deadlocks

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Chapter8

Chapter 8: Deadlocks

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- Deadlock Examples
- Deadlock Characterization
- Resource Allocation Graph
- Methods for Handling Deadlocks
  - Deadlock Prevention
  - Deadlock Avoidance
  - Deadlock Detection and Recovery from Deadlock

Chapter Objectives

- Illustrate how deadlock can occur when mutex locks are used.
- Define the *four necessary conditions* that characterize deadlock.
- Identify a deadlock situation in a resource allocation graph.
- Evaluate the four different approaches for preventing deadlocks.
- Apply banker's algorithm for deadlock avoidance.
- Apply the deadlock detection algorithm.
- Evaluate approaches for recovering from deadlock.

Example:

Deadlock in Multithreaded Application

T1

```
/* thread one runs in this function */
void *do_work_one(void *param)
{
   pthread_mutex_lock(&first_mutex);
   pthread_mutex_lock(&second_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&second_mutex);
   pthread_mutex_unlock(&first_mutex);

   pthread_exit(0);
}
```

T2

```
/* thread two runs in this function */
void *do_work_two(void *param)
{
   pthread_mutex_lock(&second_mutex);
   pthread_mutex_lock(&first_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&first_mutex);
   pthread_mutex_unlock(&second_mutex);

   pthread_exit(0);
}
```

- The order in which the threads run depends on how they are scheduled by the CPU scheduler
- This example illustrates the fact that it is difficult to identify and test for deadlocks that may occur only under certain scheduling circumstances.

Deadlock Example with Lock Ordering

```
void transaction(Account from, Account to, double amount)
{
   mutex lock1, lock2;
   lock1 = get_lock(from);
   lock2 = get_lock(to);
   acquire(lock1);
      acquire(lock2);
         withdraw(from, amount);
         deposit(to, amount);
      release(lock2);
   release(lock1);
}
```

← may be many threads running same fn, which can cause a deadlock

Transactions 1 and 2 execute concurrently. Transaction 1 transfers $25 from account A to account B, and Transaction 2 transfers $50 from account B to account A

System Model

- System consists of resources
- Resource types $R_1, R_2, \ldots, R_m$
  CPU cycles, memory space, files, I/O devices, semaphores
- Each resource type R_i has W_i instances.
- Each process P_i utilizes a resource as follows:
  - **request**
  - **use** ← resources assiged to P_i
  - **release**

Deadlock Characterization

Deadlock involving multiple processes can arise if the following **four** conditions hold **simultaneously** – they are **necessary** but **not sufficient** conditions

- **Mutual exclusion:** only one process at a time can use a resource
- **Hold and wait:** a process holding at least one resource is waiting to acquire additional resource(s) held by other processes
- **No preemption:** a resource can be released only voluntarily by the process holding it, after that process has completed its task
- **Circular wait:** there exists a set $\{P_0, P_1, \ldots, P_n\}$ of waiting processes such that P_0 is waiting for a resource that is held by P_1, P_1 is waiting for a resource that is held by P_2, …, P_{n-1} is waiting for a resource that is held by P_n, and P_n is waiting for a resource that is held by P_0.

Resource-Allocation Graph

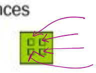
A set of vertices V and a set of edges E.

- V is partitioned into two types:
  - $P = \{P_1, P_2, \ldots, P_n\}$, the set consisting of all the processes in the system
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system
- **request edge** – directed edge $P_i \rightarrow R_j$
- **assignment edge** – directed edge $R_j \rightarrow P_i$

Resource-Allocation Graph (Cont.)

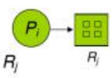
- Process

- Resource Type with 4 instances

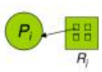


4 instances

- P_i requests instance of R_j

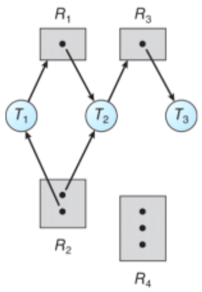


- P_i is holding an instance of R_j

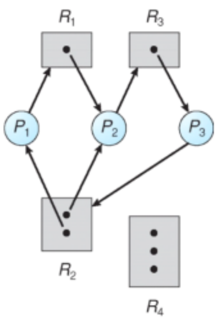


Resource Allocation Graph Example

- One instance of R1
- Two instances of R2
- One instance of R3
- Three instance of R4
- T1 holds one instance of R2 and is waiting for an instance of R1
- T2 holds one instance of R1, one instance of R2, and is waiting for an instance of R3
- T3 is holds one instance of R3



