Deadlock

Operating Systems

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(with slides borrowed from Prof. Jerry Chou)

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Outline

- System model
- Deadlock characterization
- Deadlock prevention
- Deadlock avoidance
- Deadlock detection
- Deadlock recovery

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System Model

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Deadlock Problem

- A set of blocked processes each **holding** some resources and **waiting** to acquire a resource held by another process in the set
- Example:
  - 2 processes and semaphores A and B
    - P_1 (hold B, wait A): **wait (A)**, signal (B)
    - P_2 (hold A, wait B): **wait (B)**, signal (A)
- Example:
  - Dining philosophers' problem

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Necessary Conditions

- **Mutual exclusion**
  - Only 1 process at a time can use a resource
- **Hold and wait**
  - A process holding some resources and is waiting for another resource
- **No preemption**
  - A resource can be only released by a process **voluntarily**
- **Circular wait**
  - There exists a set $\{P_0, P_1, \ldots, P_n\}$ of waiting processes such that $P_0 \rightarrow P_1 \rightarrow P_2 \rightarrow \ldots \rightarrow P_n \rightarrow P_0$

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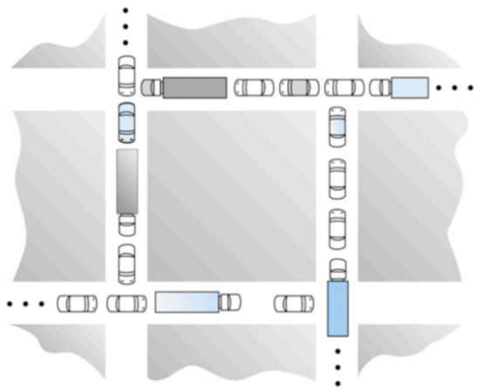
Necessary Conditions (cont.)



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System Model

- **Resources types** $R_1, R_2, \ldots, R_m$
  - E.g. CPU, memory pages, I/O devices
- Each resource type R_i has W_i **instances**
  - E.g. a computer has 2 CPUs
- Each process utilizes a resource as follows:
  - **Request → use → release**

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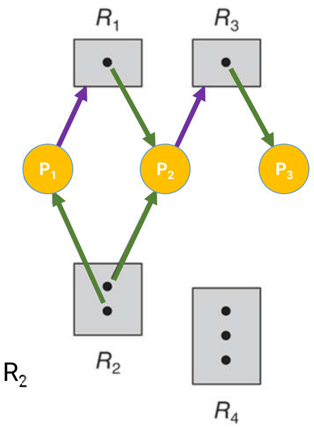
Resource-Allocation Graph

- 3 processes, $P_1 \sim P_3$
- 4 resources, $R_1 \sim R_4$
  - R_1 and R_3 each has one instance
  - R_2 has two instances
  - R_4 has three instances
- **Request edges**
  - $P_1 \rightarrow R_1$: P_1 requests R_1
- **Assignment edges**
  - $R_2 \rightarrow P_1$: one instance of R_2 is allocated to P_1

→ P_1 is **holding on** an instance of R_2 and **waiting for** an instance or R_1



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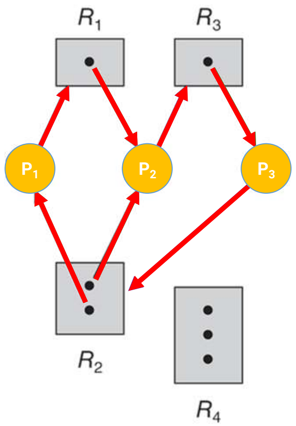
Resource-Allocation Graph w/ Deadlock

- If the graph contains a **cycle**, a deadlock **may** exist
- In the example
  - P_1 is waiting for P_2
  - P_2 is waiting for P_3
  - ➔ P_1 is also waiting for P_3
  - Since P_3 is waiting for P_1 or P_2, and they both waiting for P_3
  - ➔ **Deadlock !**



