

deadlocks

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 to carry out its designated task. Obviously, the number of resources requested may not exceed the total number of resources available in the system. In other words, a process cannot request three printers if the system has only two.

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 (for example, if the resource is being used by another process), then the requesting process must wait until it can acquire the resource.
- 2. Use.** The process can operate on the resource (for example, if the resource is a printer, the process can print on the printer).
- 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 (for example, printers, tape drives, memory space, and CPU cycles) or logical resources (for example, semaphores, mutex locks, and files). However, other types of events may result in deadlocks.

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 P_i 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

In a deadlock, processes never finish executing, and system resources are tied up, preventing other jobs from starting. Before we discuss the various methods for dealing with the deadlock problem, we look more closely at features that characterize deadlocks.

1. 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 $\{P_0, P_1, \dots, P_n\}$ of waiting processes must exist such that P_0 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_0 .

We emphasize that all four conditions must hold for a deadlock to occur. The circular-wait condition implies the hold-and-wait condition, so the four conditions are not completely independent. however, that it is useful to consider each condition separately.

2. Resource-Allocation Graph

Deadlocks can be described more precisely in terms of a directed graph called a system resource-allocation graph. This 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:

$P = \{P_1, P_2, \dots, P_n\}$, the set consisting of all the active processes in the system.

$R = \{R_1, R_2, \dots, R_m\}$, 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, we represent 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, we represent each such instance as a dot within the rectangle. Note that 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 7.1 depicts the following situation.

- The sets P, R, and E:
 - $P = \{P_1, P_2, P_3\}$

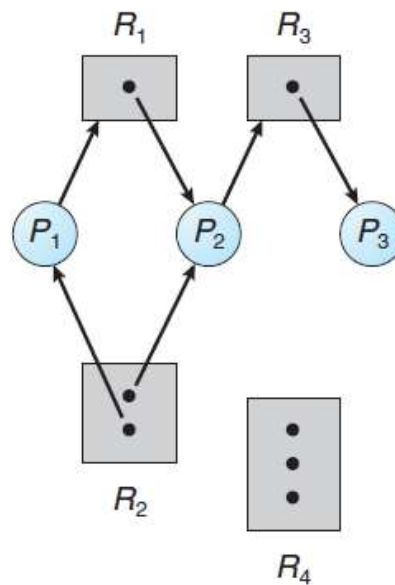


Figure 7.1 Resource-allocation graph.

- $R = \{R_1, R_2, R_3, R_4\}$
- $E = \{P_1 \rightarrow R_1, P_2 \rightarrow R_3, R_1 \rightarrow P_2, R_2 \rightarrow P_2, R_2 \rightarrow P_1, R_3 \rightarrow P_3\}$
- *Resource instances:*
 - One instance of resource type R_1

- Two instances of resource type R2
- One instance of resource type R3
- Three instances of resource type R4
- *Process states:*
 - Process P1 is holding an instance of resource type R2 and is waiting for an instance of resource type R1.
 - Process P2 is holding an instance of R1 and an instance of R2 and is waiting for an instance of R3.
 - Process P3 is holding an instance of R3.

Given the definition of a resource-allocation graph, it can be shown that, if the graph contains no cycles, then no process in the system is deadlocked. If the graph does contain a cycle, then a deadlock may exist.

If each resource type has exactly one instance, 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. In this case, a cycle in the graph is both a necessary and a sufficient condition for the existence of deadlock.

If each resource type has several instances, 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, we return to the resource-allocation graph depicted in Figure 7.1. Suppose that process P3 requests an instance of resource type R2.

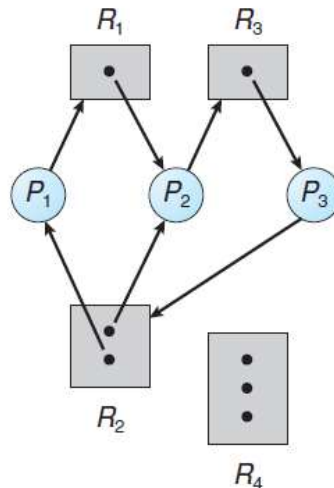


Figure 7.2 Resource-allocation graph with a deadlock.

