \leq k \leq m$ ]
   - If no such row is found then terminate

## Deadline detection algorithm example

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 0 | 1 | 0 | 0 | 1 |
| P2 | 0 | 0 | 1 | 0 | 1 |
| P3 | 0 | 0 | 0 | 0 | 1 |
| P4 | 1 | 0 | 1 | 0 | 1 |

Request matrix Q

|  | R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|---|
| P1 | 1 | 0 | 1 | 1 | 0 |
| P2 | 1 | 1 | 0 | 0 | 0 |
| P3 | 0 | 0 | 0 | 1 | 0 |
| P4 | 0 | 0 | 0 | 0 | 0 |

Allocation matrix A

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 2 | 1 | 1 | 2 | 1 |

Resource vector

| R1 | R2 | R3 | R4 | R5 |
|---|---|---|---|---|
| 0 | 0 | 0 | 0 | 1 |

Allocation vector

Deadlock: Involved process are P1 and P2

# Deadlock recovery

- **Abort all deadlocked processes.**
  - One of the most common, if not the most common, solution adopted in operating systems.

- **Back up each deadlocked process to some previously defined checkpoint, and restart all processes**.
  - This requires that rollback and restart mechanisms be built in to the system.
  - The risk in this approach is that the original deadlock may recur but the nondeterminancy of concurrent processing may ensure that this does not happen.

- **Successively abort deadlocked processes until deadlock no longer exists.**
  - The order in which processes are selected for abortion should be on the basis of some criterion of minimum cost. After each abortion, the detection algorithm must be reinvoked to see whether deadlock still exists.

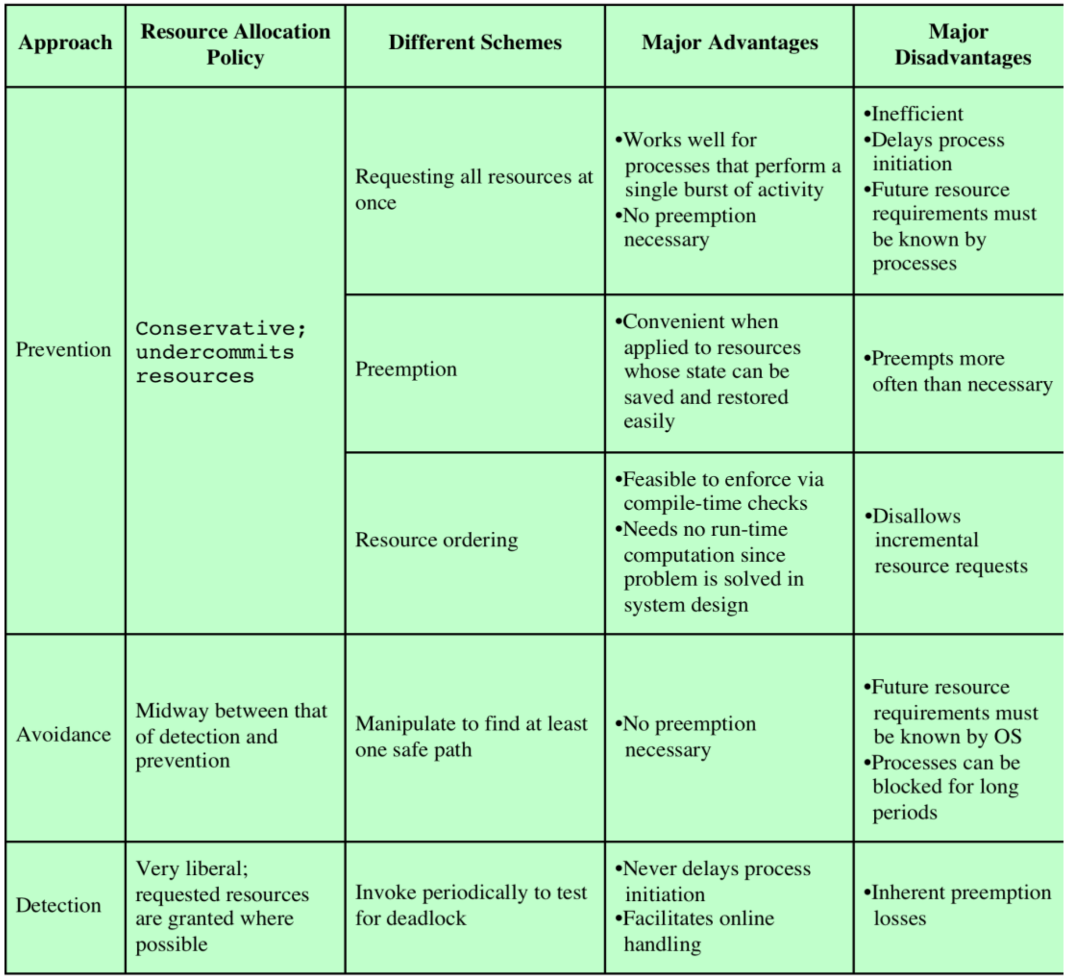
- **Successively preempt resources until deadlock no longer exists.**
  - As (3) above, a cost-based selection should be used, and reinvocation of the detection algorithm is required after each preemption.
  - A process that has a resource preempted from it must be rolled back to a point prior to its acquisition of that resource.

