Module 3(a): Process Synchronization

6.1 Background

In this module developed a model of a system consisting of cooperating sequential processes or threads, all running asynchronously and possibly sharing data. Illustrated this model with the producer-consumer problem, which is representative of operating systems.

Let's return to our consideration of the bounded buffer. As we pointed out, our original solution allowed at most BUFFER_SIZE - 1 items in the buffer at the same time. Suppose we want to modify the algorithm to remedy this deficiency. One possibility is to add an integer variable counter, initialized to 0. counter is incremented every time we add a new item to the buffer and is decremented every time we remove one item from the buffer. The code for the producer process can be modified as follows:

```
while (true) {
        /* produce an item in nextProduced */
        while (counter == BUFFER_SIZE) ;
        /* do nothing */
         buffer[in] = nextProduced;
         in = (in + 1) % BUFFER_SIZE ;
        counter++;
        }
```

The code for the consumer process can be modified as follows:

```
while (true) {
          while (counter == 0) ;
        /* do nothing */
        nextConsumed = buffer[out];
        out = (out + 1) % BUFFER_SIZE;
        counter--;
      /* consume the item in nextConsumed */
        }
```

Although both the producer and consumer routines shown above are correct separately, they may not function correctly when executed concurrently. As an illustration, suppose that the value of the variable counter is currently 5 and that the producer and consumer processes execute the statements "counter++" and "counter--" concurrently. Following the execution of these two statements, the value of the variable counter may be 4, 5, or 6! The only correct result, though, is counter == 5, which is generated correctly if the producer and consumer execute separately.

The value of counter may be incorrect as follows,the statement" counter++" may be implemented in machine language (on a typical machine) as :

$register_1$ = counter

$register_1$ = $register_1$ + 1

counter= $register_1$

where $register_1$ is one of the local CPU registers.

Similarly, the statement $register_2$ "counter--" is implemented as follows:

$register_2$ = counter

$register_2$ = $register_2$ – 1

counter= $register_2$

where again $register_2$ is one of the local CPU registers.

Even though $register_1$ and $register_2$ may be the same physical register (an accumulator, say), remember that the contents of this register will be saved and restored by the interrupt handler.

The concurrent execution of "counter++" and "counter--" is equivalent to a sequential execution in which the lower-level statements presented previously are interleaved in some arbitrary order (but the order within each high-level statement is preserved). One such interleaving is

T_0: producer execute $register_1$ =counter {$register_1$ = 5}

T_1: producer execute $register_1$ = $register_1$ + 1 {$register_1$ = 6}

T_2: consumer execute $register_2$ = counter {$register_2$ = 5}

T_3: consumer execute $register_2$ = $register_2$ - 1 {register2 = 4}

T_4: producer execute counter= $register_1$ {counter = 6}

T_5: consumer execute counter = $register_2$ {counter = 4}

Notice that we have arrived at the incorrect state "counter == 4", indicating that four buffers are full, when, in fact, five buffers are full. If we reversed the order of the statements at T_4 and T_5, we would arrive at the incorrect state "counter== 6".

A situation like this, where several processes access and manipulate the same data concurrently and the outcome of the execution depends on the particular order in which the access takes place, is called a **race condition**.

- To guard against the race condition above, we need to ensure that only one process at a time can be manipulating the variable counter. To make such a guarantee, we require that the processes be synchronized in some way.

6.1 The Critical-Section Problem

Consider a system consisting of n processes {P0, P1, ..., Pn−1}. Each process has a segment of code, called a **critical section**, in which the process may be changing common variables, updating a table, writing a file, and so on. when one process is executing in its critical section, no other process is allowed to execute in its critical section. The **critical-section problem** is to design a protocol that the processes can use to cooperate. Each process must request permission to enter its critical section. The section of code implementing this request is the **entry section**. The critical section may be followed by an **exit section**. The remaining code is the **remainder section**. The general structure of a typical process Pi is shown in Figure.

```
do {
        entry section
            critical section
        exit section
            remainder section
} while (true);
```

General structure of a typical process P_i.

A solution to the critical-section problem must satisfy the following three requirements:

1. **Mutual exclusion**. If process *Pi* is executing in its critical section, then no other processes can be executing in their critical sections. No other process can enter the critical section until the process already present inside it completes.
2. **Progress**. If no process is executing in its critical section and some processes wish to enter their critical sections, then only those processes that are not executing in their remainder sections can participate in deciding which will enter its critical section next, and this selection cannot be postponed indefinitely.
3. **Bounded waiting**. There exists a bound, or limit, on the number of times that other processes are allowed to enter their critical sections after a process has made a request to enter its critical section and before that request is granted.

We assume that each process is executing at a nonzero speed. However, we can make no assumption concerning the relative of the n processes.

Two general approaches are used to handle critical sections in operating systems:

- **Preemptive kernels:** A preemptive kernel allows a process to be preempted while it is running in kernel mode.

- **Non-preemptive kernels:** A non-preemptive kernel does not allow a process running in kernel mode to be preempted; a kernel-mode process will run until it exits kernel mode, blocks, or voluntarily yields control of the CPU.

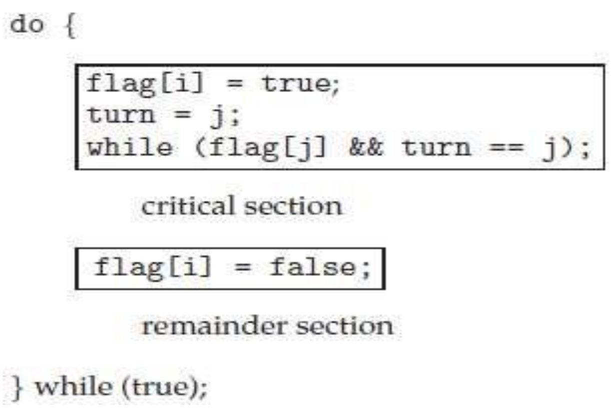
6.3 Peterson’s Solution

A classic software-based solution to the critical-section problem known as **Peterson’s solution**. Because of the way modern computer architectures perform basic machine-language instructions, such as load and store, there are no guarantees that Peterson's solution will work correctly on such architectures. However, we present the solution because it provides a good algorithmic description of solving the critical-section problem and illustrates some of the complexities involved in designing software that addresses the requirements of mutual exclusion, progress, and bounded waiting.

- It Is two process solution.
- Assume that the LOAD and STORE instructions are atomic; that is, cannot be interrupted
- The two processes share two variables:

  int turn;
  boolean flag[2] ;

  The variable turn indicates whose turn it is to enter the critical section. The flag array is used to indicate if a process is ready to enter the critical section. flag[i] = true implies that process Pi is ready.
- The structure of process *Pi* in Peterson’s solution:



```
do {

    flag[i] = true;
    turn = j;
    while (flag[j] && turn == j);

        critical section

    flag[i] = false;

        remainder section

} while (true);
```

- It proves that
  1. Mutual exclusion is preserved
  2. Progress requirement is satisfied
  3. Bounded-waiting requirement is met

  To prove property 1, we note that each P_i; enters its critical section only if either

flag [j] = = false or turn = = i. Also note that, if both processes can be executing in their critical sections at the same time, then flag [0] = = flag [1] = =true. These two observations imply that Po and P_1 could not have successfully executed their while statements at about the same time, since the value of turn can be either 0 or 1 but cannot be both. Hence, one of the processes -say, Pj -must have successfully executed the while statement, whereas P_i; had to execute at least one additional statement ("turn= = j"). However, at that time, flag [j] = = true and turn = = j, and this condition will persist as long as Pi is in its critical section; as a result, mutual exclusion is preserved.