Since no resource instance is currently available, we add a request edge

$P_3 \rightarrow R_2$ to the graph (Figure 7.2). At this point, two minimal cycles exist in the system:

$P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$

$P_2 \rightarrow R_3 \rightarrow P_3 \rightarrow R_2 \rightarrow P_2$

Processes P_1 , P_2 , and P_3 are deadlocked. Process P_2 is waiting for the resource R_3 , which is held by process P_3 . Process P_3 is waiting for either process P_1 or process P_2 to release resource R_2 . In addition, process P_1 is waiting for process P_2 to release resource R_1 .

Now consider the resource-allocation graph in Figure 7.3. In this example, we also have a cycle:

$P_1 \rightarrow R_1 \rightarrow P_3 \rightarrow R_2 \rightarrow P_1$

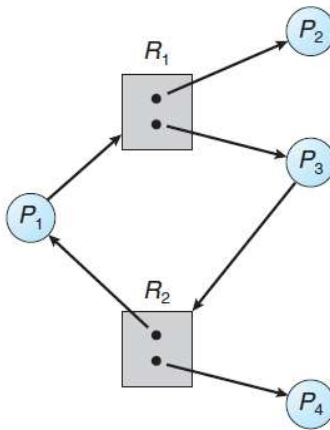


Figure 7.3 Resource-allocation graph with a cycle but no deadlock.

However, there is no deadlock. Observe that process P_4 may release its instance of resource type R_2 . That resource can then be allocated to P_3 , breaking the cycle.

In summary, if a resource-allocation graph does not have a cycle, then the system is not in a deadlocked state. If there is a cycle, then the system may or may not be in a deadlocked state. This observation is important when we deal with the deadlock problem.

Methods for Handling Deadlocks

we can deal with the deadlock problem in one of three ways:

1. We can use a protocol to prevent or avoid deadlocks, ensuring that the system will never enter a deadlocked state.
2. We can allow the system to enter a deadlocked state, detect it, and recover.
3. We can ignore the problem altogether and pretend that deadlocks never occur in the system.

The third solution is the one used by most operating systems, including Linux and Windows. It is then up to the application developer to write programs that handle deadlocks.

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

Deadlock prevention provides a set of methods to ensure 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 additional information in advance concerning which resources a process will request and use during its lifetime. With this additional knowledge, the operating system can decide for each request whether or not the process should wait.

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.

Deadlock Prevention

for a deadlock to occur, each of the four necessary conditions must hold. By ensuring that at least one of these conditions cannot hold, we can prevent the occurrence of a deadlock. We elaborate on this approach by examining each of the four necessary conditions separately.

1. Mutual Exclusion

The mutual exclusion condition must hold. That is, at least one resource must be non sharable. Sharable resources, in contrast, do not require mutually exclusive access and thus cannot be involved in a deadlock.

Read-only files are a good 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. In general, however, we cannot prevent deadlocks by denying the mutual-exclusion condition, because some resources are intrinsically nonsharable. For example, a mutex lock cannot be simultaneously shared by several processes.

2. Hold and Wait

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

One protocol that we can use requires each process to request and be allocated all its resources before it begins execution. We can implement this provision by requiring that system calls requesting resources for a process precede all other system calls.

An alternative 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.

To illustrate the difference between these two protocols, we 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 request the disk file and the printer. After copying the disk file to the printer, it releases these two resources and terminates.

Both these protocols have two main disadvantages. *First, resource utilization may be low*, since resources may be allocated but unused for a long period.

In the example given, for instance, we can release the DVD drive and disk file, and then request the disk file and printer, only if we can be sure that our data will remain on the disk file. Otherwise, we must request all resources at the beginning for both protocols.

Second, starvation is possible. A process that needs several popular resources may have to wait indefinitely, because at least one of the resources that it needs is always allocated to some other process.