# Deadlock recovery

- **Possible Selection Criteria for aborting processes for deadlock recovery**
  - Choose the process
    - Least amount of time consumed so far
    - Lease amount of output produced so far
    - Most estimated time remaining
    - Least total resources allocated so far
    - Lowest priority

# In integrated deadlock strategy

- There is no single effective strategy that can deal with all types of deadlock
- Use of different strategies in different situations



| Approach | Resource Allocation Policy | Different Schemes | Major Advantages | Major Disadvantages |
|---|---|---|---|---|
| Prevention | Conservative; undercommits resources | Requesting all resources at once | •Works well for processes that perform a single burst of activity<br>•No preemption necessary | •Inefficient<br>•Delays process initiation<br>•Future resource requirements must be known by processes |
| | | Preemption | •Convenient when applied to resources whose state can be saved and restored easily | •Preempts more often than necessary |
| | | Resource ordering | •Feasible to enforce via compile-time checks<br>•Needs no run-time computation since problem is solved in system design | •Disallows incremental resource requests |
| Avoidance | Midway between that of detection and prevention | Manipulate to find at least one safe path | •No preemption necessary | •Future resource requirements must be known by OS<br>•Processes can be blocked for long periods |
| Detection | Very liberal; requested resources are granted where possible | Invoke periodically to test for deadlock | •Never delays process initiation<br>•Facilitates online handling | •Inherent preemption losses |

# Dining Philosophers Problem

Think

…

Eat

…

Think

…

Eat

…

(and spaghetti is the best)

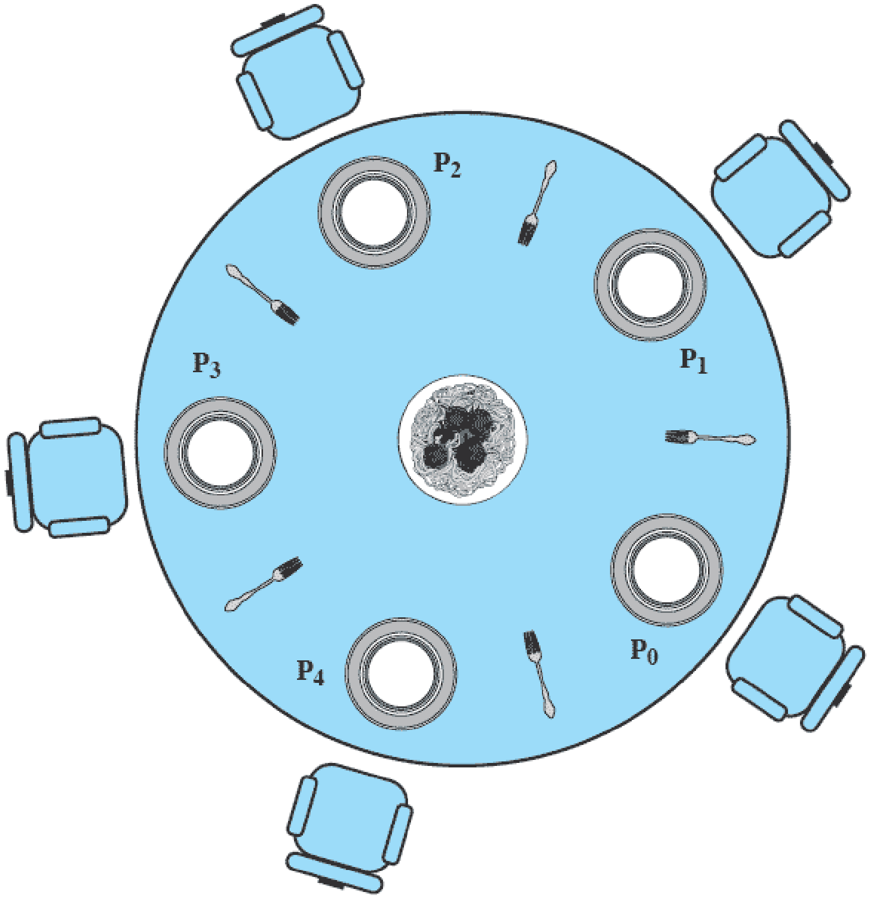


Figure 6.11 Dining Arrangement for Philosophers

# Dining Philosophers Problem

- No two philosophers can use the same fork at the same time (mutual exclusion)
- No philosopher must starve to death (avoid deadlock and starvation)

