# Concurrency: Deadlock and Starvation

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SASTRA

# Deadlock

- Permanent blocking of a set of processes that either compete for system resources or communicate with each other
- No efficient solution
- Involve conflicting needs for resources by two or more processes

# Deadlock

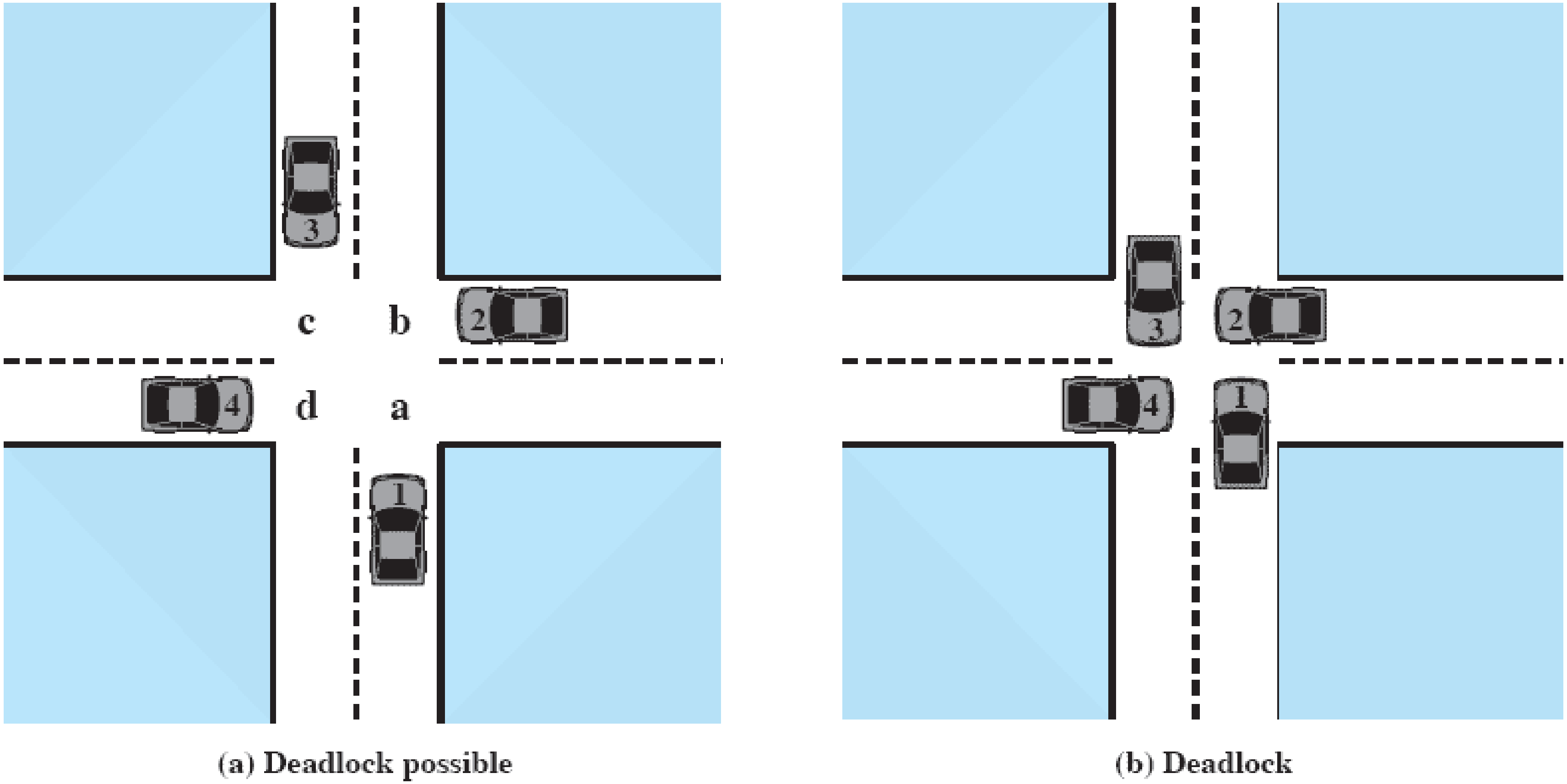



Figure 6.1 Illustration of Deadlock

# Deadlock

| Process P | Process Q |
|---|---|
| • • • | • • • |
| Get A | Get B |
| • • • | • • • |
| Get B | Get A |
| • • • | • • • |
| Release A | Release B |
| • • • | • • • |
| Release B | Release A |
| • • • | • • • |

