東南大學
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OPERATING SYSTEM CONCEPTS

Chapter 7. Deadlocks

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Warm-up

Bugs in Modern Applications

Application	What is does	Non-Deadlock	Deadlock
MySQL	Database Server	14	9
Apache	Web Server	13	4
Mozilla	Web Browser	41	16
OpenOffice	Office Suite	6	2
Total		74	31

[1] han Lu, Soyeon Park, Eunsoo Seo, Yuanyuan Zhou, “Learning from Mistakes — A Comprehensive Study on Real World Concurrency Bug Characteristics”, ASPLOS’08, March 2008, Seattle, Washington

Warm-up

Non-deadlock Bugs

- A large fraction (97%) of non-deadlock bugs are either atomicity violation or order violation.

- Atomicity violation bugs

```c
/* Thread 1 */
if (thd->proc_info) {
 ...
 fputs(thd->proc_info, ...);
 ...
}
```

```c
/* Thread 2 */
thd->proc_info = NULL;



//
```

- Order violation Bugs

```c
/* Thread 1 */
void init() {
 ...
 mThread = PR_CreateThread(mMain,
        ...);
 ...
}
```

```c
/* Thread 2 */
void mMain(...) {
 ...
 mState = mThread->State;
 ...
}
//
```

Warm-up

Deadlock Bugs

- Why Do Deadlocks Occur?
  - Complex dependencies arise between components in large code bases.
    - The virtual memory system might need to access the file system in order to page in a block from disk; the file system might subsequently require a page of memory to read the block into and thus contact the virtual memory system.
  - The nature of encapsulation — Modularity does not mesh well with locking.
    - The Java Vector class and the method *AddAll*(). The routine acquires two locks in some arbitrary order. If some other thread calls *v2.AddAll*(*v1*), a deadlock can happen.

```
Vector v1, v2;
v1.AddAll(v2);
```

Objectives

- To develop a description of deadlocks, which prevent sets of concurrent processes from completing their tasks
- To present a number of different methods for preventing or avoiding deadlocks in a computer system

Contents

1. System Model
2. Deadlock Characterization
3. Methods for Handling Deadlocks
4. Deadlock Prevention
5. Deadlock Avoidance
6. Deadlock Detection
7. Recovery from Deadlock

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System Model

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

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Deadlock Characterization

- Deadlock **can** arise if four conditions hold simultaneously.
  - **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 resources 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 $\{P_0, P_1, \cdots, P_n\}$ 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 $P_2, \cdots, P_{n-1}$ 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.
- Necessary, but NOT sufficient condition(s).

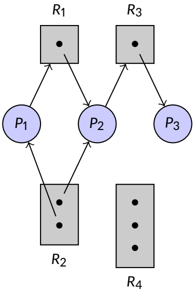
Deadlock Characterization

Resource Allocation Graph

- How to describe a deadlock?
- A resource-allocation graph, which contains a set of vertices V and a set of edges E.
  - Two types of V
    - Processes — $P = \{P_1, P_2, \cdots, P_n\}$
    - Resources — $R = \{R_1, R_2, \cdots, R_m\}$
  - Two types of E
    - Request edge — directed edge $P_i \longrightarrow R_j$
    - Assignment edge — directed edge $R_j \longrightarrow P_i$

Deadlock Characterization

Resource Allocation Graph (contd.)



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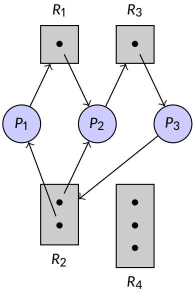

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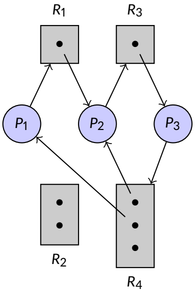

(c)

Deadlock Characterization

Resource Allocation Graph (contd.)

- Some basic facts
  - If graph contains no cycles $\Rightarrow$ no deadlock
  - If graph contains a cycle $\Rightarrow$
    - » if only one instance per resource type, then deadlock
    - » if several instances per resource type, possibility of deadlock

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Methods for Handling Deadlocks

- Ensure that the system will never enter a deadlock state
  - **Deadlock prevention** — dealing with necessary conditions
  - **Deadlock avoidance** — dealing with safe state
- Allow the system to enter a deadlock state and then recover
  - **Deadlock detection**
  - **Recovery from deadlock**
- Ignore the problem and pretend that deadlocks never occur in the system; used by most operating systems, including UNIX

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Deadlock Prevention

Circular Wait

- Impose a total ordering of all resource types, and require that each process requests resources in an increasing order of enumeration
  - total ordering
  - partial ordering
- Enforcing lock ordering by lock address

```
do_something(mutex_t *m1, mutex_t *m2) {
        ...
        if (m1 > m2) {
                pthread_mutex_lock(m1);
                pthread_mutex_lock(m2);
        }
        else {
                pthread_mutex_lock(m2);
                pthread_mutex_lock(m1);
        }
        ...
}

/* An ordering, or hierarchy, does not in itself prevent deadlock */
```