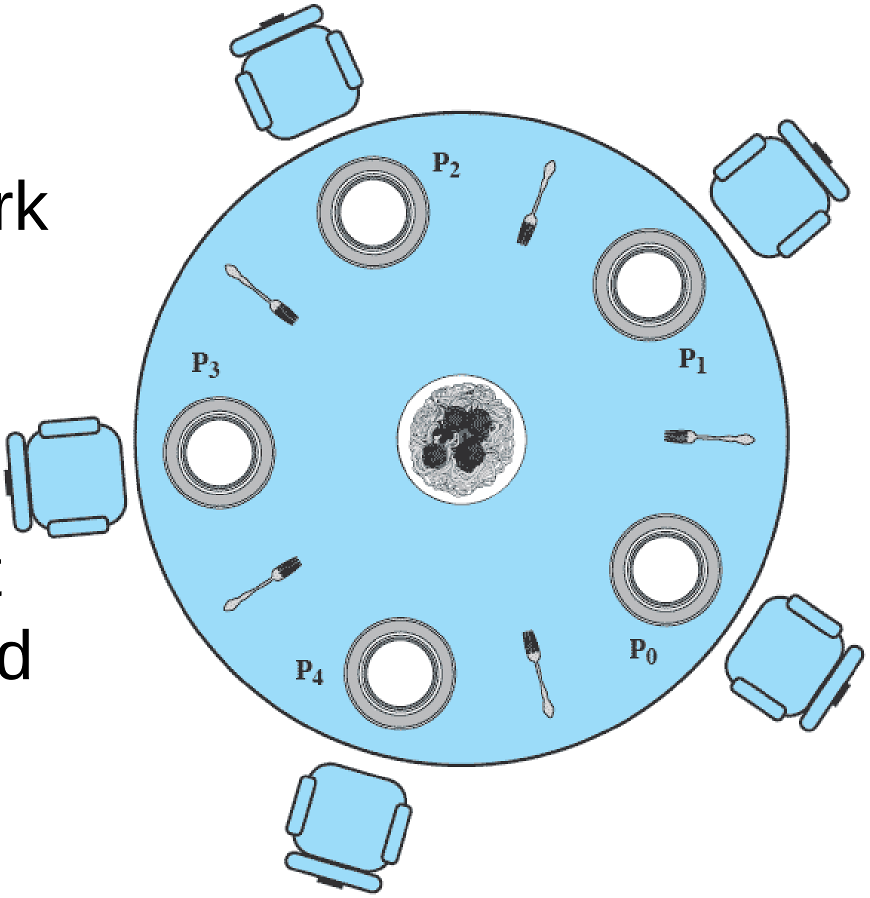
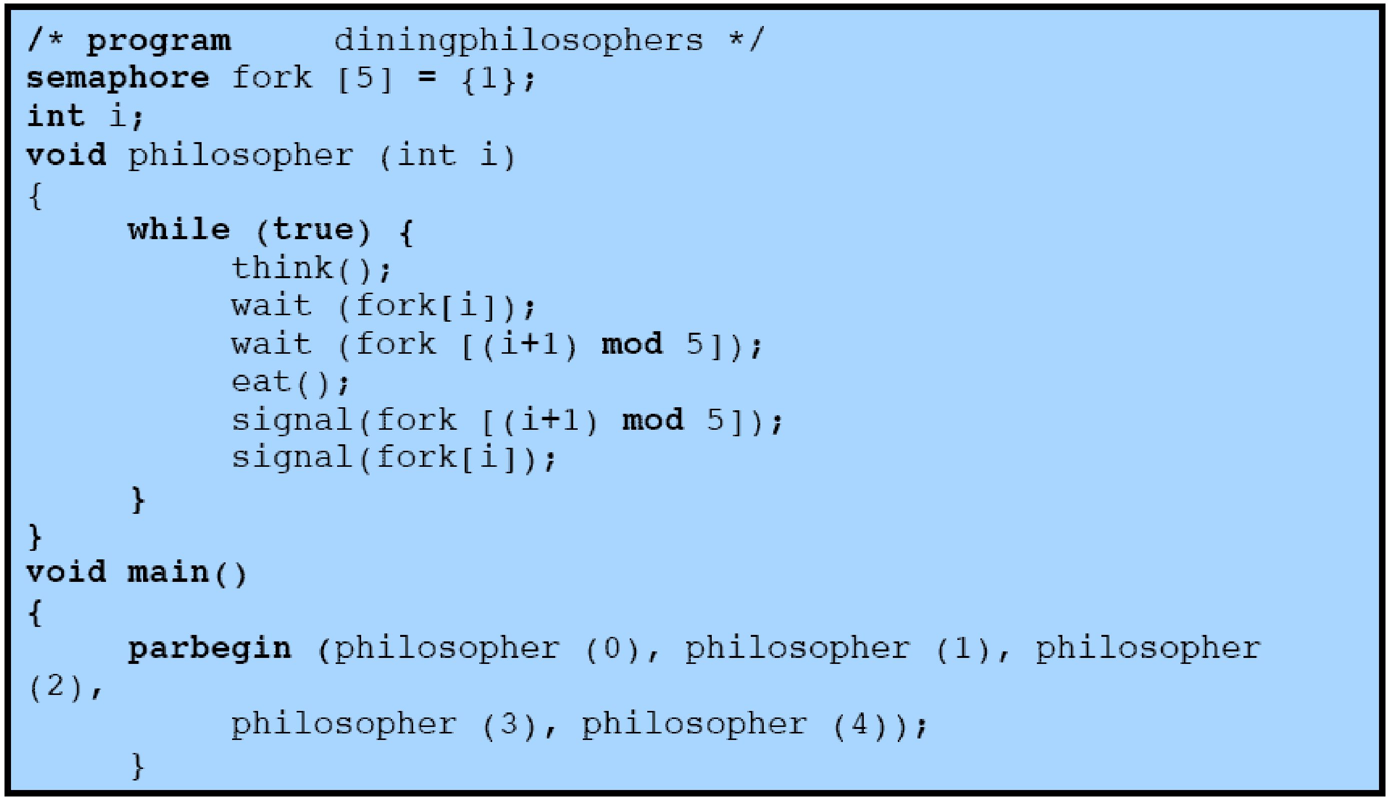