# **Deadlock** - Joint Progress Diagram

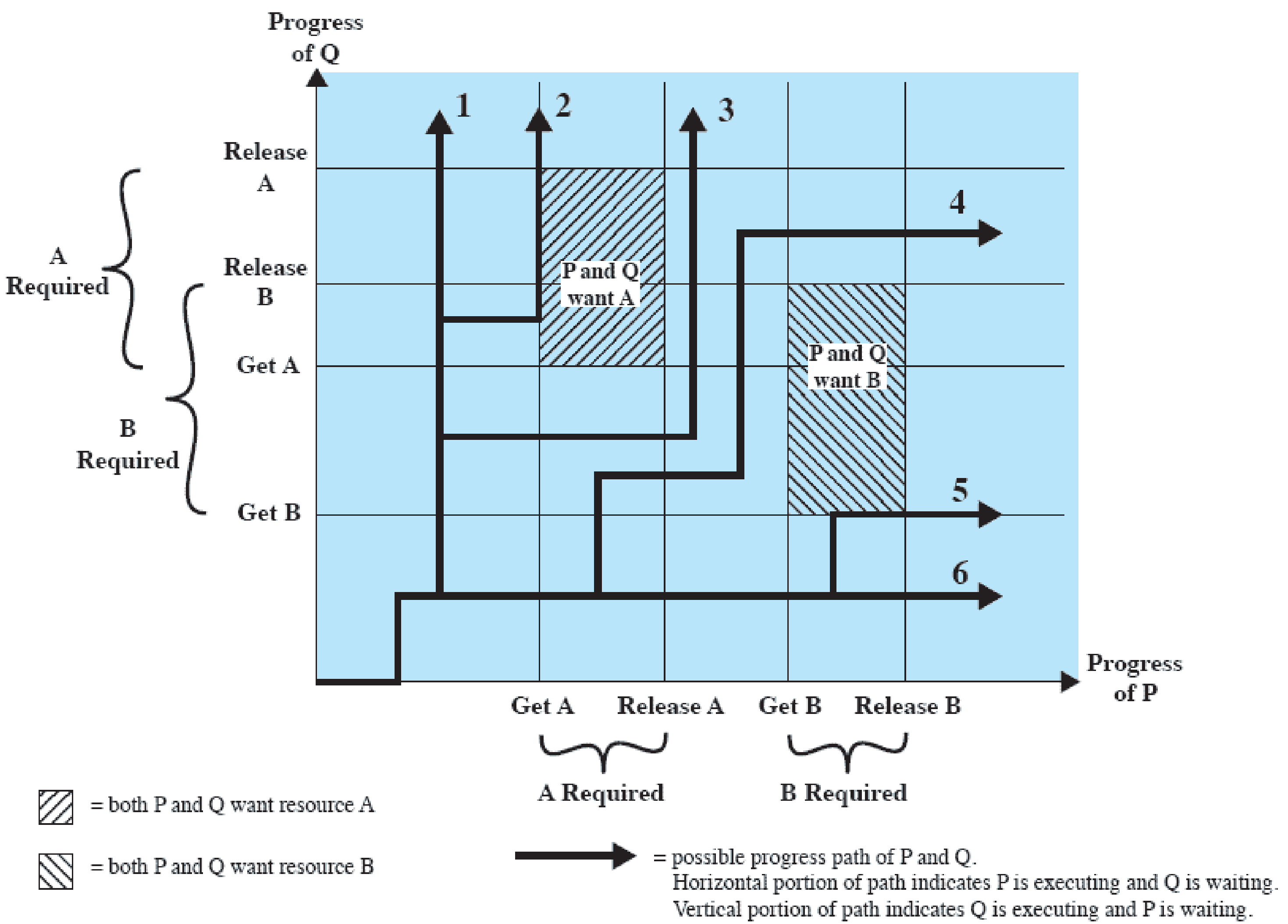



Figure 6.3 Example of No Deadlock [BACO03]

# Possible execution Paths

- 1. Q acquires B and then A and then releases B and A.
- 2. Q acquires B and then A. P executes and blocks for A.
- 3. Q acquires B  and P acquires A. -DL
- 4. P acquires A and then acquires B, latter releases B and A
- 5. P acquires A and then acquires B, Q requests B and get blocked
- 6. P acquires, Q acquires B – DL

- The gray shaded area in an ***Joint Progress Diagram*** is called ***Fata Region***

# Reusable Resources

- Used by only one process at a time and not depleted by that use
- Processes obtain resources that they later release for reuse by other processes

# Reusable Resources

- Processors, I/O channels, main and secondary memory, devices, and data structures such as files, databases, and semaphores
- Deadlock occurs if each process holds one resource and requests the other resource

# Reusable Resources

**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**

# Reusable Resources

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

| P1 | P2 |
| --- | --- |
| . . . | . . . |
| **Request 80 Kbytes;** | **Request 70 Kbytes;** |
| . . . | . . . |
| **Request 60 Kbytes;** | **Request 80 Kbytes;** |