To prove properties 2 and 3, we note that a process P_i can be prevented from entering the critical section only if it is stuck in the while loop with the condition flag [j] = = true and turn = = j; this loop is the only one possible. If Pj is not ready to enter the critical section, then flag [j] = =false, and Pi can enter its critical section. If Pj has set flag [j] to true and is also executing in its while statement, then either turn = = i or turn = = j. If turn = = i, then Pi will enter the critical section. If turn= = j, then Pj will enter the critical section. However, once Pj exits its critical section, it will reset flag [j] to false, allowing Pi to enter its critical section. If Pj resets flag [j] to true, it must also set turn to i. Thus, since Pi does not change the value of the variable turn while executing the while statement, Pi will enter the critical section (progress) after at most one entry by Pj (bounded waiting).

```
do {
     acquire lock
          critical section
     release lock
          remainder section
} while (TRUE);
```

Solution to the critical-section problem using locks

6.4 Synchronization Hardware

Software-based solutions such as Peterson's are not guaranteed to work on modern computer architectures. Simple hardware instructions can be used effectively in solving the critical-section problem. These solutions are based on the **locking** —that is, protecting critical regions through the use of locks.

Race conditions are prevented by requiring that critical regions be protected by locks. That is, a process must acquire a lock before entering a critical section; it releases the lock when it exits the critical section as shown in fig above.

We explore several more solutions to the critical-section problem using techniques ranging from hardware to software- based APIs available to application programmers.

The critical-section problem could be solved simply in a uniprocessor environment if we could prevent interrupts from occurring while a shared variable was being modified. In this manner, we could be sure that the current sequence of instructions would be allowed to execute in order without preemption. No other instructions would be run, so no unexpected modifications could be made to the shared variable. This is often the approach taken by non-preemptive kernels. Unfortunately, this solution is not as feasible in a multiprocessor environment. Disabling interrupts on a multiprocessor can be time consuming, as the message is passed to all the processors. This message passing delays entry into each critical section, and system efficiency decreases.

Many modern computer systems therefore provide special hardware instructions that allow us either to test and modify the content of a word or to swap the contents of two words **atomically** - that is, as one uninterruptible unit. We can use these special instructions to solve the critical-section problem in a relatively simple manner. Rather than discussing one specific instruction for one specific machine, we abstract the main concepts behind these types of instructions by describing the TestAndSet () and Swap() instructions.

```
boolean TestAndSet(boolean *target)
{
 boolean rv = *target;
*target = TRUE;
return rv;
}
```

Figure 6.4 The definition of the TestAndSet () instruction.

```
do
{
while (TestAndSet(&lock)) ;
// do nothing //
 critical section lock = FALSE;
 // remainder section//
  } while (TRUE);
```

Figure 6.5 Mutual-exclusion implementation with TestAndSet ().

The TestAndSet () instruction can be defined as shown in Figure 6.4. The important characteristic of this instruction is that it is executed atomically. Thus, if two TestAndSet () instructions are executed simultaneously (each on a different CPU), they will be executed sequentially in some arbitrary order. If the machine supports the TestAndSet () instruction, then mutual exclusion can be implemented by declaring a Boolean variable lock, initialized to false. The structure of process Pi is shown in Figure 6.5.

The Swap() instruction, in contrast to the TestAndSet () instruction, operates on the contents of two words; it is defined as shown in Figure 6.6. Like the TestAndSet () instruction, it is executed atomically. If the machine supports the Swap() instruction, then mutual exclusion can be provided as follows. A global Boolean variable lock is declared and is initialized to false. In addition, each process has a local Boolean variable key. The structure of process Pi is shown in Figure 6.7

```
void Swap(boolean *a, boolean *b)
{
boolean temp = *a;
*a *b; *b = temp;
}
```

Figure 6.6 The definition of the Swap () instruction.

```
do
{
key = TRUE;
while (key == TRUE)
Swap(&lock, &key);
 // critical section
 lock = FALSE;
// remainder section
} while (TRUE);
```

Figure 6.7 Mutual-exclusion implementation with the Swap() instruction.

```
boolean waiting[n];
boolean lock;
```

These data structures are initialized to false. To prove that the mutual - exclusion requirement is met, we note that process Pi can enter its critical section only if either waiting [i] = = false or key = = false. The value of key can become false only if the TestAndSet () is executed. The first process to execute the TestAndSet () will find key= = false; all others must wait. The variable waiting [i] can become false only if another process leaves its critical section; only one waiting [i] is set to false, maintaining the mutual-exclusion requirement.

```
 do
{
  waiting[i] = TRUE;
   key = TRUE;
   while (waiting[i] && key)
       key= TestAndSet(&lock);
       waiting[i] = FALSE;
   // critical section
       j = (i + 1) % n;
   while ((j != i) && !waiting[j])
    j = (j + 1) % n;
     if (j == i)
             lock = FALSE;
    else
             waiting[j] = FALSE;
    // remainder section
    } while (TRUE) ;
```

Figure 6.8 Bounded-waiting mutual exclusion with TestAndSet ().

To prove that the progress requirement is met, the arguments presented for mutual exclusion also applied here, since a process exiting the critical section either sets lock to false or sets waiting[j] to false. Both allow a process that is waiting to enter its critical section to proceed.

To prove that the bounded-waiting requirement is met, when a process leaves its critical section, it scans the array waiting in the cyclic ordering (i + 1, i + 2, ... , n 1, 0, ... , i - 1). It designates the first process in this ordering that is in the entry section (waiting[j] = = true) as the next one to enter the critical section. Any process waiting to enter its critical section will thus do so within n - 1 turns.

Unfortunately for hardware designers, implementing atomic TestAnd-Set () instructions on multiprocessors is not a trivial task.

6.5 Semaphores

The hardware-based solutions to the critical-section problem are complicated as well as generally inaccessible to application programmers. So operating-systems designers build software tools to solve the critical-section problem, and this synchronization tool called as Semaphore.

- Semaphore *S is an* integer variable.
- Two standard atomic operations modify S: wait() and signal() Originally called P() and V().

The definition of wait () is as follows:

```
wait(S)
{
  while S <= 0
  // no-operation
        S - - ;
 }
```

The definition of signal() is as follows:

```
signal(S)
{
    S++;
 }
```

All modifications to the integer value of the semaphore in the wait () and signal() operations must be executed indivisibly. That is, when one process modifies the semaphore value, no other process can simultaneously modify that same semaphore value. In addition, in the case of wait (S), the testing of the integer value of S ($S \leq 0$), as well as its possible modification (S--), must be executed without interruption.

6.5.1 Usage:

Semaphore classified into:

- Counting semaphore: Value can range over an unrestricted domain..
- Binary semaphore(Mutex locks): Value can range only between from 0 & 1. It provides mutual exclusion.

```
Semaphore mutex;    //  initialized to 1
do {
    wait (mutex);
        // Critical Section
    signal (mutex);
          // remainder section
} while (TRUE);
```

Consider two concurrently running processes:

```
S1;
signal(synch);
```

In process *P*1, and the statements

```
wait(synch);
S2;
```

Because synch is initialized to 0, *P*2 will execute *S*2 only after *P*1 has invoked signal(synch), which is after statement *S*1 has been executed.

