**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**

| | 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**

| | 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**

| | 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**

| | 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**

**Figure 6.7 Determination of a Safe 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**

**Figure 6.8 Determination of an Unsafe State**

```
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**

```
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**

```
/* 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**

```
/* 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**

```
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**

```
monitor dining_controller;
enum states (thinking, hungry, eating} state[5];
cond needFork[5]                              /* condition variable */

void get_forks(int pid)         /* pid is the philosopher id number */
{
   state[pid] = hungry;                  /* announce that I'm hungry */
   if (state[(pid+1) % 5] == eating
   || (state[(pid-1) % 5] == eating
   cwait(needFork[pid]);        /* wait if either neighbor is eating */
   state[pid] = eating;     /* proceed if neither neighbor is eating */
}

void release_forks(int pid)
{
   state[pid] = thinking;
   /* give right (higher) neighbor a chance to eat */
   if (state[(pid+1) % 5] == hungry)
   || (state[(pid+2) % 5]) != eating)
   csignal(needFork[pid+1]);
   /* give left (lower) neighbor a chance to eat */
   else if (state[(pid–1) % 5] == hungry)
   || (state[(pid–2) % 5]) != eating)
   csignal(needFork[pid–1]);
}
```

```
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 6.17 Another Solution to the Dining Philosophers Problem Using a Monitor**