Deadlock Prevention

Hold and Wait

- Must guarantee that whenever a process requests a resource, it does not hold any other resources
  - Require process to request and be allocated all its resources before it begins execution, or allow process to request resources only when the process has none allocated to it.
  - Low resource utilization; starvation possible
- Note that the solution is problematic:
  - Encapsulation works against us
  - Decreased concurrency

Deadlock Prevention

No Preemption

- If a process that is holding some resources requests another resource that cannot be immediately allocated to it, then all resources currently being held are released. Preempted resources are added to the 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.

```
top:
        lock(L1);
        if (trylock(L2) == -1) {
                unlock(L1);
                goto top;
        }
```

- Note that the solution is problematic:
  - Encapsulation works against us
  - Livelock — It is possible that two threads could both be repeatedly attempting this sequence and repeatedly failing to acquire both locks.
    - Solution is to add a random delay before looping back and trying the entire thing over again.

Deadlock Prevention

Mutual Exclusion

- Mutual Exclusion — not required for sharable resources (e.g., read-only files); must hold for non-sharable resources
- In general, we cannot prevent deadlocks by denying the mutual-exclusion condition, because some resources are intrinsically non-sharable
- Wait-free concurrency

```
/* atomically increment a value by a certain amount */
int CompareAndSwap(int *adderess, int expected, int new) {
        if (*address == expected) {
                *address = new;
                return 1;
        }
        return 0;
}
void AtomicIncrement(int *value, int amount) {
        do {
                int old = *value;
        } while (CompareAndSwap(value, old, old + amout) == 0);
}
```

Deadlock Prevention

Mutual Exclusion (contd.)

```c
/* inserts at the head of a list */
void insert(int value) {
        node_t *n = malloc(sizeof(node_t));
        assert(n != NULL);
        n->value = value;
        pthread_mutex_lock(listlock);
        n->next = head;
        head = n;
        pthread_mutex_unlock(listlock);
}

/* atomic list insertion: */
void insert(int value) {
        node_t *n = malloc(sizeof(node_t));
        assert(n != NULL);
        n->value = value;
        do {
                n->next = head;
        } while (CompareAndSwap(&head, n->next, n) == 0);
}
```

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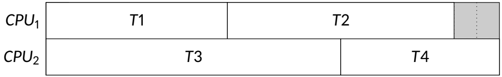
Deadlock Avoidance

- Deadlock avoidance — via scheduling
  - Assume we have two processors (CPU_1, CPU_2) and four threads (T_1, T_2, T_3, T_4) which must be scheduled upon them. Assume further we know that each thread will grab some locks L_1 or L_2 as follows.

	T_1	T_2	T_3	T_4
L_1	yes	yes	no	no
L_2	yes	yes	yes	no



Deadlock Avoidance

- Requires that the system has some additional a priori information available
  - Simplest and most useful model requires that each process declare 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 there can never be a circular-wait condition
  - Resource-allocation state is defined by the number of available and allocated resources, and the maximum demands of the processes

Deadlock Avoidance

Safe State

- When a process requests an available resource, system must decide if immediate allocation leaves the system in a safe state
- System is in **safe state** if there exists a sequence $< P_1, P_2, \cdots, P_n >$ of ALL the processes in the systems such that for each P_i, the resources that P_i can still request can be satisfied by currently available resources + resources held by all the P_j, with $j < i$
  - 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

Deadlock Avoidance

Safe State (contd.)

- Consider a system with 12 magnetic tape drives and three processes: P_0, P_1, P_2.

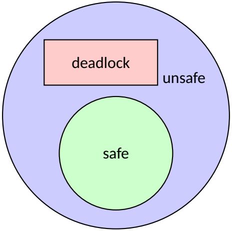
	Maximum Needs	Current Needs
P_0	10	5
P_1	4	2
P_2	9	2

- At time t_0, the system is in a safe state. The sequence $< P_1, P_0, P_2 >$ satisfies the safety condition.
- Show by an example that a system can go from a safe state to an unsafe state.
- Suppose that, at time t_1, process P_2 requests and is allocated one more tape drive. The system is no longer in a safe state.

Deadlock Avoidance

Safe State (contd.)

- If a system is in safe state ⇒ no deadlocks
- If a system is in unsafe state ⇒ possibility of deadlock
- Avoidance — ensure that a system will never enter an unsafe state.