6.5.2 Implementation:

The disadvantage of the semaphore is **busy waiting** i.e While a process is in critical section, any other process that tries to enter its critical section must loop continuously in the entry code. Busy waiting wastes CPU cycles that some other process might be able to use productively. This type of semaphore is also called a **spin lock** because the process spins while waiting for the lock.

Solution for Busy Waiting problem:

Modify the definition of the wait() and signal()operations as follows:

- When a process executes the wait() operation and finds that the semaphore value is not positive, it must wait.
- Rather than engaging in busy waiting, the process can block itself.
- The block operation places a process into a waiting queue associated with the semaphore, and the state of the process is switched to the waiting state.

- Then control is transferred to the CPU scheduler, which selects another process to execute.

A process that is blocked, waiting on a semaphore S, should be restarted when some other process executesa signal() operation. The process is restarted by a wakeup() operation, which changes the process from the waiting state to the ready state. The process is then placed in the ready queue.

To implement semaphores under this definition, define a semaphore as follows:

```
typedef struct
{
 int value;
 struct process *list;
} semaphore;
```

Each semaphore has an integer value and a list of processes list. When a process must wait on a semaphore, it is added to the list of processes. A signal() operation removes one process from the list of waiting processes and awakens that process. Now, the wait() semaphore operation can be defined as:

```
wait(semaphore *S)
{
        S->value--;
        if (S->value < 0)
        {
                add this process to S->list;
                block();
        }
}
```

and the signal() semaphore operation can be defined as

```
signal(semaphore *S)
{
        S->value++;
        if (S->value <= 0)
        {
                remove a process P from S->list;
                wakeup(P);
        }
}
```

The block() operation suspends the process that invokes it. The wakeup(P) operation resumes the execution of a blocked process P.

6.5.3 Deadlocks and Starvation

The implementation of a semaphore with a waiting queue may result in a situation where two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes, these processes are said to be deadlocked.

Consider below example: a system consisting of two processes, *P*0 and *P*1, each accessing two semaphores, S and Q, set to the value 1:

```
     P0               P1

wait(S);         wait(Q);
wait(Q);         wait(S);
    .                .
    .                .
    .                .
signal(S);       signal(Q);
signal(Q);       signal(S);
```

Suppose that *P*0 executes wait(S) and then *P*1 executes wait(Q).When *P*0 executes wait(Q), it must wait until *P*1 executes signal(Q). Similarly, when *P*1 executes wait(S), it must wait until *P*0 executes signal(S). Since these signal() operations cannot be executed, *P*0 and *P*1 are deadlocked.

Another problem related to deadlocks is **indefinite blocking** or **starvation**.

6.6 Classic Problems of Synchronization

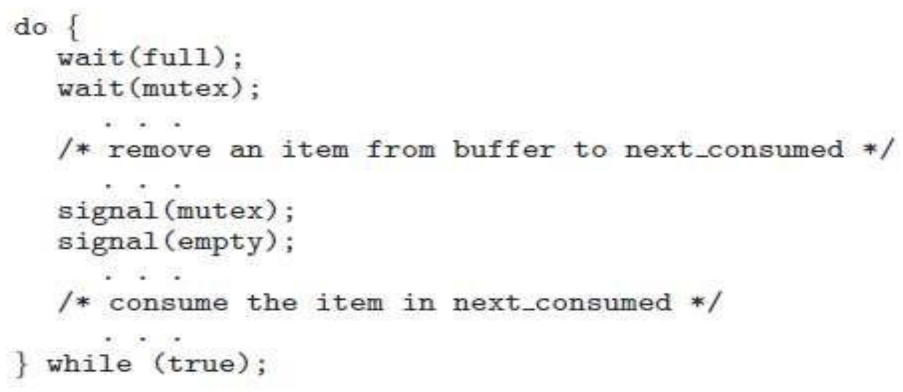
6.6.1 The Bounded-Buffer Problem:

- *N* buffers, each can hold one item
- Semaphore mutex initialized to the value 1
- Semaphore full initialized to the value 0
- Semaphore empty initialized to the value N

  Code for producer is given below:

```
do {
     . . .
   /* produce an item in next_produced */
     . . .
   wait(empty);
   wait(mutex);
     . . .
   /* add next_produced to the buffer */
     . . .
   signal(mutex);
   signal(full);
} while (true);
```

Code for consumer is given below:



```
do {
   wait(full);
   wait(mutex);
      . . .
   /* remove an item from buffer to next_consumed */
      . . .
   signal(mutex);
   signal(empty);
      . . .
   /* consume the item in next_consumed */
      . . .
} while (true);
```

6.6.2 The Readers–Writers Problem

- A data set is shared among a number of concurrent processes
  - ✓ Readers – only read the data set; they do **not** perform any updates
  - ✓ Writers– can both read and write
- Problem – allow multiple readers to read at the same time
  - ✓ Only one single writer can access the shared data at the same time
- Several variations of how readers and writers are treated – all involve priorities.
  - ✓ *First* variation – no reader kept waiting unless writer has permission to use shared object.
  - ✓ *Second* variation- Once writer is ready, it performs as soon as possible. In other words, if a writer is waiting to access the object, no new readers may start reading.
- Shared Data
  - ✓ Data set
  - ✓ Semaphore mutex initialized to 1
  - ✓ Semaphore wrt initialized to 1
  - ✓ Integer readcount initialized to 0

In the solution to the first readers-writers problem, the reader processes share the following data structures:

semaphore mutex, wrt;

int readcount;

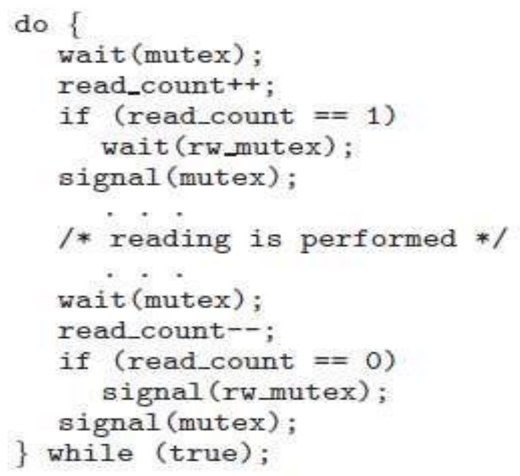
The mutex semaphore is used to ensure mutual exclusion when the variable readcount is updated. The readcount variable keeps track of how many processes are currently reading the object. The semaphore wrt functions as a mutual-exclusion semaphore for the writers. It is also used by the first or last reader that enters or exits the critical section. It is not used by readers who enter or exit while other readers are in their critical sections.

The structure of writer process:

```
do
{
wait(wrt);
 // writing is performed
 signal(wrt);
} while (TRUE);
```

Figure 6.12 The structure of a writer process.

