Deadlock

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Outline

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Synchronization Issues

- Liveness
  - Deadlock
  - Starvation
  - Priority inversion

Liveness

- *Liveness* refers to a set of properties that a system must satisfy to ensure processes make progress.
  - Processes may have to wait indefinitely while trying to acquire a synchronization tool such as a mutex lock or semaphore.
  - Waiting indefinitely violates the progress and bounded-waiting criteria discussed at the beginning of this chapter.
  - Indefinite waiting is an example of a liveness failure.

Deadlock

- Two or more processes are waiting indefinitely for an event that can be caused by only one of the waiting processes
- Consider the following example,
  Let S and Q be two semaphores initialized to 1

P0

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

P1

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

- Consider if P0 executes wait(S) and P1 wait(Q). When P0 executes wait(Q), it must wait until P1 executes signal(Q)
- However, P1 is waiting until P0 execute signal(S).
- Since these signal() operations will never be executed, P0 and P1 are deadlocked.

Starvation

- Indefinite blocking. A process may never be removed from the semaphore queue in which it is suspended.

Priority Inversion

- Scheduling problem when lower-priority process holds a lock needed by higher-priority process
  - Consider the scenario with three processes P1, P2,and P3.
  - P1 has the highest priority, P2 the next highest, and P3 the lowest.
  - Assume a resouce P3 is assigned a resource R that P1 wants. Thus, P1 must wait for P3 to finish using the resource.
  - However, P2 becomes runnable and preempts P3.
  - What has happened is that P2, a process with a lower priority than P1 has indirectly prevented P3 from gaining access to the resource.
- Solved via priority-inheritance protocol.

Priority Inheritance Protocol

- The protocol simply allows the priority of the highest thread waiting to access a shared resource to be assigned to the thread currently using the resource.
- Thus, the current owner of the resource is assigned the priority of the highest priority thread wishing to acquire the resource.

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Necessary Conditions for Deadlocks

Four conditions hold simultaneously (the 4 necessary conditions for deadlocks):

- 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 $\{P_0, P_1, \ldots, P_n\}$ 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.

Handling Deadlocks

- Ensure that the system will never enter a deadlock state.
  - Deadlock prevention (by structurally negating one of the four required conditions)
  - Deadlock avoidance (by carefully allocating resources)
- Allow the system to enter a deadlock state and then recover
  - Deadlock detection and recovery (Let deadlocks occur, detect them, and then take action)
- Ignore the problem and pretend that deadlocks never occur in the system.
  - The Ostrich algorithm

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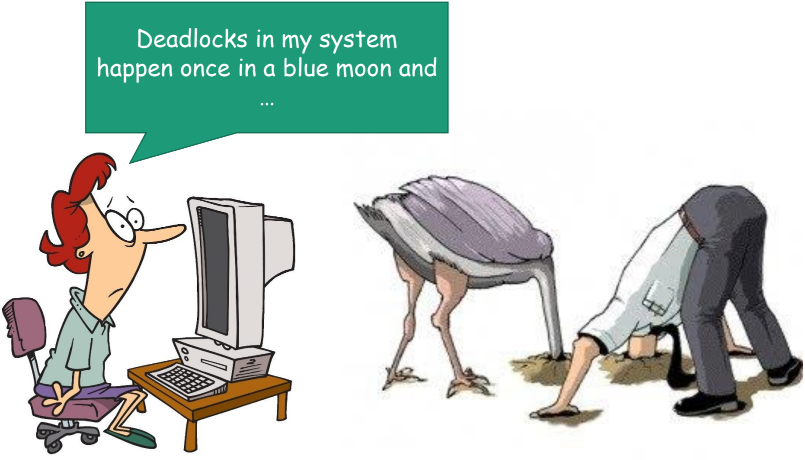

Figure: The Ostrich Algorithm

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Deadlock Prevention

By invalidating one of the four required conditions

- Mutual Exclusion
- Hold and wait
- No preemption
- Circular wait

But is it possible, and if possible how and at what cost?

Invalidating Mutual Exclusion?