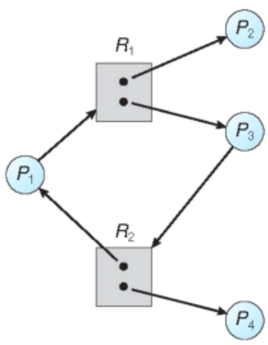
Resource Allocation Graph With A Deadlock



Cycles exist

- P1 → R1 → P2 → R3 → P3 → R2 → P1
- P2 → R3 → P3 → R2 → P2
- Processes P1, P2, and P3 are deadlocked

Graph With A Cycle But No Deadlock



A cycle exists

- P1 → R1 → P3 → R2 → P1
- However, there is no deadlock. Observe that thread P4 may release its instance of resource type R2. That resource can then be allocated to P3, breaking the cycle.

wait for P2 & P4 to finish

Basic Facts

- If a graph contains no cycles ⇒ no deadlock
- If a graph contains a cycle ⇒ the system may or may not be in a deadlocked state
  - if only one instance per resource type, then deadlock
  - if several instances per resource type, possibility of deadlock

Methods for Handling Deadlocks

← usually expensive so sometimes they don't implement & rely on user to fix problem ie restart machine. Sometimes this can't be done ↗

- Ensure that the system will ***never*** enter a deadlock state:
  - **Deadlock prevention**: it provides a set of methods to ensure at least one of the necessary conditions cannot hold
  - **Deadlock avoidance**: this requires additional information given in advance concerning which resources a process will request and use during its lifetime. Within such knowledge, the OS can decide for each resource request whether or not a process should wait
- **Deadlock detection** - allow the system to enter a deadlock state, periodically detect if there is a deadlock and then recover from it
- Many commercial operating systems, esp., for desktops, laptops, and smart phones ignore the deadlock problem because of the overhead and pretend that deadlocks never occur in the system
  - It will cause the system's performance to deteriorate, 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 – restart the system manually

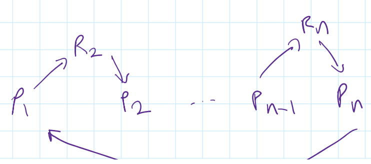
Deadlock Prevention

Restrain the ways request can be made

- **Mutual Exclusion** – not required for sharable resources (e.g., read-only files); but it must hold for non-sharable resources
- **Hold and Wait** – must guarantee that whenever a process requests a resource, it does not hold any other resources
  - Require each process to request and be allocated all its resources before it begins execution, or request resources only when the process has none
  - The **disadvantages** - low resource utilization, and possible starvation ← resources are allocated in an all or nothing manner
- **No Preemption** – ← could lead to starvation.
  - If a process that is holding some resources requests another that cannot be immediately allocated to it, then all resources currently being held are released
  - Preempted resources added to list of resources for which the process is waiting
  - Process will be restarted only when it can regain its old resources, as well as the new ones that it is requesting
  - This can only be applied to resources whose state can be easily saved and restored such as registers, memory space and database transactions. It cannot generally be applied to resources such as locks and semaphores

Deadlock Prevention (Cont.)

- **Circular Wait** – impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration – R = {$<R_1, R_2, \ldots, R_m>$}
  - This requires that a process cannot request a resource R_j before requesting a resource R_i if j > i
- This can be proved by contradiction
  - Let the set of processes involved in a circular wait be P = {$<P_0, P_1, \ldots, P_n>$}, where P_i is waiting for a resource R_i, which is held by process P_{i+1}, so that P_n is waiting for a resource R_n held by P_0.
  - Since process P_{i+1} is holding resource R_i while requesting resource R_{i+1}, we must have $R_i < R_{i+1}$ for all *i*.
  - This implies $R_0 < R_1 < R_2 \ldots < R_n < R_0$
  - $R_0 < R_0$, this is impossible, therefore there can be no circular wait