The structure of reader process:



```
do {
   wait(mutex);
   read_count++;
   if (read_count == 1)
      wait(rw_mutex);
   signal(mutex);
      . . .
   /* reading is performed */
      . . .
   wait(mutex);
   read_count--;
   if (read_count == 0)
      signal(rw_mutex);
   signal(mutex);
} while (true);
```

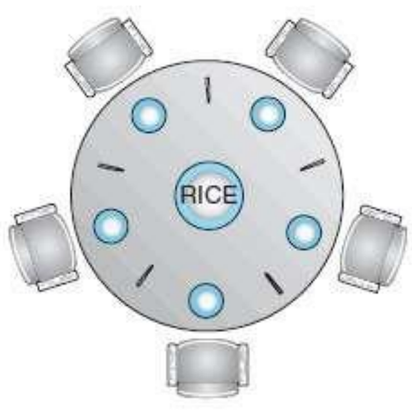
The readers-writers problem and its solutions have been generalized to provide locks on some systems. Acquiring a reader-writer lock requires specifying the mode of the lock either read or write access. When a process wishes only to read shared data, it requests the reader-writer lock in read mode; a process wishing to modify the shared data must request the lock in write mode. Multiple processes are permitted to concurrently acquire a reader-writer lock in read mode, but only one process may acquire the lock for writing, as exclusive access is required for writers.

Reader-writer locks are most useful in the following situations:

- In applications where it is easy to identify which processes only read shared data and which processes only write shared data.
- In applications that have more readers than writers. This is because reader- writer locks generally require more overhead to establish than semaphores or mutual-exclusion locks. The increased concurrency of allowing multiple readers compensates for the overhead involved in setting up the reader - writer lock.

6.6.3 The Dining-Philosophers Problem

Consider five philosophers who spend their lives thinking and eating. The philosophers share a circular table surrounded by five chairs, each belonging to one philosopher. In the center of the table is a bowl of rice, and the table is laid with five single chopsticks.



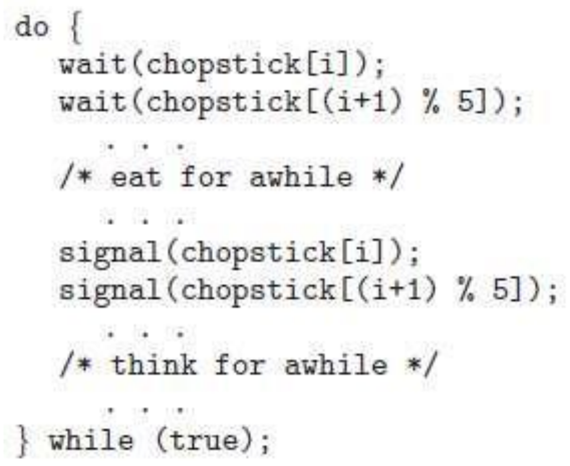
A philosopher gets hungry and tries to pick up the two chopsticks that are closest to her (the chopsticks that are between her and her left and right neighbors). A philosopher may pick up only one chopstick at a time. When a hungry philosopher has both her chopsticks at the same time, she eats without releasing the chopsticks. When she is finished eating, she puts down both chopsticks and starts thinking again.

It is a simple representation of the need to allocate several resources among several processes in adeadlock-free and starvation-free manner.

Solution: One simple solution is to represent each chopstick with a semaphore. A philosopher tries to grab a chopstick by executing a wait() operation on that semaphore. She releases her chopsticks by executing the signal() operation on the appropriate semaphores. Thus, the shared data are

```
semaphore chopstick[5];
```

where all the elements of chopstick are initialized to 1. The structure of philosopher *i* is shown in Figure



```
do {
   wait(chopstick[i]);
   wait(chopstick[(i+1) % 5]);
      . . .
   /* eat for awhile */
      . . .
   signal(chopstick[i]);
   signal(chopstick[(i+1) % 5]);
      . . .
   /* think for awhile */
      . . .
} while (true);
```

Several possible remedies to the deadlock problem are replaced by:

- Allow at most four philosophers to be sitting simultaneously at the table.
- Allow a philosopher to pick up her chopsticks only if both chopsticks are available.
- Use an asymmetric solution—that is, an odd-numbered philosopher picks up first her left chopstick and then her right chopstick, whereas an even numbered philosopher picks up her right chopstick and then her left chopstick.

Module 3(b) : DEADLOCKS

A process requests resources, if the resources are not available at that time, the process enters a waiting state. Sometimes, a waiting process is never again able to change state, because the resources it has requested are held by other waiting processes. This situation is called a **Deadlock.**

SYSTEM MODEL

- A system consists of a finite number of resources to be distributed among a number of competing processes. The resources are partitioned into several types, each consisting of some number of identical instances. Memory space, CPU cycles, files, and I/0 devices are examples of resource types.
- A process must request a resource before using it and must release the resource after using it. A process may request as many resources as it requires carrying out its designated task. The number of resources requested may not exceed the total number of resources available in the system.

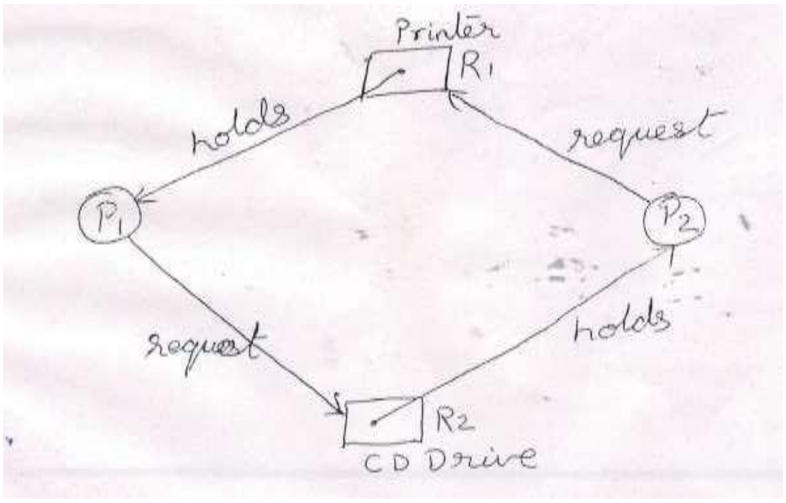
Under the normal mode of operation, a process may utilize a resource in only the following sequence:

1. **Request:** The process requests the resource. If the request cannot be granted immediately, then the requesting process must wait until it can acquire the resource.
2. **Use:** The process can operate on the resource.
3. **Release:** The process releases the resource.

A set of processes is in a deadlocked state when every process in the set is waiting for an event that can be caused only by another process in the set. The events with which we are mainly concerned here are resource acquisition and release. The resources may be either physical resources or logical resources

To illustrate a deadlocked state, consider a system with three CD RW drives.
Suppose each of three processes holds one of these CD RW drives. If each process now requests another drive, the three processes will be in a deadlocked state.
Each is waiting for the event "CD RW is released," which can be caused only by one of the other waiting processes. This example illustrates a deadlock involving the same resource type.

Deadlocks may also involve different resource types. For example, consider a system with one printer and one DVD drive. Suppose that process Pi is holding the DVD and process P_j is holding the printer. If P_i requests the printer and P_j requests the DVD drive, a deadlock occurs.



DEADLOCK CHARACTERIZATION

Necessary Conditions

A deadlock situation can arise if the following four conditions hold simultaneously in a system:

1. **Mutual exclusion:** At least one resource must be held in a non-sharable mode, that is, only one process at a time can use the resource. If another process requests that resource, the requesting process must be delayed until the resource has been released.