3. 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, we can use the following protocol. If a process is holding some resources and requests another resource that cannot be immediately allocated to it (that is, the process must wait), then all resources the process is currently holding are preempted. In other words, these resources are implicitly released. 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 well as the new ones that it is requesting.

Alternatively, if a process requests some resources, we first check whether they are available. If they are, we allocate them. If they are not, we check whether they are allocated to some other process that is waiting for additional resources. If so, we 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.

4. 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, we let $R = \{R_1, R_2, \dots, R_m\}$ be the set of resource types. We assign to each resource type a unique integer number, which allows us to compare two resources and to determine whether one precedes another in our ordering. Formally, we define a one-to-one function

$F: R \rightarrow N$, where N is the set of natural numbers.

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

$F(\text{tape drive}) = 1$

$F(\text{disk drive}) = 5$

$F(\text{printer}) = 12$

We can 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 —say, R_i . After that, the process can request instances of resource type R_j if and only if $F(R_j) > F(R_i)$. For example, using the function defined previously, a process that wants to use the tape drive and printer at the same time must first request the tape drive and then request the printer. Alternatively, we can require that a process requesting an instance of resource type R_j must have released any resources R_i such that $F(R_i) \geq F(R_j)$. Note also that if several instances of the same resource type are needed, a single request for all of them must be issued.

If these two protocols are used, then the circular-wait condition cannot hold. We can demonstrate this fact by assuming that a circular wait exists (proof by contradiction). Let the set of processes involved in the circular wait be $\{P_0, P_1, \dots, P_n\}$, where P_i is waiting for a resource R_i , which is held by process P_{i+1} . (Modulo arithmetic is used on the indexes, so that P_n is waiting for a resource R_n held by P_0 .) Then, since process P_{i+1} is holding resource R_i while requesting resource R_{i+1} , we must have $F(R_i) < F(R_{i+1})$ for all i . But this condition means that $F(R_0) < F(R_1) < \dots < F(R_n)$

$< F(R_0)$. By transitivity, $F(R_0) < F(R_0)$, which is impossible. Therefore, there can be no circular wait.

Deadlock Avoidance

Deadlock-prevention algorithms, prevent deadlocks by limiting how requests can be made. The limits ensure that at least one of the necessary conditions for deadlock cannot occur. Possible side effects of preventing deadlocks by this method, however, are low device utilization and reduced system throughput.

An alternative method for avoiding deadlocks is to require additional information about how resources are to be requested. For example, in a system with one tape drive and one printer, the system might need to know that process P will request first the tape drive and then the printer before releasing both resources, whereas process Q will request first the printer and then the tape drive. With this 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 and most useful 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. A deadlock-avoidance algorithm dynamically examines the resource-allocation state to ensure that a circular-wait condition can never exist. The resource allocation state is defined by the number of available and allocated resources and the maximum demands of the processes. In the following sections, we explore two deadlock-avoidance algorithms.

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. More formally, a system is in a safe state only if there exists a safe sequence. A sequence of processes $\langle P_1, P_2, \dots, P_n \rangle$ is a safe sequence for the current allocation state if, for each P_i , the resource requests that P_i can still make can be satisfied by the currently available resources plus the resources held by all P_j , with $j < i$. In this situation, if the resources that P_i needs are not immediately available, then P_i can wait until all P_j have finished. When they have finished, P_i can obtain all of its needed resources, complete its designated task, return its allocated resources, and terminate. When P_i terminates, P_{i+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, however (Figure 7.6).

An unsafe state may lead to a deadlock. As long as the state is safe, the operating system can avoid unsafe (and deadlocked) states. In an unsafe state, the operating system cannot prevent processes from requesting resources in such a way that a deadlock occurs. The behavior of the processes controls unsafe states.

To illustrate, we consider a system with twelve magnetic tape drives and three processes: P0, P1, and P2. Process P0 requires ten tape drives, process P1 may need as many as four tape drives, and process P2 may need up to nine tape drives. Suppose that, at time t_0 , process P0 is holding five tape drives, process P1 is holding two tape drives, and process P2 is holding two tape drives. (Thus, there are three free tape drives.)