Figure 6.11 Dining Arrangement for Philosophers

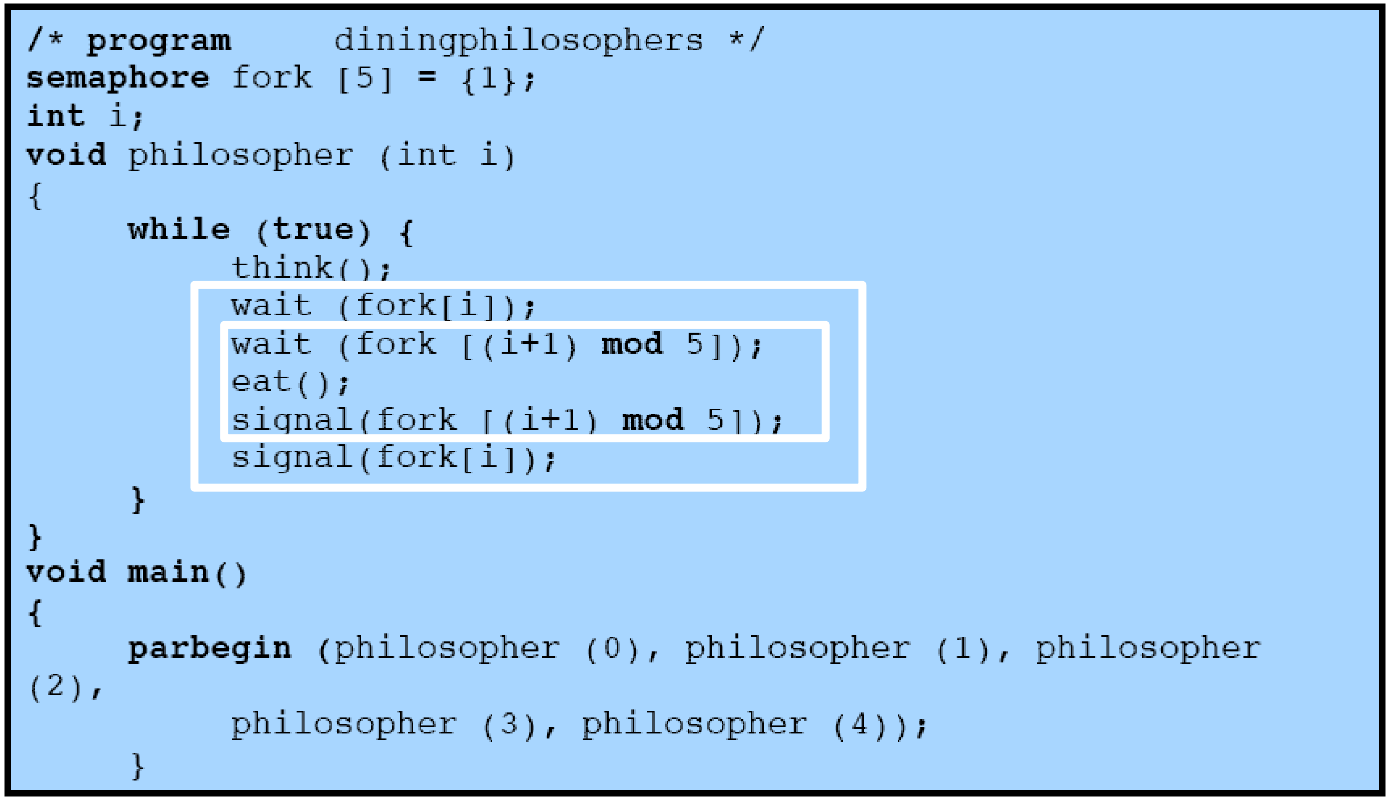
## Using semaphores (1)



```
/* program     diningphilosophers */
semaphore fork [5] = {1};
int i;
void philosopher (int i)
{
     while (true) {
          think();
          wait (fork[i]);
          wait (fork [(i+1) mod 5]);
          eat();
          signal(fork [(i+1) mod 5]);
          signal(fork[i]);
     }
}
void main()
{
     parbegin (philosopher (0), philosopher (1), philosopher
(2),
          philosopher (3), philosopher (4));
     }
```