- Deadlock occurs if both processes progress to their second request

# Consumable Resources

- Created (produced) and destroyed (consumed)
- Interrupts, signals, messages, and information in I/O buffers
- Deadlock may occur if a Receive message is blocking
- May take a rare combination of events to cause deadlock

# Example of Deadlock

- Deadlock occurs if receives blocking

**P1**

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

**P2**

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

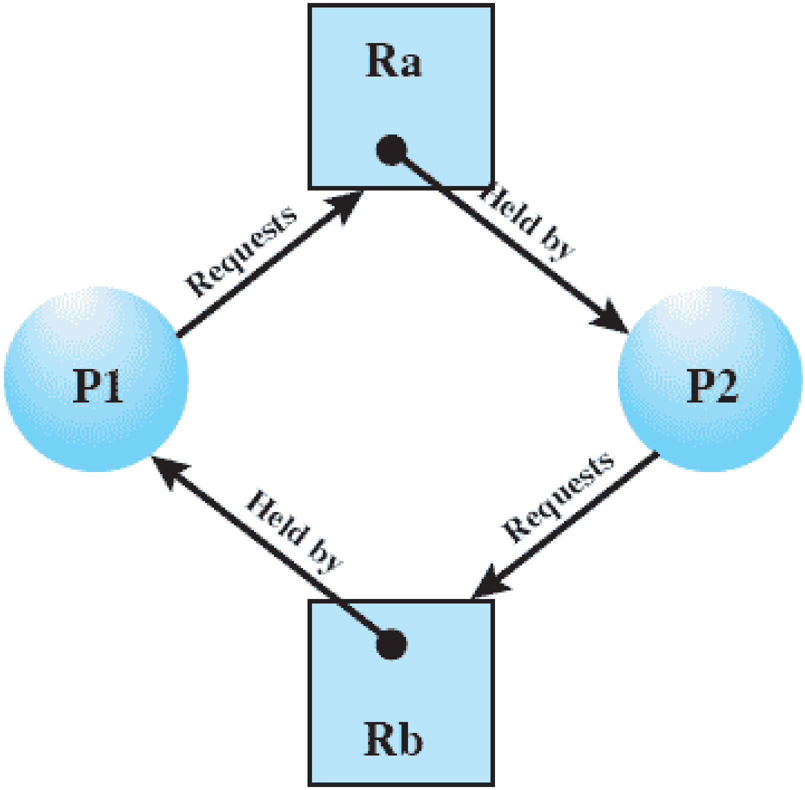
# Resource Allocation Graphs

- Directed graph that depicts a state of the system of resources and processes

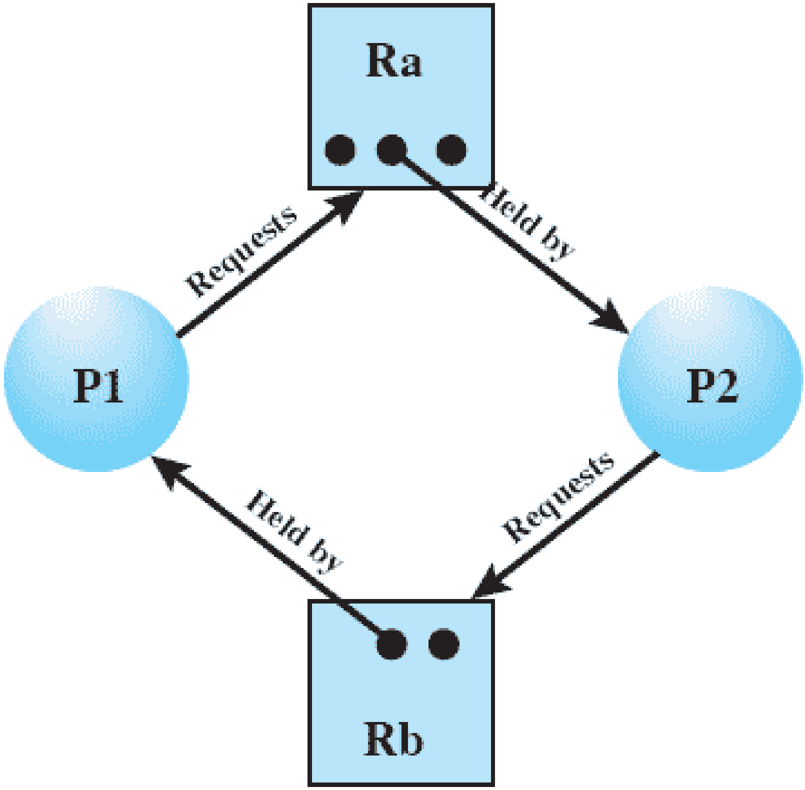

(a) Resouce is requested

(b) Resource is held

# Resource Allocation Graphs




(c) Circular wait




(d) No deadlock

# Resource Allocation Graphs

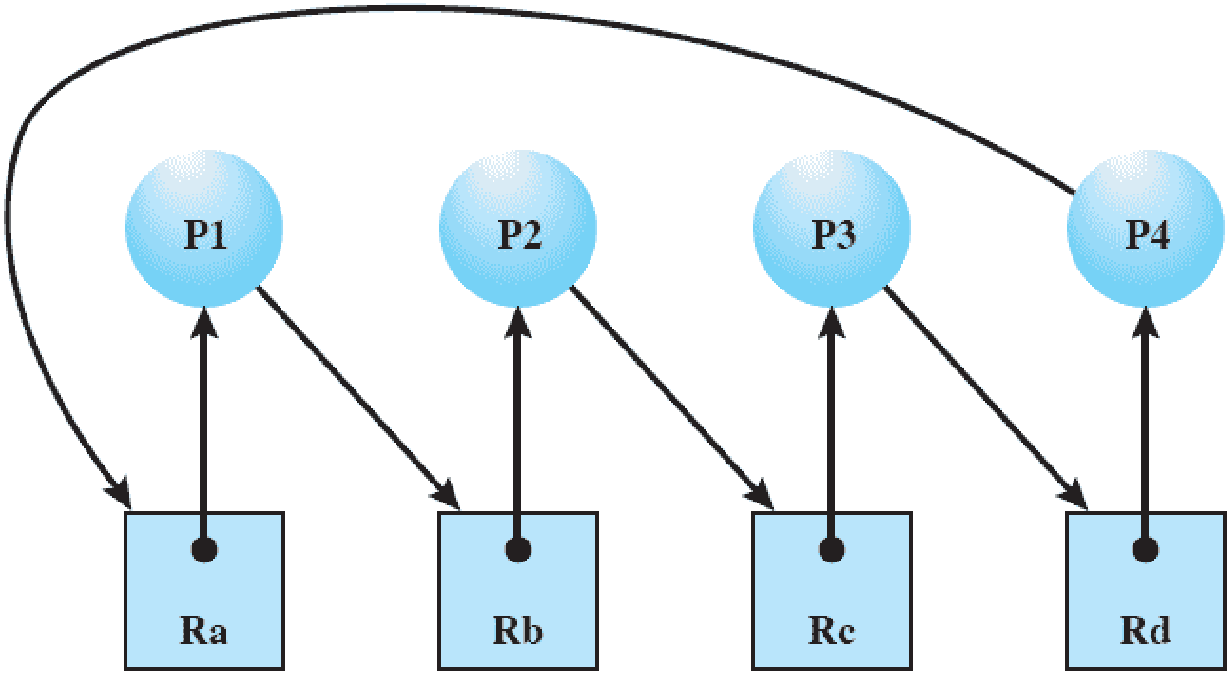



Figure 6.6 Resource Allocation Graph for Figure 6.1b

# Conditions for Deadlock

- Mutual exclusion
  - Only one process may use a resource at a time
- Hold-and-wait
  - A process may hold allocated resources while awaiting assignment of others

# Conditions for Deadlock

- No preemption
  - No resource can be forcibly removed form a process holding it
- Circular wait
  - A closed chain of processes exists, such that each process holds at least one resource needed by the next process in the chain

# Possibility of Deadlock

- Mutual Exclusion
- No preemption
- Hold and wait

# Existence of Deadlock

- Mutual Exclusion
- No preemption
- Hold and wait
- Circular wait

# Solution for deadlocks

- Prevention
- Avoidance
- Detection

# Deadlock Prevention

- Mutual Exclusion
  - Must be supported by the OS
- Hold and Wait
  - Require a process request all of its required resources at one time
  - Inefficient because
  - 1. A process waiting for all its resources when it could have progressed with available resources
  - 2. The resources allotted to a process may remain unused for a long time

# Deadlock Prevention

- No Preemption
  - Process must release resource and request again
  - OS may preempt a process to require it releases its resources

- Circular Wait
  - Define a linear ordering of resource types
  - Assign an index with each resource
  - Then Resource Ri precedes Rj in the ordering if i<j
  - Then if process P1 holding Ri and demanding Rj while P2 holding Rj demanding Ri is impossible
  - Because, P2 holding Rj should not ask for Ri
  - It should either give up Rj before asking Ri or should ask for some other resource Rj+1

# Deadlock Avoidance

- Allows the three necessary conditions but makes judicious choices to assure that deadlock point is never reached.
- A decision is made dynamically whether the current resource allocation request will, if granted, potentially lead to a deadlock
- Requires knowledge of future process resource requests