We introduce terms, “shareable resources” and “non-shareable resources”

- Shareable resources. Resources that allow simultaneous access, e.g., a read-only file. There isn’t a mutual exclusion requirement to shareable resources.
- Non-shareable resources. Resources that do not allow simultaneous access, e.g., a printer or a mutex lock.

Cannot prevent deadlocks by denying the mutual-exclusion condition?

Invalidating Hold-and-Wait?

That is to say, we must guarantee that whenever a process requests a resource, it does not hold any other resources. How do we achieve this?

1. Require a process to request and be allocated all its resources before it begins execution, or
2. allow a process to request resources only when the process has none allocated to it (e.g., by releasing it)

At what cost?

- Low resource utilization;
- starvation possible;
- also impractical

Invalidating No-Preemption?

To invalidate no-preemption, we consider that the OS may do the following,

1. Check whether requested resources by process P_i are allocated to process P_j that is waiting for additional resources.
2. If so, we preempt the desired resources from P_j and allocate the resources to P_i.

Is it possible?

- Possible for resources whose state can be easily saved and restored later, such as, a database transaction
- However, not generally possible, e.g., mutex locks and semaphores.

Invalidating Circular Wait?

Consider the following approach.

1. Impose a total ordering of all resource types by assigning each resource (i.e., mutex locks) a unique number.
2. Resources must be acquired in order based on the numbers

Does it invalidating circular wait? (Circular wait cease to happen)

- Yes, we can prove it by contradiction.

However,

- Resource ordering does not in itself prevent deadlock. Application developers must write programs that follow the ordering.
- However, establishing an ordering of all resources can be sometimes difficult.
  - Considering on a system with hundreds or even thousands of locks [1]
  - What if locks can be acquired dynamically?

[1] To address this challenge, many Java developers have adopted the strategy of using the method `System.identityHashCode()` as the function for ordering lock acquisition

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Resource Allocation Graph

Use it to determine whether there is a circular wait condition.

- 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 (*drawn in ovals*)
  - $R = \{R_1, R_2, \ldots, R_m\}$, the set consisting of all resource types in the system (*drawn in rectangles*)
- E is partitioned into two types:
  - Request edge. Directed edge $P_i \rightarrow R_j$, which reads "P_i requests or waits for R_j"
  - Assignment edge. Directed edge $R_j \rightarrow P_i$, which reads "R_j is assigned to or is held by P_i"

Resource Allocation Algorithms: Example 1

Circle: process; Square: resource; arrow: (Resource → Process, Process → Resource, i.e., is being held/assigned to or requests)

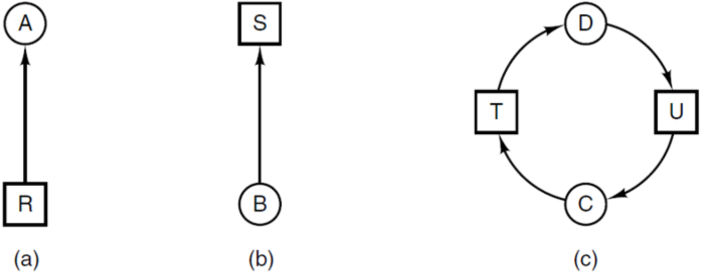


Figure: Resource allocation graphs. (a) Holding a resource. (b) Requesting a resource. (c) Deadlock. [Figure 6-3 in Tanenbaum & Bos, 2014]

Resource Allocation Algorithms: Example 2 (a)

Consider three processes (A, B, and C) and three resources (R, S, T)

A	B	C
Request R	Request S	Request T
Request S	Request T	Request R
Release R	Release S	Release T
Release S	Release T	Release R

How should we schedule these three processes?