- This implies $R_0 < R_1 < R_2 \ldots < R_n < R_0$
- $R_0 < R_0$, this is impossible, therefore there can be no circular wait

$P_1 \quad P_2 \quad \ldots \quad P_{n-1} \quad P_n$

R_{11}

$R_1 < R_2 < R_3 \cdots < R_n < R_1$

Circular Wait

- Invalidating the circular wait condition is most common.
- Simply assign each resource (i.e. mutex locks) a unique number.
- Resources must be acquired in order.
- If:

first_mutex = 1
second_mutex = 5

code for **thread_two** could not be written as follows:

```
/* thread_one runs in this function */
void *do_work_one(void *param)
{
   pthread_mutex_lock(&first_mutex);
   pthread_mutex_lock(&second_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&second_mutex);
   pthread_mutex_unlock(&first_mutex);

   pthread_exit(0);
}

/* thread_two runs in this function */
void *do_work_two(void *param)
{
   pthread_mutex_lock(&second_mutex);
   pthread_mutex_lock(&first_mutex);
   /**
    * Do some work
    */
   pthread_mutex_unlock(&first_mutex);
   pthread_mutex_unlock(&second_mutex);

   pthread_exit(0);
}
```

← not allowed

Deadlock Avoidance

Requires that the system has some additional **a priori** information available

- For instance, with the knowledge of complete sequence of request and release for each process, system can decide for each request whether the process should wait to avoid a possible future deadlock.

- The simplest and most useful model requires that each process declares the ***maximum number*** of resources of each type that it may need
- The **deadlock-avoidance** algorithm dynamically examines the resource-allocation state to ensure that a circular-wait condition can never exist
- **Resource-allocation state** is defined by the number of (1) available and (2) allocated resources, and (3) the maximum demands of the processes

Safe State

- When a process requests an available resource, system must decide whether such an allocation will leave the system in a **safe state**
- System is in safe state if there exists a sequence $<P_1, P_2, \ldots, P_n>$ consisting of **all processes** in the systems such that for each P_i, the resources that P_i can still request (based on prior declaration) can be satisfied by currently available resources plus resources held by **all** P_j, with $j < i$. That is:
  - If P_i resource needs are not immediately available, then P_i can wait until all P_j have finished
  - When P_j is finished, P_i can obtain needed resources, execute, return 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**.

$P_i \rightarrow \begin{cases} a_i \leftarrow \text{current} \\ D_i \leftarrow \text{remaining} \end{cases}$

Max # of resources = $\boxed{D_i - a_i}$

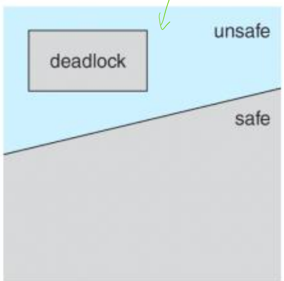
$\sum_{i=1} a_i + A \geq D_i - a_i$ For all P_i → then all processes can finish
→ safe state

A ↓ current Available resources in system

Basic Facts

- If a system is in safe state $\Rightarrow$ no deadlocks
- If a system is in unsafe state $\Rightarrow$ possibility of deadlock
- **Avoidance** $\Rightarrow$ ensure that a system will never enter an unsafe state
  - In this scheme, if a process requests a resource that is currently available, it may still have to wait (if the allocation leads to unsafe state).
  - The resource utilization may be lower than it would be otherwise

deadlock may occur



Avoidance algorithms

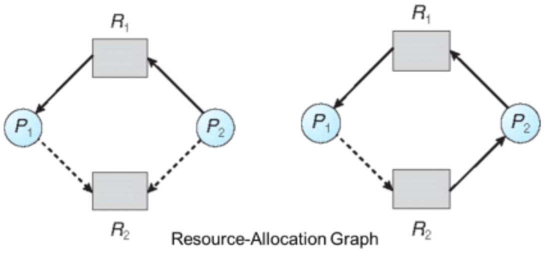
- Single instance of a resource type
  - Use a resource-allocation graph
- Multiple instances of a resource type
  - Use the banker's algorithm