Deadlock Avoidance

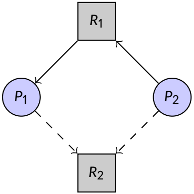
Avoidance Algorithms

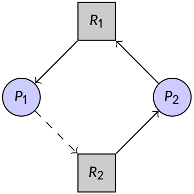
- Single instance of a resource type
  - Use the resource-allocation-graph algorithm
- Multiple instances of a resource type
  - Use the banker's algorithm

Deadlock Avoidance

Resource-Allocation-Graph Algorithm

- Claim edge: $P_i \dashrightarrow R_j$ indicated 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 converted to an assignment edge when the resource is allocated to the process
  - When a resource is released by a process, assignment edge reconverts to a claim edge
  - Resources must be claimed a priori in the system





Deadlock Avoidance

Resource-Allocation-Graph Algorithm (contd.)

- 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

Deadlock Avoidance

Banker's Algorithm

- Multiple instances
- Assumptions:
  - Each process must a priori claim maximum use
  - When a process requests a resource it may have to wait
  - When a process gets all its resources it must return them in a finite amount of time

Deadlock Avoidance

Banker's Algorithm (contd.)

- n = number of processes
- m = number of resources types.
- *Available*: Vector of length m. If $Available[j] = k$, then 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

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

Deadlock Avoidance

Safety Algorithm

1. Let *Work* and *Finish* be vectors of length m and n, respectively. Initialize:

   $Work = Available$

   $Finish[i] = false$, for $i = 0, 1, \cdots, n-1$

2. Find an 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

Deadlock Avoidance

Resource-Request Algorithm

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

$$Available = Available - Request_i$$
$$Allocation_i = Allocation_i + Request_i$$
$$Need_i = Need_i - Request_i$$

   - If safe $\Rightarrow$ the resources are allocated to P_i
   - If unsafe $\Rightarrow$ P_i must wait, and the old resource-allocation state is restored

Deadlock Avoidance

In Class Exercise

A computer system has 3 types of resources A, B, and C with different numbers of instances. There are 4 running processes P_1, P_2, P_3, P_4. The total resources, the resource's *Allocation* and *Max* matrices for the four processes are shown as follows:

	Allocation			*Max*		
Process	*A*	*B*	*C*	*A*	*B*	*C*
P_1	1	3	1	6	5	3
P_2	0	2	2	3	5	3
P_3	2	0	0	3	5	2
P_4	0	1	3	2	4	3
total	6	9	6			

1. What are the matrices *Need* and *Available* for the system?
2. Please check if the system is currently deadlocked. Show your steps clearly.
3. At the current state, if P_2 requests additional resources $[1, 0, 0]$, can the request be granted without any possible deadlock? Show your steps clearly.
4. At the current state, if P_1 requests additional resources $[1, 0, 0]$, can the request be granted without any possible deadlock? Show your steps clearly.

Deadlock Avoidance

Key

- $n = 4$, $m = 3$, *Allocation* and *Max* are already defined.
- Key to **Q1**: Compute *Available* and *Need*

Process	*Need* A	B	C
P_1	5	2	2
P_2	3	3	1
P_3	1	5	2
P_4	2	3	0
Available	3	3	0

- Key to **Q3 Q4**: Resource-Request Alg.
- Assume the request is granted, use the Safety Alg. to determine whether the system is in safe state.

- Key to **Q2**: Safety Alg.
  1. $Work = Available$, $Finish[i] = false$, $0 \leq i < n$.
  2. Find an $i = 4$.
  3. $Work = Work + Allocation_i$, $Finish[4] = true$

	A	B	C
Work	3	4	3

  4. Go to step 2.
  5. Find an $i = 2$.
  6. $Work =< 3, 6, 5 >$, $Finish[2] = true$
  7. Go to step 2.
  8. Find an $i = 3$.
- Safe sequence: $< P_4, P_2, P_3, P_1 >$

Deadlock Avoidance

Key (Contd.)

Key to **Q3**

1. Pretend to grant.
2. Current state:

Process	Allocation A	B	C	Need A	B	C
P_1	1	3	1	5	2	2
P_2	1	2	2	2	3	1
P_3	2	0	0	1	5	2
P_4	0	1	3	2	3	0
Total	6	9	6			
Avai.				2	3	0

3. Find a safe sequence: $(2, 3, 0) \longrightarrow P_4(2, 4, 3) \longrightarrow P_2(3, 6, 5) \longrightarrow P_3(5, 6, 5) \longrightarrow P_1(6, 9, 6)$
4. Safe $\longrightarrow$ Yes!