2. **Hold and wait:** A process must be holding at least one resource and waiting to acquire additional resources that are currently being held by other processes.

3. **No preemption:** Resources cannot be preempted; that is, a resource can be released only voluntarily by the process holding it, after that process has completed its task.

4. **Circular wait:** A set {P_0, P_l, ... , P_n} of waiting processes must exist such that P_o is waiting for a resource held by P_1, P_1 is waiting for a resource held by P_2, ... , P_{n-1} is waiting for a resource held by P_n and P_n is waiting for a resource held by P_o.

Resource-Allocation Graph

Deadlocks can be described in terms of a directed graph called **System Resource-Allocation Graph**

The graph consists of a set of vertices V and a set of edges E. The set of vertices V is partitioned into two different types of nodes:

- P = {P_1, P_2, ...,P_n}, the set consisting of all the active processes in the system.
- R = {R_1, R_2, ..., R_m} the set consisting of all resource types in the system.

A directed edge from process P_i to resource type R_j is denoted by $P_i \rightarrow R_j$ it signifies that process

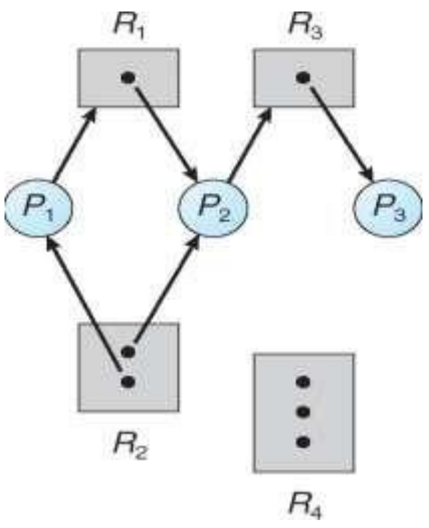
P_i has requested an instance of resource type R_j and is currently waiting for that resource.
A directed edge from resource type R_j to process P_i is denoted by $R_j \rightarrow P_i$ it signifies that an instance of resource type R_j has been allocated to process P_i.

- A directed edge $P_i \rightarrow R_j$ is called a Request Edge.
- A directed edge $R_j \rightarrow P_i$ is called an Assignment Edge.

Pictorially each process P_i as a circle and each resource type R_j as a rectangle. Since resource type R_j may have more than one instance, each instance is represented as a dot within the rectangle. A request edge points to only the rectangle R_j, whereas an assignment edge must also designate one of the dots in the rectangle.

When process P_i requests an instance of resource type R_j, a request edge is inserted in the resource-allocation graph. When this request can be fulfilled, the request edge is *instantaneously* transformed to an assignment edge. When the process no longer needs access to the resource, it releases the resource; as a result, the assignment edge is deleted.

The resource-allocation graph shown in Figure depicts the following situation.



The sets P, K and E:

- $P = \{P_1, P_2, P_3\}$
- $R= \{R_1, R_2, R_3, R_4\}$
- $E = \{P_l \rightarrow R_l, P_2 \rightarrow R_3, R_l \rightarrow P_2, R_2 \rightarrow P_2, R_2 \rightarrow P_1, R_3 \rightarrow P_3 \}$

Resource instances:

- One instance of resource type R_1
- Two instances of resource type R_2
- One instance of resource type R_3
- Three instances of resource type R_4

Process states:

- Process P_1 is holding an instance of resource type R_2 and is waiting for an instance of resource type R_1.
- Process P_2 is holding an instance of R_1 and an instance of R_2 and is waiting for an

instance of R_3.
- Process P_3 is holding an instance of R_3

<u>If the graph does contain a cycle, then a deadlock may exist.</u>

- If each resource type has exactly **<u>one instance</u>**, then a cycle implies that a deadlock has occurred. If the cycle involves only a set of resource types, each of which has only a single instance, then a deadlock has occurred. Each process involved in the cycle is deadlocked.
- If each resource type has **<u>several instances</u>**, then a cycle does not necessarily imply that a deadlock has occurred. In this case, a cycle in the graph is a necessary but not a sufficient condition for the existence of deadlock.

To illustrate this concept, the resource-allocation graph depicted in below figure:
Suppose that process P3 requests an instance of resource type R2. Since no resource instance is currently available, a request edge P3 → R2 is added to the graph. At this point, two minimal cycles exist in the system:

1. P1 →R1 → P2 → R3 → P3 → R2→P1
2. P2 →R3 → P3 → R2 → P2

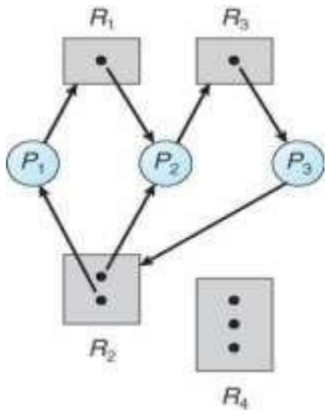


Figure: Resource-allocation graph with a deadlock.

Processes P1, P2, and P3 are deadlocked. Process P2 is waiting for the resource R3, which is held by process P3. Process P3 is waiting for either process P1 or process P2 to release resourceR2. In addition, process P1 is waiting for process P2 to release resource R1.

Consider the resource-allocation graph in below Figure. In this example also have a cycle:
P1→R1→P3→R2→P1

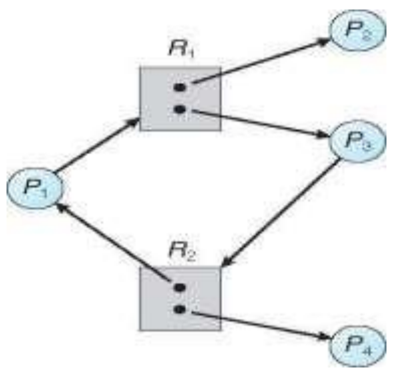


Figure: Resource-allocation graph with a cycle but no deadlock

However, there is no deadlock. Observe that process P4 may release its instance of resource type R2. That resource can then be allocated to P3, breaking the cycle.

METHODS FOR HANDLING DEADLOCKS

The deadlock problem can be handled in one of three ways:

1. Use a protocol to prevent or avoid deadlocks, ensuring that the system will never enter a deadlocked state.
2. Allow the system to enter a deadlocked state, detect it, and recover.
3. Ignore the problem altogether and pretend that deadlocks never occur in the system.

To ensure that deadlocks never occur, the system can use either deadlock prevention or a deadlock-avoidance scheme.

Deadlock prevention provides a set of methods for ensuring that at least one of the necessary conditions cannot hold. These methods prevent deadlocks by constraining how requests for resources can be made.

Deadlock-avoidance requires that the operating system be given in advance additional information concerning which resources a process will request and use during its lifetime. With this additional knowledge, it can decide for each request whether or not the process should wait. To decide whether the current request can be satisfied or must be delayed, the system must consider the resources currently available, the resources currently allocated to each process, and the future requests and releases of each process

If a system does not employ either a deadlock-prevention or a deadlock avoidance algorithm, then a deadlock situation may arise. In this environment, the system can provide an **algorithm** that examines the state of the system to determine whether a deadlock has occurred and an algorithm to recover from the deadlock.

In the absence of algorithms to detect and recover from deadlocks, then the system is in a deadlock state yet has no way of recognizing what has happened. In this case, the undetected deadlock will result in deterioration of the system's performance, because resources are being held by processes that cannot run and because more and more processes, as they make requests for resources, will enter a deadlocked state. Eventually, the system will stop functioning and will need to be restarted manually.