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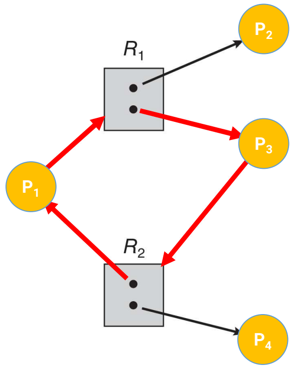
RA Graph w/ Cycle but NO Deadlock

- If the graph contains a **cycle**, a deadlock **may** exist
- In the example
  - P_1 is waiting for P_2 or P_3
  - P_3 is waiting for P_1 or P_4
  - Since P_2 and P_4 wait for no one
  - ➔ **No Deadlock between P_1 and P_3**



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Deadlock Detection

- If the graph contains **no cycle** ➔ **no deadlock**
  - **Circular wait cannot be held**
- If the graph contains a cycle
  - If **one instance** per resource type ➔ **deadlock**
  - If **multiple instances** per resource type ➔ **possibility** of deadlock

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Handling Deadlocks

- Ensure the system will **never** enter a deadlock state
  - **Deadlock prevention**: ensure that at least one of the **4 necessary conditions** cannot hold
  - **Deadlock avoidance**: **dynamically** examines the resource-allocation state before allocation
- Allow to **enter a deadlock state** and then **recover**
  - **Deadlock detection**
  - **Deadlock recovery**
- **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

Deadlock Prevention

- **Mutual exclusion (ME):** do not require ME on sharable resources
  - E.g. there is no need to ensure ME on read-only files
  - However, some resources are not shareable (e.g. printer)
- **Hold and wait:**
  - When a process requests a resource, it does not hold any resource
  - Pre-allocate all resources before executing
  - **Resource utilization is low; starvation is possible**

Deadlock Prevention (cont.)

- **No preemption:**
  - When a process is waiting on a resource, all its holding resources are preempted
    - E.g. P_1 request R_1, which is allocated to P_2, which in turn is waiting on R_2 ($P_1 \rightarrow R_1 \rightarrow P_2 \rightarrow R_2$)
    - **R1 can be preempted and reallocated to P1**
  - **Applied to resources whose states can be easily saved and restored later**
    - E.g. CPU registers and memory
  - It cannot easily be applied to other resources
    - E.g. printers and tape drives

Deadlock Prevention (cont.)

- **Circular wait:**
  - Impose a **total ordering** of all resource types
  - A process requests resources in an increasing order
    - Let R = $\{R_0, R_1, \ldots R_n\}$ be the set of resource types
    - **When request R_k, should release all R_i, $i \geq k$**
- Example
  - F (disk drive) = 5, F(printer) = 12
  - A process must request disk drive before printer
- Proof: counter-example does not exist
  - $P_0(R_0) \rightarrow R_1, P_1(R_1) \rightarrow R_2, \ldots, P_n(R_n) \rightarrow R_0$ ← P_n **holds on** R_n, **waiting for** R_0
  - Conflict: $R_0 < R_1 < R_2 < \ldots R_n < R_0$

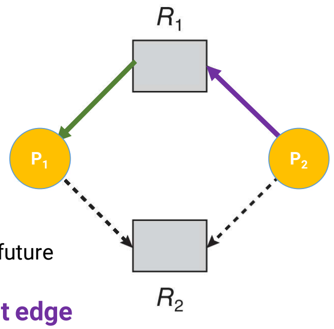
Deadlock Avoidance

Avoidance Algorithms

- **Single instance of a resource type**
  - **Resource-allocation graph (RAG) algorithm** based on **circle detection**
- **Multiple instance of a resource type**
  - **banker's algorithm** based on safe **sequence detection**