# Two Approaches to Deadlock Avoidance

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

# Resource Allocation Denial

- Referred to as the banker's algorithm
- State of the system is the current allocation of resources to process
- ***Safe state*** is where there is at least one sequence that does not result in deadlock
- ***Unsafe state*** is a state that is not safe

# Necessary data structures

| | |
|---|---|
| Resource $= \mathbf{R} = (R_1, R_2, \ldots, R_m)$ | Total amount of each resource in the system |
| Available $= \mathbf{V} = (V_1, V_2, \ldots, V_m)$ | Total amount of each resource not allocated to any process |
| Claim $= \mathbf{C} = \begin{pmatrix} C_{11} & C_{12} & \ldots & C_{1m} \\ C_{21} & C_{22} & \ldots & C_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ C_{n1} & C_{n2} & \ldots & C_{nm} \end{pmatrix}$ | $C_{ij}$ = requirement of process $i$ for resource $j$ |
| Allocation $= \mathbf{A} = \begin{pmatrix} A_{11} & A_{12} & \ldots & A_{1m} \\ A_{21} & A_{22} & \ldots & A_{2m} \\ \vdots & \vdots & \vdots & \vdots \\ A_{n1} & A_{n2} & \ldots & A_{nm} \end{pmatrix}$ | $A_{ij}$ = current allocation to process $i$ of resource $j$ |

1. $R_j = V_j + \sum_{i=1}^{n} A_{ij}$, for all $j$ — All resources are either available or allocated.
2. $C_{ij} \le R_j$, for all $i,j$ — No process can claim more than the total amount of resources in the system.
3. $A_{ij} \le C_{ij}$, for all $i,j$ — No process is allocated more resources of any type than the process originally claimed to need.

# Determination of a Safe State

Start a new process $P_{n+1}$ only if

$$R_j \geq C_{(n+1)j} + \sum_{i=1}^{n} C_{ij} \quad \text{for all } j$$

| | 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**

# Determination of a Safe State

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

Claim matrix **C**

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

Allocation matrix **A**

| | R1 | R2 | R3 |
|---|---|---|---|
| P1 | 2 | 2 | 2 |
| 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 |
|---|---|---|
| 6 | 2 | 3 |

Available vector **V**

(b) **P2 runs to completion**

# Determination of a Safe State

| | 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**

# Determination of a Safe State

| | 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**

# Determination of an Unsafe State

**Claim matrix C**

| | 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**

# Deadlock Avoidance Logic

```
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 Logic

```
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

- Maximum resource requirement must be stated in advance
- Processes under consideration must be independent; no synchronization requirements
- There must be a fixed number of resources to allocate
- No process may exit while holding resources

# Deadlock Detection

| | 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

**Figure 6.10 Example for Deadlock Detection**

# Strategies Once Deadlock Detected

- Abort all deadlocked processes
- Back up each deadlocked process to some previously defined checkpoint, and restart all process
  - Original deadlock may occur

# Strategies Once Deadlock Detected

- Successively abort deadlocked processes until deadlock no longer exists
- Successively preempt resources until deadlock no longer exists