DEADLOACK PREVENTION

Deadlock can be prevented by ensuring that at least one of the four necessary conditions cannot hold.

Mutual Exclusion

- The mutual-exclusion condition must hold for non-sharable resources. Sharable resources, do not require mutually exclusive access and thus cannot be involved in a deadlock.
- Ex: Read-only files are example of a sharable resource. If several processes attempt to open a read-only file at the same time, they can be granted simultaneous access to the file. A process never needs to wait for a sharable resource.
- Deadlocks cannot prevent by denying the mutual-exclusion condition, because some resources are intrinsically non-sharable.

Hold and Wait

To ensure that the hold-and-wait condition never occurs in the system, then guarantee that, whenever a process requests a resource, it does not hold any other resources.

- One protocol that can be used requires each process to request and be allocated all its resources before it begins execution.
- Another protocol allows a process to request resources only when it has none. A process may request some resources and use them. Before it can request any additional resources, it must release all the resources that it is currently allocated.

Ex:

- Consider a process that copies data from a DVD drive to a file on disk, sorts the file, and then prints the results to a printer. If all resources must be requested at the beginning of the process, then the process must initially request the DVD drive, disk file, and printer. It will hold the printer for its entire execution, even though it needs the printer only at the end.
- The second method allows the process to request initially only the DVD drive and disk file. It copies from the DVD drive to the disk and then releases both the DVD drive and the disk file. The process must then again request the disk file and the printer. After copying the disk file to the printer, it releases these two resources and terminates.

The two main disadvantages of these protocols:

1. Resource utilization may be low, since resources may be allocated but unused for a long period.
2. Starvation is possible.

No Preemption

The third necessary condition for deadlocks is that there be no preemption of resources that have already been allocated.

To ensure that this condition does not hold, the following protocols can be used:

- If a process is holding some resources and requests another resource that cannot be immediately allocated to it, then all resources the process is currently holding are preempted.
- The preempted resources are added to the list of resources for which the process is waiting. The process will be restarted only when it can regain its old resources, as wellas the new ones that it is requesting.

If a process requests some resources, first check whether they are available. If they are, allocate them.
If they are not available, check whether they are allocated to some other process that is waiting for additional resources. If so, preempt the desired resources from the waiting process and allocate them to the requesting process.
If the resources are neither available nor held by a waiting process, the requesting process must wait. While it is waiting, some of its resources may be preempted, but only if another process requests them.
A process can be restarted only when it is allocated the new resources it is requesting and recovers any resources that were preempted while it was waiting.

Circular Wait

One way to ensure that this condition never holds is to impose a total ordering of all resource types and to require that each process requests resources in an increasing order of enumeration.

To illustrate, let R = {R1, R2, ... , Rm} be the set of resource types. Assign a unique integer number to each resource type, which allows to compare two resources and to determinewhether one precedes another in ordering. Formally, it defined as a one-to-one function
F: R ->N, where N is the set of natural numbers.

Example: if the set of resource types R includes tape drives, disk drives, and printers, then the function F might be defined as follows:

F (tape drive) = 1
F (disk drive) = 5
F (printer) = 12

Now consider the following protocol to prevent deadlocks. Each process can request resources only in an increasing order of enumeration. That is, a process can initially request any number of instances of a resource type -R_i. After that, the process can request instances of resource typeR_j if and only if $F(R_j) > F(R_i)$.

DEADLOCK AVOIDANCE

- To avoid deadlocks an additional information is required about how resources are to be requested. With the knowledge of the complete sequence of requests and releases for each process, the system can decide for each request whether or not the process should wait in order to avoid a possible future deadlock
- Each request requires that in making this decision the system consider the resources currently available, the resources currently allocated to each process, and the future requests and releases of each process.
- The various algorithms that use this approach differ in the amount and type of information required. The simplest model requires that each process declare the *maximum number* of resources of each type that it may need. Given this a priori information, it is possible to construct an algorithm that ensures that the system will never enter a deadlocked state. Such an algorithm defines the ***deadlock-avoidance approach.***

Safe State

- **Safe state:** A state is safe if the system can allocate resources to each process (up to its maximum) in some order and still avoid a deadlock. A system is in a safe state only if there exists a safe sequence.

- **Safe sequence:** A sequence of processes <P1, P2, ... , Pn> is a safe sequence for the current allocation state if, for each Pi, the resource requests that Pi can still make can be satisfied by the currently available resources plus the resources held by all Pj, with j <i.

In this situation, if the resources that Pi needs are not immediately available, then Pi can wait until all Pj have finished. When they have finished, Pi can obtain all of its needed resources, complete its designated task, return its allocated resources, and terminate. When Pi terminates, Pi+1 can obtain its needed resources, and so on. If no such sequence exists, then the system state is said to be unsafe.

A safe state is not a deadlocked state. Conversely, a deadlocked state is an unsafe state. Not all unsafe states are deadlocks as shown in figure. An unsafe state may lead to a deadlock. As long as the state is safe, the operating system can avoid unsafe states

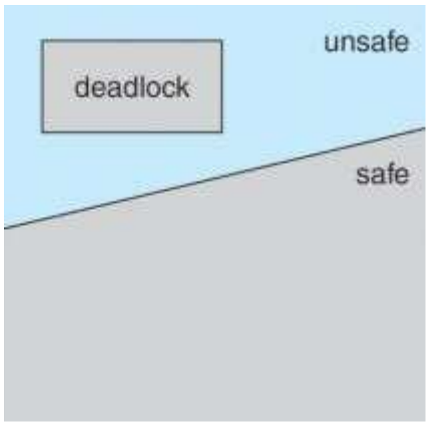


Figure: Safe, unsafe, and deadlocked state spaces.

<u>Resource-Allocation-Graph Algorithm</u>

- If a resource-allocation system has only one instance of each resource type, then a variant of the resource-allocation graph is used for deadlock avoidance.
- In addition to the request and assignment edges, a new type of edge is introduced, called a claim edge.
- A claim edge *Pi* ->*Rj* indicates that process *Pi* may request resource *Rj* at some time in the future. This edge resembles a request edge in direction but is represented in the graph by a **dashed line**.
- When process *Pi* requests resource *Rj*, the claim edge *Pi* ->*Rj* is converted to a request edge. When a resource *Rj* is released by *Pi* the assignment edge *Rj*->*Pi* is reconverted to a claim edge *Pi*->*Rj*.

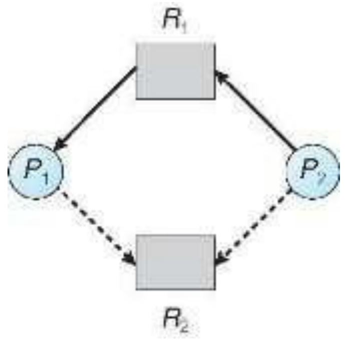


Figure: Resource-allocation graph for deadlock avoidance.

Note that the resources must be claimed a priori in the system. That is, before process *Pi* starts executing, all its claim edges must already appear in the resource-allocation graph.
We can relax this condition by allowing a claim edge *Pi* ->*Rj* to be added to the graph only if all the edges associated with process *Pi* are claim edges.