**Figure 6.12** **A First Solution to the Dining Philosophers Problem**

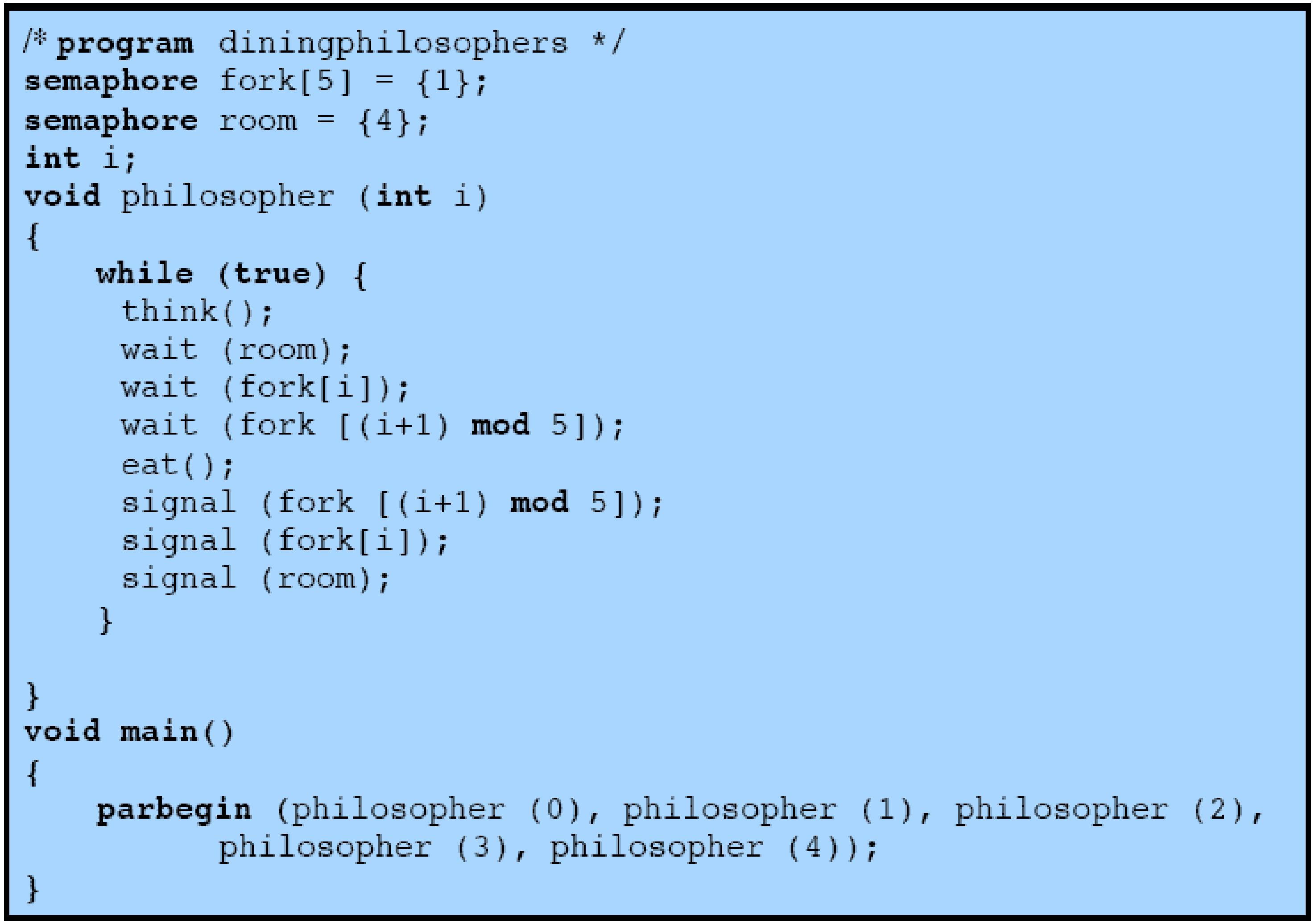
## Using semaphores (1)



```
/* program     diningphilosophers */
semaphore fork [5] = {1};
int i;
void philosopher (int i)
{
     while (true) {
          think();
          wait (fork[i]);
          wait (fork [(i+1) mod 5]);
          eat();
          signal(fork [(i+1) mod 5]);
          signal(fork[i]);
     }
}
void main()
{
     parbegin (philosopher (0), philosopher (1), philosopher
(2),
          philosopher (3), philosopher (4));
     }
```