# Advantages and Disadvantages

**Table 6.1 Summary of Deadlock Detection, Prevention, and Avoidance Approaches for Operating Systems [ISLO80]**

| 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

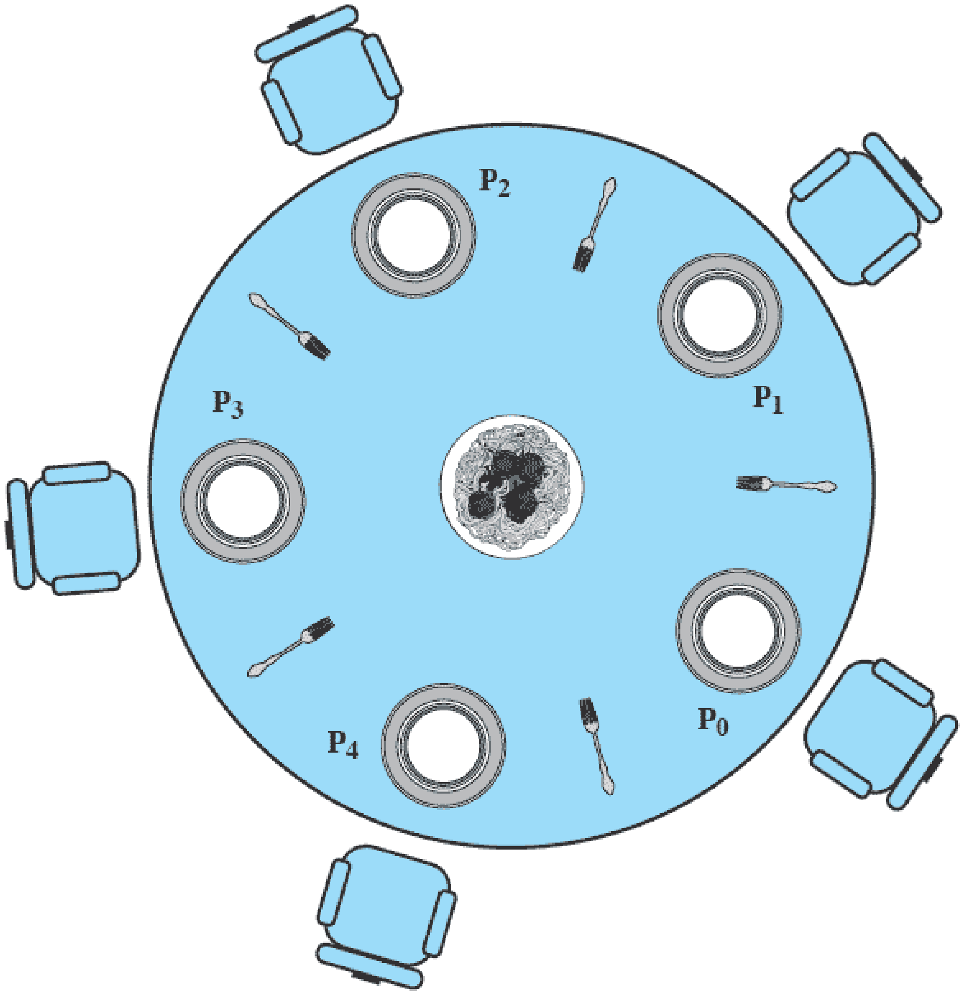



Figure 6.11 Dining Arrangement for Philosophers

# Dining Philosophers Problem

```
/* 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**

# Dining Philosophers Problem