Now suppose that process *Pi* requests resource *Rj*. The request can be granted only if converting the request edge *Pi* ->*Rj* to an assignment edge *Rj*->*Pi* does not result in the formation of a cycle in the resource-allocation graph.

There is need to check for safety by using a cycle-detection algorithm. An algorithm for detecting a cycle in this graph requires an order of n^2 operations, where n is the number of processes in the system.

- If no cycle exists, then the allocation of the resource will leave the system in a safe state.
- If a cycle is found, then the allocation will put the system in an unsafe state. In that case, process Pi will have to wait for its requests to be satisfied.

To illustrate this algorithm, consider the resource-allocation graph as shown above. Suppose that P2 requests R2. Although R2 is currently free, we cannot allocate it to P2, since this action will create a cycle in the graph.
A cycle, indicates that the system is in an unsafe state. If P1 requests R2, and P2 requests R1, then a deadlock will occur.

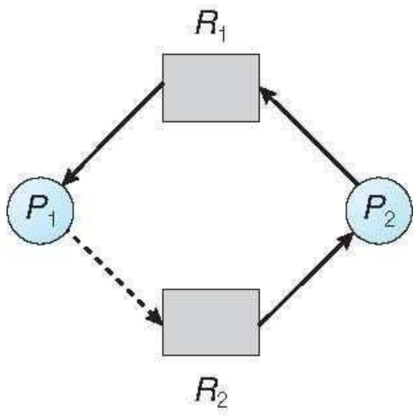


Figure: An unsafe state in a resource-allocation graph

Banker's Algorithm

The Banker's algorithm is applicable to a resource allocation system with multiple instances of each resource type.

- When a new process enters the system, it must declare the maximum number of instances of each resource type that it may need. This number may not exceed the total number of resources in the system.
- When a user requests a set of resources, the system must determine whether the allocation of these resources will leave the system in a safe state. If it will, the resources are allocated; otherwise, the process must wait until some other process releases enough resources.

To implement the banker's algorithm the following data structures are used.

Let n = number of processes, and m = number of resources types

Available: A vector of length *m* indicates the number of available resources of each type. If available [j] = k, there are k instances of resource type Rj available.

Max: An *n x m* matrix defines the maximum demand of each process. If Max [i,j] = k, then process Pi may request at most k instances of resource type Rj

Allocation: An *n x m* matrix defines the number of resources of each type currently allocated to each process. If Allocation[i,j] = k then Pi is currently allocated k instances of Rj

Need: An n x m matrix indicates the remaining resource need of each process. If Need[i,j] = k, then Pi may need k more instances of Rj to complete its task.

$$\text{Need}[i,j] = \text{Max}[i,j] - \text{Allocation}[i,j]$$

Safety Algorithm

The algorithm for finding out whether or not a system is in a safe state. This algorithm can be described as follows:

```
1. Let Work and Finish be vectors of length m and n, respectively. Initialize:
        Work = Available
        Finish [i] = false for i = 0, 1,…,n- 1

2. Find an index i such that both:
        (a) Finish[i] = false
        (b) $Need_i \leq Work$
    If no such i exists, go to step 4

3. $Work = Work + Allocation_i$
        Finish[i] = true
        go to step 2

4. If Finish [i] == true for all i, then the system is in a safe state
```

This algorithm may require an order of m x n^2 operations to determine whether a state is safe.

Resource-Request Algorithm

The algorithm for determining whether requests can be safely granted.
Let $Request_i$ be the request vector for process P_i. If $Request_i$ [j] == k, then process P_i wants k instances of resource type R_j. When a request for resources is made by process Pi, the following actions are taken:

1. If $\mathit{Request}_i \le \mathit{Need}_i$ *go* to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim

2. If $\mathit{Request}_i \le \mathit{Available}$, go to step 3. Otherwise P_i must wait, since resources are not available

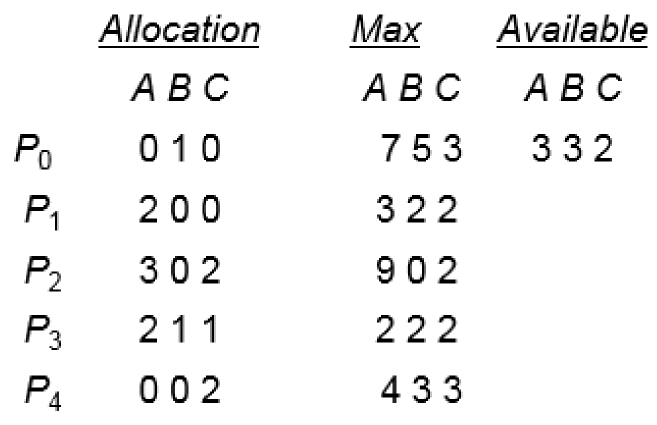
3. Have the system pretend to allocate requested resources to P_i by modifying the state as follows:

$$\mathit{Available} = \mathit{Available} - \mathit{Request};$$
$$\mathit{Allocation}_i = \mathit{Allocation}_i + \mathit{Request}_i;$$
$$\mathit{Need}_i = \mathit{Need}_i - \mathit{Request}_i;$$

If safe ⇒ the resources are allocated to Pi
If unsafe ⇒ Pi must wait, and the old resource-allocation state is restored

Example

Consider a system with five processes P_0 through P_4 and three resource types *A*, *B,* and C. Resource type *A* has ten instances, resource type *B* has five instances, and resource type C has seven instances. Suppose that, at time T_0 the following snapshot of the system has been taken:



	Allocation	Max	Available
	A B C	A B C	A B C
P_0	0 1 0	7 5 3	3 3 2
P_1	2 0 0	3 2 2	
P_2	3 0 2	9 0 2	
P_3	2 1 1	2 2 2	
P_4	0 0 2	4 3 3	

The content of the matrix *Need* is defined to be *Max* - *Allocation*

	Need
	A B C
P_0	7 4 3
P_1	1 2 2
P_2	6 0 0
P_3	0 1 1
P_4	4 3 1

The system is currently in a safe state. Indeed, the sequence <P_1, P_3, P_4, P_2, P_0> satisfies the safety criteria.

Suppose now that process P_1 requests one additional instance of resource type A and two instances of resource type C, so $\text{Request}_1 = (1,0,2)$. Decide whether this request can be immediately granted.

Check that Request ≤ Available

$(1,0,2) \leq (3,3,2) \Rightarrow$ true

Then pretend that this request has been fulfilled, and the following new state is arrived.

	Allocation	*Need*	*Available*
	A B C	*A B C*	*A B C*
P_0	0 1 0	7 4 3	2 3 0
P_1	3 0 2	0 2 0	
P_2	3 0 2	6 0 0	
P_3	2 1 1	0 1 1	
P_4	0 0 2	4 3 1	

Executing safety algorithm shows that sequence <P_1, P_3, P_4, P_0, P_2> satisfies safety requirement.

DEADLOCK DETECTION

If a system does not employ either a deadlock-prevention or a deadlock avoidance algorithm, then a deadlock situation may occur. In this environment, the system may provide:

- An algorithm that examines the state of the system to determine whether a deadlock has occurred
- An algorithm to recover from the deadlock

Single Instance of Each Resource Type

- If all resources have only a single instance, then define a deadlock detection algorithm that uses a variant of the resource-allocation graph, called a ***wait-for*** graph**.**
- This graph is obtained from the resource-allocation graph by removing the resource nodes and collapsing the appropriate edges.
- An edge from P_i to P_j in a wait-for graph implies that process P_i is waiting for process P_j to release a resource that P_i needs. An edge $P_i \rightarrow P_j$ exists in a wait-for graph if and only if the corresponding resource allocation graph contains two edges $P_i \rightarrow R_q$ and $R_q \rightarrow P_i$ for some resource R_q.