Resource-Allocation Graph Scheme

- **Claim edge** $P_i \rightarrow R_j$ indicates that process P_i may request resource R_j; represented by a dashed line
- Claim edge converts to request edge when a process requests a resource
- Request edge converts to an assignment edge when the resource is allocated to the process
- When a resource is released by a process, assignment edge reconverts to claim edge
- Resources must be claimed a priori in the system

Resource-Allocation Graph Algorithm

- Suppose that process P_i requests a resource R_j
- The request can be granted only if converting the request edge to an assignment edge does not result in the formation of a cycle in the resource allocation graph



Resource-Allocation Graph

Banker's Algorithm

- Multiple instances
- Each process must declare a priori maximum usage
- When a process requests a resource, it may have to wait – check to see if this allocation results in a safe state or not
- When a process gets all its resources it must return them in a finite amount of time after use
- This is analogous to banking loan system, which has a maximum amount, total, that can be loaned at one time to a set of businesses each with a credit line.

Data Structures for the Banker's Algorithm

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

- **Available**: Vector of length m. If available $[j] = k$, there are k instances of resource type R_j available
- **Max**: $n \times m$ matrix. If $Max[i,j] = k$, then process P_i may request at most k instances of resource type R_j
- **Allocation**: $n \times m$ matrix. If Allocation$[i,j] = k$ then P_i is currently allocated k instances of R_j
- **Need**: $n \times m$ matrix. If $Need[i,j] = k$, then P_i may need k more instances of R_j to complete its task

$$Need[i,j] = Max[i,j] - Allocation[i,j]$$

Safety Algorithm

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 ***i*** such that both:

   (a) ***Finish*** **[*i*] = *false***

   (b) $\boldsymbol{Need_i \le Work}$

   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, otherwise unsafe

Resource-Request Algorithm for Process P_i

Request = request vector for process P_i. If $Request_i[j] = k$ then process P_i wants ***k*** instances of resource type R_j

1. If $Request_i \le Need_i$ go to step 2. Otherwise, raise error condition, since process has exceeded its maximum claim
2. If $Request_i \le Available$, go to step 3. Otherwise, P_i must wait, since resources are not available
3. Pretend to have allocated requested resources to P_i by modifying the state as follows:

   Available = Available – Request;

   Allocation$_i$ = Allocation$_i$ + Request$_i$;

   Need$_i$ = Need$_i$ – Request$_i$;

   - Run safety algorithm: If safe ⇒ the resources can be allocated to P_i
   - If unsafe ⇒ P_i must wait, and the old resource-allocation state is restored

Example of Banker's Algorithm

- 5 processes P_0 through P_4;

  3 resource types:

  A (10 instances), *B* (5 instances), and *C* (7 instances)

Snapshot at time T_0:

	Allocation	*Max*	*Available*	Need
	A B C	*A B C*	*A B C*	
P_0	0 1 0	7 5 3	3 3 2	7 4 3
P_1	2 0 0	3 2 2		1 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		

Need = Max - Alloc

P_0 need $\overset{A\,B\,C}{743} > \overset{A\,B\,C}{332}$ ∴ can't run

Example (Cont.)

- 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 in a safe state since the sequence < P_1, P_3, P_4, P_2, P_0> satisfies the safety criteria

Example (Cont.)

- 5 processes P_0 through P_4; 3 resource types:
  A (10 instances), *B* (5 instances), and *C* (7 instances)

Snapshot at time T_0:

	Allocation	*Max*	*Available*	*Need*
	A B C	*A B C*	*A B C*	*A B C*
P_0	0 1 0	7 5 3	3 3 2	7 4 3
✓ P_1	~~2 0 0~~ 3 0 0	3 2 2	5 3 2	1 2 2
P_2	3 0 2	9 0 2		6 0 0
✓ P_3	~~2 1 1~~	2 2 2	7 4 3	0 1 1
P_4	0 0 2	4 3 3		4 3 1

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

this order don't matter

Example: P_1 Request (1,0,2)

- Check that Request ≤ Available, that is, (1,0,2) ≤ (3,3,2) ⇒ true

	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	

1. 020 ≤ 230
2. 230 − 020
   = 210
3. P_0 010 + 020
   = 030

210 can't service any "need"