```
/* 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**

# Dining Philosophers Problem

```
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]);
}
```

# Dining Philosophers Problem

```
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**

# UNIX Concurrency Mechanisms

- Pipes
- Messages
- Shared memory
- Semaphores
- Signals

# UNIX Signals

| Value | Name | Description |
|---|---|---|
| 01 | SIGHUP | Hang up; sent to process when kernel assumes that the user of that process is doing no useful work |
| 02 | SIGINT | Interrupt |
| 03 | SIGQUIT | Quit; sent by user to induce halting of process and production of core dump |
| 04 | SIGILL | Illegal instruction |
| 05 | SIGTRAP | Trace trap; triggers the execution of code for process tracing |
| 06 | SIGIOT | IOT instruction |
| 07 | SIGEMT | EMT instruction |
| 08 | SIGFPE | Floating-point exception |
| 09 | SIGKILL | Kill; terminate process |
| 10 | SIGBUS | Bus error |
| 11 | SIGSEGV | Segmentation violation; process attempts to access location outside its virtual address space |
| 12 | SIGSYS | Bad argument to system call |
| 13 | SIGPIPE | Write on a pipe that has no readers attached to it |
| 14 | SIGALRM | Alarm clock; issued when a process wishes to receive a signal after a period of time |
| 15 | SIGTERM | Software termination |
| 16 | SIGUSR1 | User-defined signal 1 |
| 17 | SIGUSR2 | User-defined signal 2 |
| 18 | SIGCHLD | Death of a child |
| 19 | SIGPWR | Power failure |

# Linux Kernel Concurrency Mechanism

- Includes all the mechanisms found in UNIX
- Atomic operations execute without interruption and without interference

# Linux Atomic Operations

**Table 6.3 Linux Atomic Operations**

| Atomic Integer Operations | |
|---|---|
| `ATOMIC_INIT (int i)` | At declaration: initialize an atomic_t to i |
| `int atomic_read(atomic_t *v)` | Read integer value of v |
| `void atomic_set(atomic_t *v, int i)` | Set the value of v to integer i |
| `void atomic_add(int i, atomic_t *v)` | Add i to v |
| `void atomic_sub(int i, atomic_t *v)` | Subtract i from v |
| `void atomic_inc(atomic_t *v)` | Add 1 to v |
| `void atomic_dec(atomic_t *v)` | Subtract 1 from v |
| `int atomic_sub_and_test(int i, atomic_t *v)` | Subtract i from v; return 1 if the result is zero; return 0 otherwise |
| `int atomic_add_negative(int i, atomic_t *v)` | Add i to v; return 1 if the result is negative; return 0 otherwise (used for implementing semaphores) |
| `int atomic_dec_and_test(atomic_t *v)` | Subtract 1 from v; return 1 if the result is zero; return 0 otherwise |
| `int atomic_inc_and_test(atomic_t *v)` | Add 1 to v; return 1 if the result is zero; return 0 otherwise |

# Linux Atomic Operations

| Atomic Bitmap Operations | |
|---|---|
| `void set_bit(int nr, void *addr)` | Set bit nr in the bitmap pointed to by addr |
| `void clear_bit(int nr, void *addr)` | Clear bit nr in the bitmap pointed to by addr |
| `void change_bit(int nr, void *addr)` | Invert bit nr in the bitmap pointed to by addr |
| `int test_and_set_bit(int nr, void *addr)` | Set bit nr in the bitmap pointed to by addr; return the old bit value |
| `int test_and_clear_bit(int nr, void *addr)` | Clear bit nr in the bitmap pointed to by addr; return the old bit value |
| `int test_and_change_bit(int nr, void *addr)` | Invert bit nr in the bitmap pointed to by addr; return the old bit value |
| `int test_bit(int nr, void *addr)` | Return the value of bit nr in the bitmap pointed to by addr |

# Linux Spinlocks

| | |
|---|---|
| `void spin_lock(spinlock_t *lock)` | Acquires the specified lock, spinning if needed until it is available |
| `void spin_lock_irq(spinlock_t *lock)` | Like spin_lock, but also disables interrupts on the local processor |
| `void spin_lock_irqsave(spinlock_t *lock, unsigned long flags)` | Like spin_lock_irq, but also saves the current interrupt state in flags |
| `void spin_lock_bh(spinlock_t *lock)` | Like spin_lock, but also disables the execution of all bottom halves |
| `void spin_unlock(spinlock_t *lock)` | Releases given lock |
| `void spin_unlock_irq(spinlock_t *lock)` | Releases given lock and enables local interrupts |
| `void spin_unlock_irqrestore(spinlock_t *lock, unsigned long flags)` | Releases given lock and restores local interrupts to given previous state |