**Figure 6.12** **A First Solution to the Dining Philosophers Problem**

## Using semaphores (2)

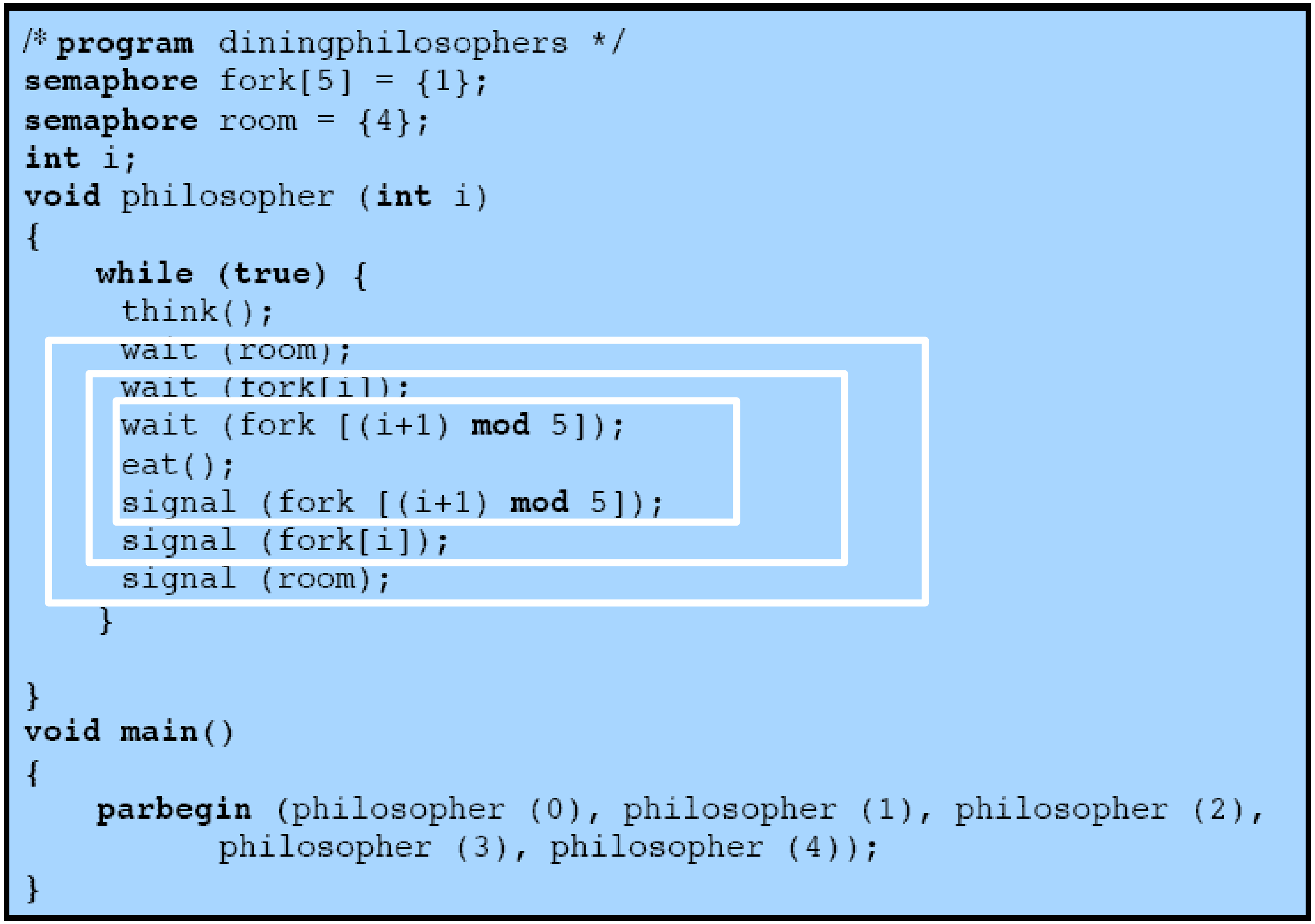


```
/* program diningphilosophers */
semaphore fork[5] = {1};
semaphore room = {4};
int i;
void philosopher (int i)
{
    while (true) {
     think();
     wait (room);
     wait (fork[i]);
     wait (fork [(i+1) mod 5]);
     eat();
     signal (fork [(i+1) mod 5]);
     signal (fork[i]);
     signal (room);
    }

}
void main()
{
    parbegin (philosopher (0), philosopher (1), philosopher (2),
          philosopher (3), philosopher (4));
}
```