- Executing safety algorithm shows that sequence < P_1, P_3, P_4, P_0, P_2> satisfies safety requirement
- Can request for (3,3,0) by $\boldsymbol{P_4}$ be granted? – resource not available
- Can request for (0,2,0) by $\boldsymbol{P_0}$ be granted? – state is not safe

Deadlock Detection

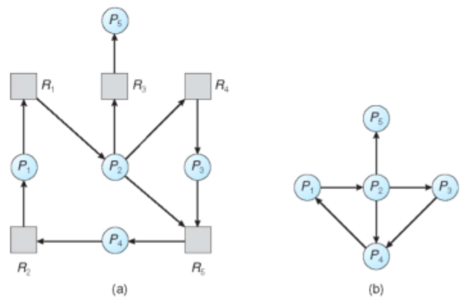
If a system does not use either a deadlock-prevention, or deadlock-avoidance algorithm, then a deadlock situation may occur. In this environment, the system may provide

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

Single Instance of Each Resource Type

- Maintain **wait-for** graph
  - Nodes are processes
  - $P_i \rightarrow P_j$ if P_i is waiting for P_j
- Periodically invoke an algorithm that searches for a cycle in the graph. If there is a cycle, there exists a deadlock
- 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
- The wait-for graph scheme is not applicable to a resource-allocation system with multiple instances for each resource type

Resource-Allocation Graph and Wait-for Graph



Resource-Allocation Graph   Corresponding Wait-for Graph

Several Instances for a Resource Type

- **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*] = *k***, then process P_i is requesting ***k*** instances of resource type R_j.

Detection 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 $\textbf{\textit{Allocation}}_i \neq 0$, then ***Finish*[i] = *false***; otherwise, ***Finish*[i] = *true***
2. Find an index ***i*** such that both:
   (a) ***Finish*[*i*] == *false***
   (b) $\textbf{\textit{Request}}_i \leq \textbf{\textit{Work}}$
   If no such ***i*** exists, go to step 4
3. $\textbf{\textit{Work}} = \textbf{\textit{Work}} + \textbf{\textit{Allocation}}_i$
   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

This algorithm requires an order of O(*m* x *n*²) operations to detect whether the system is in deadlocked state

Example of Detection Algorithm

- Five processes P_0 through P_4; three resource types A (7 instances), *B* (2 instances), and *C* (6 instances)
- Snapshot at time T_0:

	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	

1. P_0 (R) < A
2. A = 000 + 010 = 010
3. P_2 (R) < A
4. A = 010 + 303

⋮

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

Example (Cont.)

- P_2 requests an additional instance of type *C*

	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

- State of system?
  - Can reclaim resources held by process P_0, but insufficient resources to fulfill other processes; requests
  - Deadlock exists, consisting of processes P_1, P_2, P_3, and P_4

Detection-Algorithm Usage

- When, and how often, to invoke depends on:
  - How often a deadlock is likely to occur?
  - How many processes will be affected by a deadlock when it occurs
    - one for each disjoint cycle
- If detection algorithm is invoked arbitrarily, there may be many cycles in the resource graph; we would not be able to tell which of the many deadlocked processes "caused" the deadlock.
- Invoking the deadlock detection algorithm for every resource request will incur considerable overhead in computation.
  - A less expensive alternative is to invoke the algorithm at defined intervals – for example, once per hour, or whenever CPU utilization drops below 40%

Recovery from Deadlock: Process Termination

- Abort all deadlocked processes: This clearly breaks the deadlock cycle, but at great expense
- Abort one process at a time until the deadlock cycle is eliminated: This incurs considerable overhead, since after each process is aborted, the deadlock-detection algorithm needs to run
- In which order should we choose to abort? – many factors:
  1. Priority of the process
  2. How long process has computed, and how much longer to complete?
  3. Resources the process has used
  4. Resources the process needs to complete
  5. How many processes will need to be terminated?
  6. Is process interactive or batch?

Recovery from Deadlock: Resource Preemption

To successively preempt some resources from processes and give these resources to other processes until the deadlock cycle is broken

- Selecting a victim – minimize cost (which resources and which processes are to be preempted)
- Rollback – return to some safe state, restart process from that state
- Starvation – the same process may always be picked as victim, including the number of rollback in cost factor might help to reduce the starvation

End of Chapter 8