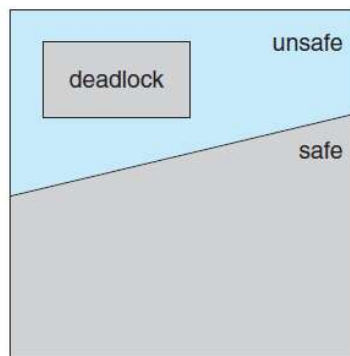


Figure 7.6 Safe, unsafe, and deadlocked state spaces.

	Maximum Needs	Current Needs
P0	10	5
P1	4	2
P2	9	2

At time t_0 , the system is in a safe state. The sequence $\langle P1, P0, P2 \rangle$ satisfies the safety condition. Process P1 can immediately be allocated all its tape drives and then return them (the system will then have five available tape drives); then process P0 can get all its tape drives and return them (the system will then have ten available tape drives); and finally process P2 can get all its tape drives and return them (the system will then have all twelve tape drives available).

A system can go from a safe state to an unsafe state. Suppose that, at time t_1 , process P2 requests and is allocated one more tape drive. The system is no longer in a safe state. At this point, only process P1 can be allocated all its tape drives. When it returns them, the system will have only four available tape drives. Since process P0

is allocated five tape drives but has a maximum of ten, it may request five more tape drives. If it does so, it will have to wait, because they are unavailable. Similarly, process P2 may request six additional tape drives and have to wait, resulting in a deadlock. Our mistake was in granting the request from process P2 for one more tape drive. If we had made P2 wait until either of the other processes had finished and released its resources, then we could have avoided the deadlock.

Given the concept of a safe state, we can define avoidance algorithms that ensure that the system will never deadlock. The idea is simply to ensure that the system will always remain in a safe state. Initially, the system is in a safe state.

Whenever a process requests a resource that is currently available, the system must decide whether the resource can be allocated immediately or whether the process must wait. The request is granted only if the allocation leaves the system in a safe state.

In this scheme, if a process requests a resource that is currently available, it may still have to wait. Thus, resource utilization may be lower than it would otherwise be.

Resource-Allocation-Graph Algorithm

If we have a resource-allocation system with only one instance of each resource type, we can use a variant of the resource-allocation graph defined in Section 7.2.2 for deadlock avoidance. In addition to the request and assignment edges already described, we introduce a new type of edge, called a claim edge.

A claim edge $P_i \rightarrow R_j$ indicates that process P_i may request resource R_j 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 P_i requests resource R_j , the claim edge $P_i \rightarrow R_j$ is converted to a request edge. Similarly, when a resource R_j is released by P_i , the assignment edge $R_j \rightarrow P_i$ is reconverted to a claim edge $P_i \rightarrow R_j$.

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

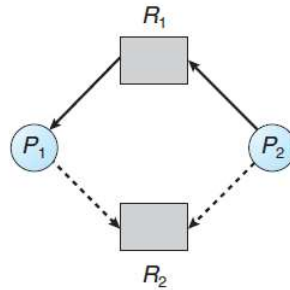


Figure 7.7 Resource-allocation graph for deadlock avoidance.

Now suppose that process P_i requests resource R_j . The request can be granted only if converting the request edge $P_i \rightarrow R_j$ to an assignment edge $R_j \rightarrow P_i$ does not result in the formation of a cycle in the resource-allocation graph. We 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 P_i will have to wait for its requests to be satisfied.

To illustrate this algorithm, we consider the resource-allocation graph of Figure 7.7. Suppose that P_2 requests R_2 . Although R_2 is currently free, we cannot allocate it to P_2 , since this action will create a cycle in the graph (Figure 7.8). A cycle, as mentioned, indicates that the system is in an unsafe state. If P_1 requests R_2 , and P_2 requests R_1 , then a deadlock will occur.