Figure 6.13 A Second Solution to the Dining Philosophers Problem

# Using semaphores (2)

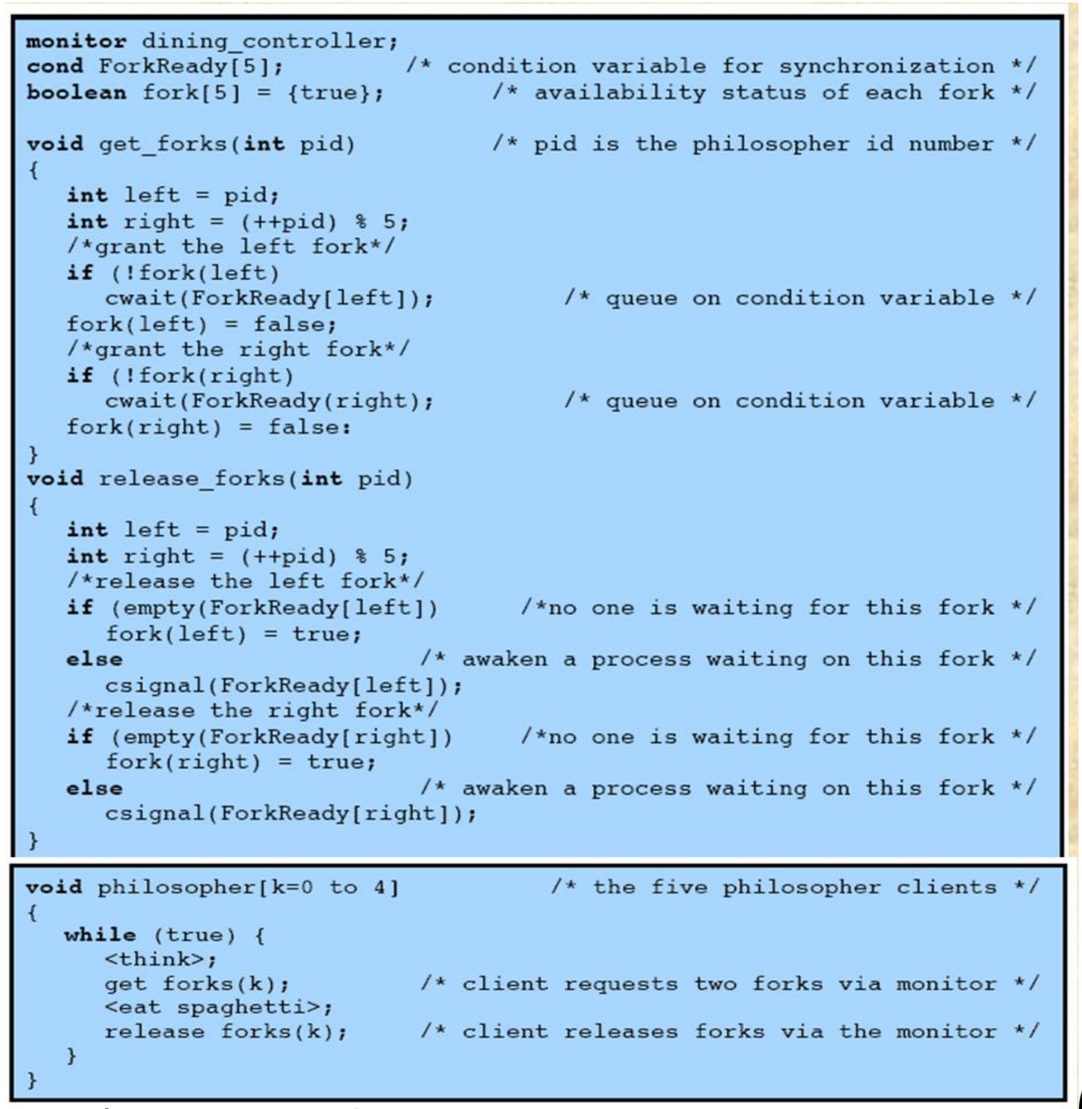


```
/* program diningphilosophers */
semaphore fork[5] = {1};
semaphore room = {4};
int i;
void philosopher (int i)
{
    while (true) {
     think();
     wait (room);
     wait (fork[i]);
     wait (fork [(i+1) mod 5]);
     eat();
     signal (fork [(i+1) mod 5]);
     signal (fork[i]);
     signal (room);
    }

}
void main()
{
    parbegin (philosopher (0), philosopher (1), philosopher (2),
        philosopher (3), philosopher (4));
}
```