Key to **Q4**

1. Pretend to grant.
2. Current state:

Process	Allocation A	B	C	Need A	B	C
P_1	2	3	1	4	2	2
P_2	0	2	2	3	3	1
P_3	2	0	0	1	5	2
P_4	0	1	3	2	3	0
Total	6	9	6			
Avai.				2	3	0

3. Find a safe sequence: $(2, 3, 0) \longrightarrow P_4(2, 4, 3) \longrightarrow ?$
4. Unsafe $\longrightarrow$ No!

Deadlock Avoidance

In Class Exercise

Consider the following system snapshot using the data structures in the Banker's algorithm, with resources *A*, *B*, *C*, and *D*, and processes P_0 to P_4:

	Max				*Allocation*				*Need*				*Available*			
Processes	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
P_0	6	0	1	2	4	0	0	1								
P_1	1	7	5	0	1	1	0	0								
P_2	2	3	5	6	1	2	5	4								
P_3	1	6	5	3	0	6	3	3								
P_4	1	6	5	6	0	2	1	2								
Total													3	2	1	1

1. How many resources of type A, B, C, and D are there?
2. What are the contents of the Need matrix? Fill in the above table.
3. Is the system in a safe state? Provide your reasons.
4. If a request from process P_4 arrives for additional resources of $(1, 2, 0, 0)$, can the Banker's algorithm grant the request immediately? Show the new system state and other criteria.

Deadlock Avoidance

Key

1. How many resources of type A, B, C, and D are there?
   - 9,13,10,11
2. What are the contents of the Need matrix? Fill in the above table.
3. Is the system in a safe state? Provide your reasons.
   - Yes, $P_0(7, 2, 1, 2) \rightarrow P_2(8, 4, 6, 6) \rightarrow P3(8, 10, 9, 9) \rightarrow \cdots$
4. If a request from process P_4 arrives for additional resources of $(1, 2, 0, 0)$, can the Banker's algorithm grant the request immediately? Show the new system state and other criteria.
   - This state is NOT safe. P_0 can be satisfied, but the available resources at that point $(6, 0, 1, 2)$ cannot satisfy the needs of the remaining processes.

Deadlock Avoidance

In Class Exercise

Consider the following system snapshot using the data structures in the Banker's algorithm, with resources A, B, C, and D, and processes P0 to P4:

	Max				Allocation				Need				Available			
	A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D
P0	2	3	3	3	1	2	1	2								
P1	1	4	1	0	1	1	0	0								
P2	2	1	1	1	0	1	0	1								
P3	5	4	3	3	1	1	2	2								
P4	4	2	6	3	1	2	1	2								
Total													2	0	2	0

1. How many resources of type A, B, C, and D are there?
2. What are the contents of the Need matrix?
3. Is the system in a safe state? Why?
4. If a request from process P2 arrives for additional resources of (0,0,2,0), can the Banker's algorithm grant the request immediately? Why?

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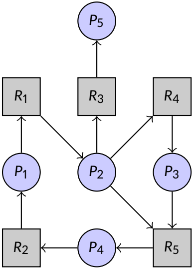
Deadlock Detection

Single Instance of Each Resource Type

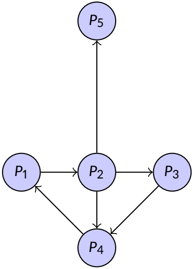
- Maintain wait-for graph
  - Nodes are processes
  - $P_i \longrightarrow P_j$, if P_i is waiting for P_j
- Periodically invoke an algorithm that searches for a cycle in the graph. If there is a cycle, there exists a deadlock
- An algorithm to detect a cycle in a graph requires an order of n^2 operations, where n is the number of vertices in the graph

Deadlock Detection

Wait-for Graph



Resource-Allocation Graph



Wait-for Graph

Deadlock Detection

Several Instances of a Resource Type

- *Available*: A vector of length m indicates the number of available resources of each type
- *Allocation*: An $n \times m$ matrix defines the number of resources of each type currently allocated to each process
- *Request*: An $n \times m$ matrix indicates the current request of each process. If $Request[i][j] = k$, then process P_i is requesting k more instances of resource type R_j.

Deadlock Detection

Detection Algorithm

1. Let *Work* and *Finish* be vectors of length m and n, respectively. Initialize:
   $Work = Available$
   For $i = 1, 2, \cdots, n$, 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. P_i is deadlocked.

Deadlock Detection

Detection-Algorithm Usage

- When, and how often, to invoke depends on:
  - How often a deadlock is likely to occur?
  - How many processes will need to be rolled back?
    - one for each disjoint cycle
- 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.

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Recovery from Deadlock

Process Termination

- Abort all deadlocked processes
- Abort one process at a time until the deadlock cycle is eliminated
- In which order should we choose to abort?
  - Priority of the process
  - How long process has computed, and how much longer to completion
  - Resources the process has used
  - Resources process needs to complete
  - How many processes will need to be terminated
  - Is process interactive or batch?

Recovery from Deadlock

Resource Preemption

- Selecting a victim — minimize cost
- Rollback — return to some safe state, restart process for that state
- Starvation — same process may always be picked as victim, include number of rollback in cost factor