Example: In below Figure, a resource-allocation graph and the corresponding wait-for graph is presented.

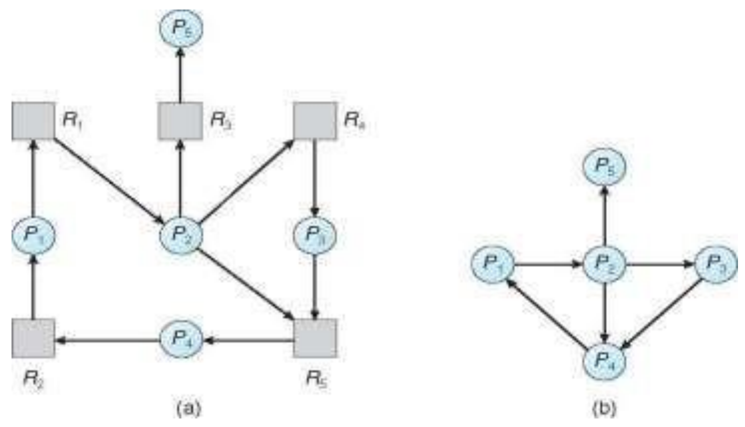


Figure: (a) Resource-allocation graph. (b) Corresponding wait-for graph.

- A deadlock exists in the system if and only if the wait-for graph contains a cycle. To detect deadlocks, the system needs to *maintain* the wait-for graph and periodically *invoke an algorithm* that searches for a cycle in the graph.
- An algorithm to detect a cycle in a graph requires an order of n^2 operations, where n is the number of vertices in the graph.

Several Instances of a Resource Type

A deadlock detection algorithm that is applicable to several instances of a resource type. The algorithm employs several time-varying data structures that are similar to those used in the banker's algorithm.

- **Available**: A vector of length *m* indicates the number of available resources of each type.
- **Allocation:** An*n x m* matrix defines the number of resources of each type currently allocated to each process.
- **Request:** An *n* x *m* matrix indicates the current request of each process. If *Request[i][j]* equals *k*, then process *P;* is requesting *k* more instances of resource type *Rj*.

Algorithm:

1. Let *Work* and *Finish* be vectors of length *m* and *n*, respectively Initialize:
    (a) Work = Available
    (b) For *i* = 1,2, …, *n*, if $Allocation_i \neq 0$, then *Finish*[i] = false;
    otherwise, *Finish*[i] = *true*

2. Find an index *i*such that both:
    (a) Finish[*i*] == *false*
    (b)$Request_i \leq Work$

    If no such *i* exists, go to step 4

3. $Work = Work + Allocation_i$
    Finish[*i*] = *true*
    go to step 2

4. If *Finish*[*i*] == false, for some *i*, $1 \leq i \leq n$, then the system is in deadlock state. Moreover, if *Finish*[*i*] == *false*, then P_i is deadlocked

Algorithm requires an order of O(*m* x $n^{2)}$ operations to detect whether the system is in deadlocked state

Example of Detection Algorithm

Consider a system with five processes *Po* through *P4* and three resource types *A*, *B*, and C. Resource type *A* has seven instances, resource type *B* has two instances, and resource type C has six instances. Suppose that, at time T_0, the following resource-allocation state:

	Allocation	Request	Available
	A B C	A B C	A B C
P_0	0 1 0	0 0 0	0 0 0
P_1	2 0 0	2 0 2	
P_2	3 0 3	0 0 0	
P_3	2 1 1	1 0 0	
P_4	0 0 2	0 0 2	

After executing the algorithm, Sequence <P_0, P_2, P_3, P_1, P_4> will result in *Finish*[*i*] = true for all *i*

Suppose now that process P2 makes one additional request for an instance of type C. The Request matrix is modified as follows:

	Request
	A B C
P_0	0 0 0
P_1	2 0 2
P_2	0 0 1
P_3	1 0 0
P_4	0 0 2

The system is now deadlocked. Although we can reclaim the resources held by process Po, the number of available resources is not sufficient to fulfill the requests of the other processes. Thus, a deadlock exists, consisting of processes P1, P2, P3, and P4.

Detection-Algorithm Usage

The detection algorithm can be invoked on two factors:

1. How *often* is a deadlock likely to occur?
2. How *many* processes will be affected by deadlock when it happens?

If deadlocks occur frequently, then the detection algorithm should be invoked frequently. Resources allocated to deadlocked processes will be idle until the deadlock can be broken.

If detection algorithm is invoked arbitrarily, there may be many cycles in the resource graph and so we would not be able to tell which of the many deadlocked processes "caused" the deadlock.

RECOVERY FROM DEADLOCK

The system recovers from the deadlock automatically. There are two options for breaking a deadlock one is simply to abort one or more processes to break the circular wait. The other is to preempt some resources from one or more of the deadlocked processes.

Process Termination

To eliminate deadlocks by aborting a process, use one of two methods. In both methods, the system reclaims all resources allocated to the terminated processes.

1. **Abort all deadlocked processes:** This method clearly will break the deadlock cycle, but at great expense; the deadlocked processes may have computed for a long time, and the results of these partial computations must be discarded and probably will have to be recomputed later.
2. **Abort one process at a time until the deadlock cycle is eliminated:** This method incurs considerable overhead, since after each process is aborted, a deadlock-detection algorithm must be invoked to determine whether any processes are still deadlocked.

If the partial termination method is used, then we must determine which deadlocked process (or processes) should be terminated. Many factors may affect which process is chosen, including:

1. What the priority of the process is
2. How long the process has computed and how much longer the process will compute before completing its designated task
3. How many and what types of resources the process has used.
4. How many more resources the process needs in order to complete
5. How many processes will need to be terminated?
6. Whether the process is interactive or batch

Resource Preemption

To eliminate deadlocks using resource preemption, we successively preempt some resources from processes and give these resources to other processes until the deadlock cycle is broken. If preemption is required to deal with deadlocks, then three issues need to be addressed:

1. **Selecting a victim.** Which resources and which processes are to be preempted? As in process termination, we must determine the order of preemption to minimize cost. Cost factors may include such parameters as the number of resources a deadlocked process is holding and the amount of time the process has thus far consumed during its execution.
2. **Rollback.** If we preempt a resource from a process, what should be done with that process? Clearly, it cannot continue with its normal execution; it is missing some neededresource. We must roll back the process to some safe state and restart it from that state. Since it is difficult to determine what a safe state is, the simplest solution is a total rollback: abort the process and then restart it.
3. **Starvation.** How do we ensure that starvation will not occur? That is, how can we guarantee that resources will not always be preempted from the same process?
   In a system where victim selection is based primarily on cost factors, it may happen that the same process is always picked as a victim. As a result, this process never completes its designated task, a starvation situation that must be dealt with in any practical system. It must ensure that a process can be picked as a victim" only a (small) finite number of times. The most common solution is to include the number of rollbacks in the cost factor.