Figure 6.13 A Second Solution to the Dining Philosophers Problem

# Using a monitor



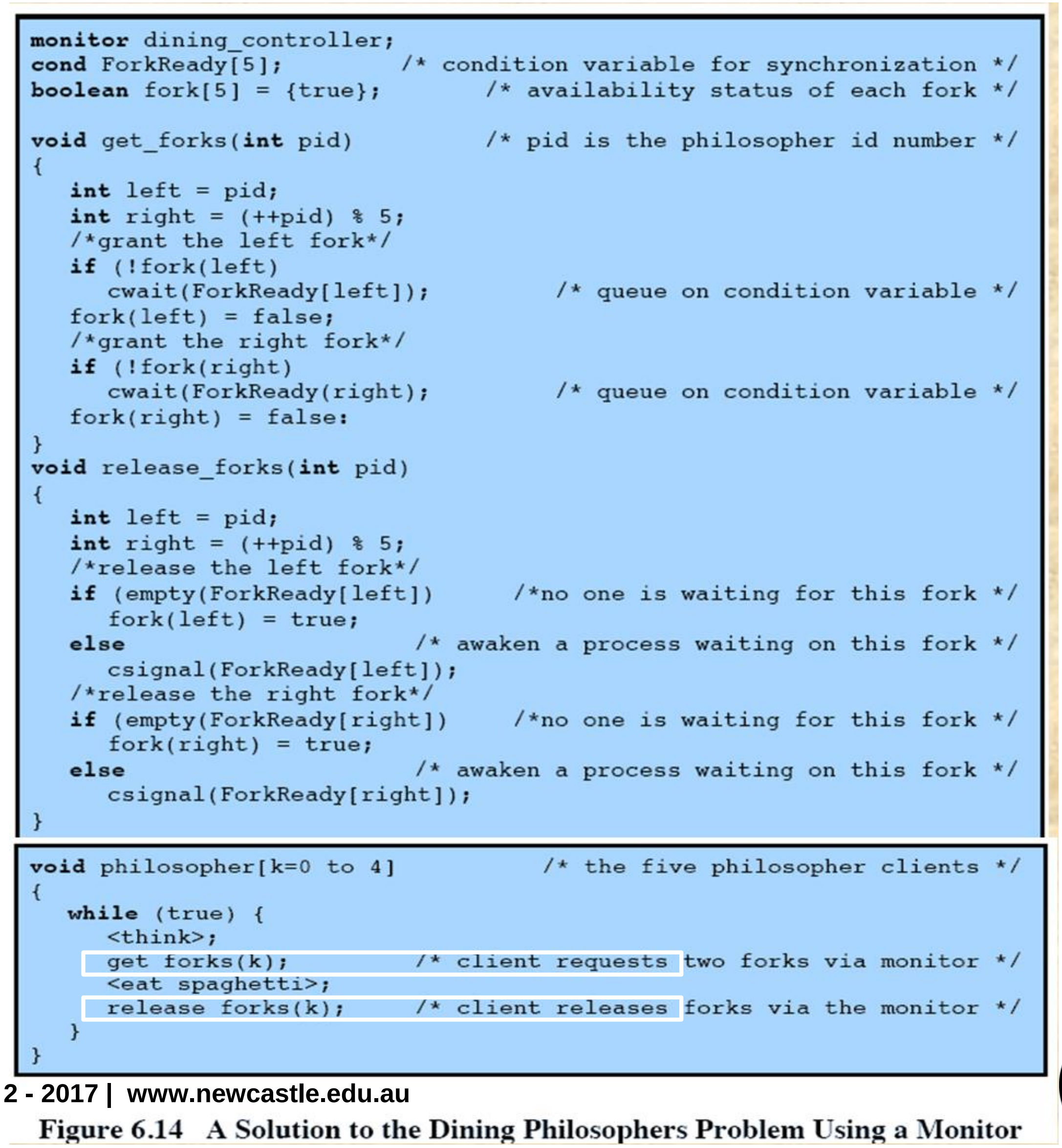
```
monitor dining_controller;
cond ForkReady[5];          /* condition variable for synchronization */
boolean fork[5] = {true};         /* availability status of each fork */

void get_forks(int pid)           /* pid is the philosopher id number */
{
   int left = pid;
   int right = (++pid) % 5;
   /*grant the left fork*/
   if (!fork(left)
      cwait(ForkReady[left]);          /* queue on condition variable */
   fork(left) = false;
   /*grant the right fork*/
   if (!fork(right)
      cwait(ForkReady(right);          /* queue on condition variable */
   fork(right) = false:
}
void release_forks(int pid)
{
   int left = pid;
   int right = (++pid) % 5;
   /*release the left fork*/
   if (empty(ForkReady[left])      /*no one is waiting for this fork */
      fork(left) = true;
   else                    /* awaken a process waiting on this fork */
      csignal(ForkReady[left]);
   /*release the right fork*/
   if (empty(ForkReady[right])     /*no one is waiting for this fork */
      fork(right) = true;
   else                    /* awaken a process waiting on this fork */
      csignal(ForkReady[right]);
}
```

```
void philosopher[k=0 to 4]            /* the five philosopher clients */
{
   while (true) {
      <think>;
      get forks(k);         /* client requests two forks via monitor */
      <eat spaghetti>;
      release forks(k);     /* client releases forks via the monitor */
   }
}
```

Figure 6.14 A Solution to the Dining Philosophers Problem Using a Monitor

# Using a monitor



```
monitor dining_controller;
cond ForkReady[5];        /* condition variable for synchronization */
boolean fork[5] = {true};       /* availability status of each fork */

void get_forks(int pid)         /* pid is the philosopher id number */
{
   int left = pid;
   int right = (++pid) % 5;
   /*grant the left fork*/
   if (!fork(left)
      cwait(ForkReady[left]);          /* queue on condition variable */
   fork(left) = false;
   /*grant the right fork*/
   if (!fork(right)
      cwait(ForkReady(right);          /* queue on condition variable */
   fork(right) = false:
}
void release_forks(int pid)
{
   int left = pid;
   int right = (++pid) % 5;
   /*release the left fork*/
   if (empty(ForkReady[left])      /*no one is waiting for this fork */
      fork(left) = true;
   else                       /* awaken a process waiting on this fork */
      csignal(ForkReady[left]);
   /*release the right fork*/
   if (empty(ForkReady[right])     /*no one is waiting for this fork */
      fork(right) = true;
   else                       /* awaken a process waiting on this fork */
      csignal(ForkReady[right]);
}
```

```
void philosopher[k=0 to 4]            /* the five philosopher clients */
{
   while (true) {
      <think>;
      get forks(k);          /* client requests two forks via monitor */
      <eat spaghetti>;
      release forks(k);      /* client releases forks via the monitor */
   }
}
```

Figure 6.14 A Solution to the Dining Philosophers Problem Using a Monitor

## Summary

- Deadlock is blocking of a set of processes that either compete for resources or communicate with each other
- The blocking is permanent unless external intervention (e.g. OS action - such as killing of one or more processes or forcing process to release resource) is enforced
- Deadlock may involve reusable or consumable resources
  - Reusable – not depleted or destroyed by use
    - Memory, I/O channel
  - Consumable – destroyed when acquired by a process
    - Signal, message

# Summary

- Three general approaches to deadlock: prevention, avoidance, detection
- Deadlock Prevention guarantees that deadlock will not occur
  - By assuring that one of the necessary conditions for deadlock will not occur
- Deadlock Avoidance involves analysis of each new resource request to determine if it could lead to deadlock and granting it only if deadlock is not possible
- Deadlock detection OS always grant resource requests but periodically OS check for deadlock and take action to break the deadlock

## References

- **Operating Systems – Internal and Design Principles**
  - By William Stallings
- Chapter 6
- Appendix A