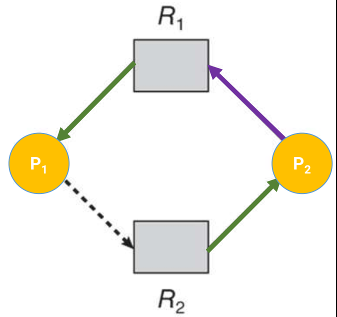
Resource-Allocation Graph Algorithm

- **Request edges**
  - $P_i \rightarrow R_j$: P_i **is waiting** for resource R_j
- **Assignment edges**
  - $R_j \rightarrow P_i$: Resource R_j **is allocated** and held by P_i
- **Claim edge**
  - Process P_i **may** request R_j in the future
- **Claim edge** converts to **request edge**
  - When a resource **is requested** by process
- **Assignment edge** converts back to a **claim edge**
  - When a resource is released by a process



Resource-Allocation Graph Algorithm (cont.)

- Resource **must be claimed a priori** in the system
- **Grant a request** only if NO cycle created
- Check for safety using a **cycle-detection algorithm**, $O(n^2)$
- Example: R_2 cannot be allocated to P_2



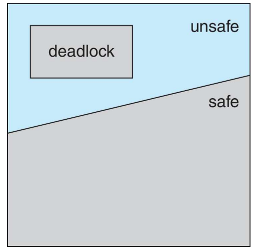
Avoidance Algorithms

- Single instance of a resource type
  - **Resource-allocation graph (RAG) algorithm** based on **circle detection**
- Multiple instance of a resource type
  - **banker's algorithm** based on safe **sequence detection**

Deadlock Avoidance

- **Safe state:** a system is in a safe state if there exists **a sequence of allocations** to satisfy requests by all processes
  - This sequence of allocations is called **safe sequence**
- **Safe state ➔ no deadlock**
- **Unsafe state ➔ possibility of deadlock**
- **Deadlock avoidance ➔**

  ensure that a system never enters an unsafe state



Safe State with Safe Sequence

- There are 12 tape drives
- Assuming at t_0:

hints from processes

	Max Needs	Current Holding
P0	10	5
P1	4	2
P2	9	2

➔ $<P_1, P_0, P_2>$ is a safe sequence

Safe State with Safe Sequence

- There are 12 tape drives
- Assuming at t_0:

	Max Needs	Current Holding	Available
P0	10	5	
P1	4	2	3
P2	9	2	

➔ $<P_1, P_0, P_2>$ is a safe sequence

1. P_1 satisfies its allocation with 3 available resources

Safe State with Safe Sequence

- There are 12 tape drives
- Assuming at t_0:

	Max Needs	Current Holding	Available
P0	10	5	5
P1	4	0	
P2	9	2	

➔<P_1, P_0, P_2> is a safe sequence

1. P_1 satisfies its allocation with 3 available resources
2. P_0 satisfies its allocation with 5 available resources

Safe State with Safe Sequence

- There are 12 tape drives
- Assuming at t_0:

	Max Needs	Current Holding	Available
P0	10	5	
P1	4	0	
P2	9	2	10

➔<P_1, P_0, P_2> is a safe sequence

1. P_1 satisfies its allocation with 3 available resources
2. P_0 satisfies its allocation with 5 available resources
3. P_2 satisfies its allocation with 10 available resources

Safe State with Safe Sequence

- There are 12 tape drives
- Assuming at t_1:

	Max Needs	Current Holding	Available
P0	10	5	
P1	4	2	2
P2	9	3	

- If P_2 requests and is allocated 1 more resource
  - ➔ No safe sequence exist …
  - ➔ This allocation makes the system enter an unsafe state
- **A request is only granted if the allocation leaves the system in a safe state**

Banker's Algorithm

- Use for **multiple instances** of each resource type

- **Banker's Algorithm**
  - Use a general safety algorithm to **pre-determine** if any **safe sequence** exists after allocation
  - **Only proceed the allocation if safe sequence exists**
- **Safety algorithm**
  1. Assume processes need **maximum** resources
  2. Find a process that can be satisfied by free resources
  3. Free the resource usage of the process
  4. Repeat to step 2 until all processes are satisfied