| `void spin_unlock_bh(spinlock_t *lock)` | Releases given lock and enables bottom halves |
| `void spin_lock_init(spinlock_t *lock)` | Initializes given spinlock |
| `int spin_trylock(spinlock_t *lock)` | Tries to acquire specified lock; returns nonzero if lock is currently held and zero otherwise |
| `int spin_is_locked(spinlock_t *lock)` | Returns nonzero if lock is currently held and zero otherwise |

# Linux Semaphores

| Traditional Semaphores | |
|---|---|
| `void sema_init(struct semaphore *sem, int count)` | Initializes the dynamically created semaphore to the given count |
| `void init_MUTEX(struct semaphore *sem)` | Initializes the dynamically created semaphore with a count of 1 (initially unlocked) |
| `void init_MUTEX_LOCKED(struct semaphore *sem)` | Initializes the dynamically created semaphore with a count of 0 (initially locked) |
| `void down(struct semaphore *sem)` | Attempts to acquire the given semaphore, entering uninterruptible sleep if semaphore is unavailable |
| `int down_interruptible(struct semaphore *sem)` | Attempts to acquire the given semaphore, entering interruptible sleep if semaphore is unavailable; returns -EINTR value if a signal other than the result of an `up` operation is received. |
| `int down_trylock(struct semaphore *sem)` | Attempts to acquire the given semaphore, and returns a nonzero value if semaphore is unavailable |
| `void up(struct semaphore *sem)` | Releases the given semaphore |
| **Reader-Writer Semaphores** | |
| `void init_rwsem(struct rw_semaphore, *rwsem)` | Initalizes the dynamically created semaphore with a count of 1 |
| `void down_read(struct rw_semaphore, *rwsem)` | Down operation for readers |
| `void up_read(struct rw_semaphore, *rwsem)` | Up operation for readers |
| `void down_write(struct rw_semaphore, *rwsem)` | Down operation for writers |
| `void up_write(struct rw_semaphore, *rwsem)` | Up operation for writers |

# Linux Memory Barrier Operations

**Table 6.6 Linux Memory Barrier Operations**

| | |
|---|---|
| `rmb()` | Prevents loads from being reordered across the barrier |
| `wmb()` | Prevents stores from being reordered across the barrier |
| `mb()` | Prevents loads and stores from being reordered across the barrier |
| `Barrier()` | Prevents the compiler from reordering loads or stores across the barrier |
| `smp_rmb()` | On SMP, provides a `rmb()` and on UP provides a `barrier()` |
| `smp_wmb()` | On SMP, provides a `wmb()` and on UP provides a `barrier()` |
| `smp_mb()` | On SMP, provides a `mb()` and on UP provides a `barrier()` |

SMP = symmetric multiprocessor
UP = uniprocessor

# Solaris Thread Synchronization Primitives

- Mutual exclusion (mutex) locks
- Semaphores
- Multiple readers, single writer (readers/writer) locks
- Condition variables

# Solaris Synchronization Data Structures

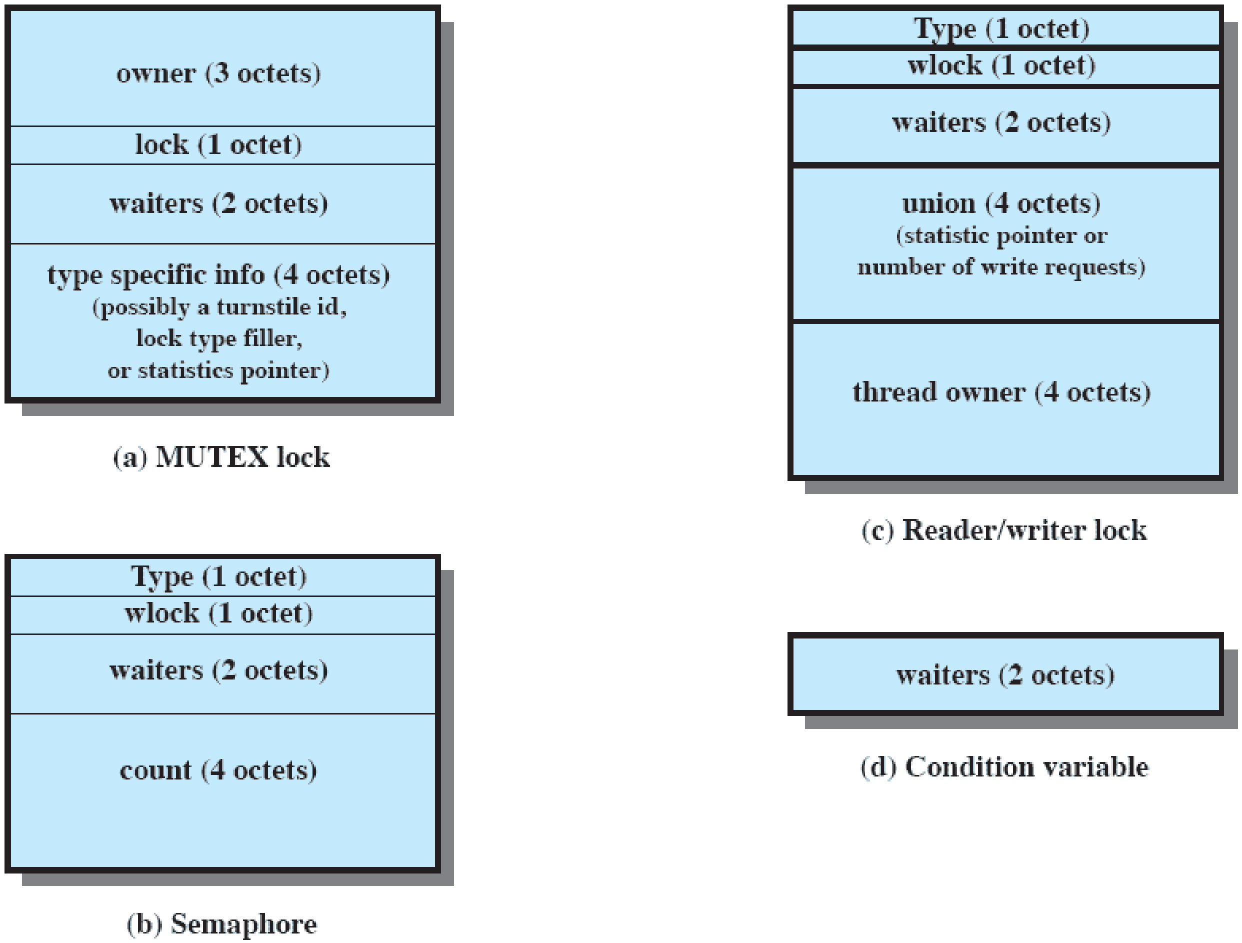



Figure 6.15 Solaris Synchronization Data Structures

# Windows Synchronization Objects

| Object Type | Definition | Set to Signaled State When | Effect on Waiting Threads |
|---|---|---|---|
| Notification Event | An announcement that a system event has occurred | Thread sets the event | All released |
| Synchronization event | An announcement that a system event has occurred. | Thread sets the event | One thread released |
| Mutex | A mechanism that provides mutual exclusion capabilities; equivalent to a binary semaphore | Owning thread or other thread releases the mutex | One thread released |
| Semaphore | A counter that regulates the number of threads that can use a resource | Semaphore count drops to zero | All released |
| Waitable timer | A counter that records the passage of time | Set time arrives or time interval expires | All released |
| File | An instance of an opened file or I/O device | I/O operation completes | All released |
| Process | A program invocation, including the address space and resources required to run the program | Last thread terminates | All released |
| Thread | An executable entity within a process | Thread terminates | All released |

*Note:* Shaded rows correspond to objects that exist for the sole purpose of synchronization.