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: 3, B: 3, C: 2

	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	2	0	0	1	2	2
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	0	0	2	4	3	1

- Safe sequence: P_1

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: **5**, B: 3, C: 2

	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	2	0	0	1	2	2
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	0	0	2	4	3	1

- Safe sequence: P_1, P_3

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: **7**, B: **4**, C: **3**

	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	2	0	0	1	2	2
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	0	0	2	4	3	1

- Safe sequence: P_1, P_3, P_4

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: 7, B: 4, C: **5**

	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	2	0	0	1	2	2
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	0	0	2	4	3	1

- Safe sequence: P_1, P_3, P_4, P_2

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: **10**, B: 4, C: **7**

	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	2	0	0	1	2	2
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	0	0	2	4	3	1

- Safe sequence: P_1, P_3, P_4, P_2, P_0

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: 3, B: 3, C: 2

	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	2	0	0	1	2	2
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	0	0	2	4	3	1

- If Request (P_1) = (1, 0, 2) …

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: **2**, B: 3, C: **0**

	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	**3**	**0**	**2**	**0**	**2**	**0**
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	0	0	2	4	3	1

- If Request (P_1) = (1, 0, 2): P1 allocation ➔ (3, 0, 2)
  - Enter another safe state (Safe sequence: P_1, P_3, P_4, P_0, P_2)

Banker's Algorithm Example

- Total instances: A: 10, B: 5, C: 7
- Available instances: A: **0**, B: **0**, C: 2

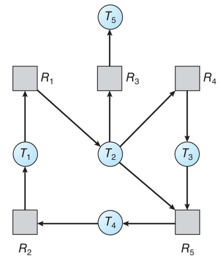
	Max			Allocation			Need (Max – Alloc.)		
	A	B	C	A	B	C	A	B	C
P_0	7	5	3	0	1	0	7	4	3
P_1	3	2	2	2	0	0	1	2	2
P_2	9	0	2	3	0	2	6	0	0
P_3	2	2	2	2	1	1	0	1	1
P_4	4	3	3	**3**	**3**	**2**	**1**	**0**	**1**

- If Request (P_4) = (3, 3, 0): P_4 allocation ➔ (3, 3, 2)
  - Enter into an unsafe state (no safe sequence can be found)

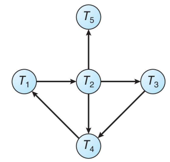
Deadlock Detection

Deadlock Detection

- **Single instance** of each resource type
  - Convert request/assignment edges into **wait-for graph**
  - Deadlock exists if there is a cycle in the wait-for graph



Resource-Allocation graph



corresponding wait-for graph

Multiple Instance for Each Resource Type

- Total instances: A: 7, B: 2, C: 6
- Available instances: A: 0, B: 0, C: 0

	Allocation			Request		
	A	B	C	A	B	C
P_0	0	1	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

- The system is in a safe state ➔ $<P_0, P_2, P_3, P_1, P_4>$
  ➔ No deadlock

Multiple Instance for Each Resource Type

- Total instances: A: 7, B: 2, C: 6
- Available instances: A: 0, B: 0, C: 0

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

- If P_2 requests (0, 0, 1) ➔ no safe sequence can be found
  ➔ The system is deadlocked

Deadlock Recovery

Deadlock Recovery

- **Process termination**
  - Abort all deadlocked processes
  - Abort 1 process at a time until the deadlock cycle is eliminated
    - Which process should we abort first?
- **Resource preemption**
  - Select a victim: which one to preempt?
  - Rollback: partial rollback or total rollback?
  - Starvation: can the same process be preempted always?

Objective Review

- Illustrate how deadlock can occur
- 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 the banker’s algorithm for deadlock avoidance
- Apply the deadlock detection algorithm