Resource Allocation Algorithms: Example 2 (b)

Consider three processes (A, B, and C) and three resources (R, S, T)

A	B	C
Request R	Request S	Request T
Request S	Request T	Request R
Release R	Release S	Release T
Release S	Release T	Release R

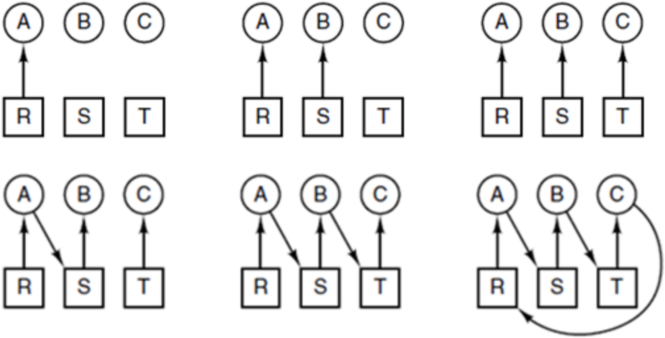
How about this scheduling sequence (will there be a deadlock?)

1. A requests R
2. B requests S
3. C requests T
4. A requests S
5. B requests T
6. C requests R

Resource Allocation Algorithms: Example 2 (b)

How about this scheduling sequence (will there be a deadlock?)

1.	A requests R	4.	A requests S
2.	B requests S	5.	B requests T
3.	C requests T	6.	C requests R



Resource Allocation Algorithms: Example 2 (c)

Consider three processes (A, B, and C) and three resources (R, S, T)

A	B	C
Request R	Request S	Request T
Request S	Request T	Request R
Release R	Release S	Release T
Release S	Release T	Release R

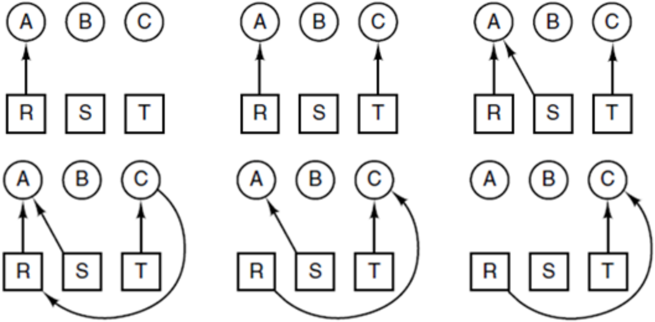
How about this scheduling sequence (will there be a deadlock?)

1. A requests R
2. C requests T
3. A requests S
4. C requests R
5. A releases R
6. A releases S

Resource Allocation Algorithms: Example 2 (c)

How about this scheduling sequence (will there be a deadlock?)

1.	A requests R	4.	C requests R
2.	C requests T	5.	A releases R
3.	A requests S	6.	A releases S



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Banker's Algorithm

Use it to determine whether there is a circular wait condition when a resource has multiple instances.

Data Structures

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

- Available (or Free): 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 (or Has): $n \times m$ 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. Do the following initialization,
   `Work = Available`
   For `i = 0, 1, ..., n-1`:
   `Finish[i] = false`
2. Find an index `i` such that both
   2.1 `Finish[i] == false`
   2.2 `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*; otherwise, *unsafe state*.

This algorithm may require an order $O(m \times n^2)$ operations to determine whether a state is safe.

Examples of Running Safety Algorithm

Let's examine a few examples ...

Banker's Algorithm: Example for Determining Safe State

	Allocation	Max	Available
	A B C	A B C	A B C
T_0	0 1 0	7 5 3	3 3 2
T_1	2 0 0	3 2 2	
T_2	3 0 2	9 0 2	
T_3	2 1 1	2 2 2	
T_4	0 0 2	4 3 3	

	Need
	A B C
T_0	7 4 3
T_1	1 2 2
T_2	6 0 0
T_3	0 1 1
T_4	4 3 1

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Deadlock Avoidance

Use Resource Allocation Graph or a variant of Banker's algorithm to determine if current resource allocation is in a safe state.

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Deadlock Detection and Recovery

1. Use Resource Allocation Graph (Wait-for Graph) or a variant of Banker's algorithm to determine if there is a deadlock.
2. Recovery from the deadlock (multiple approaches)

Wait-for Graph for Deadlock Detection: Example

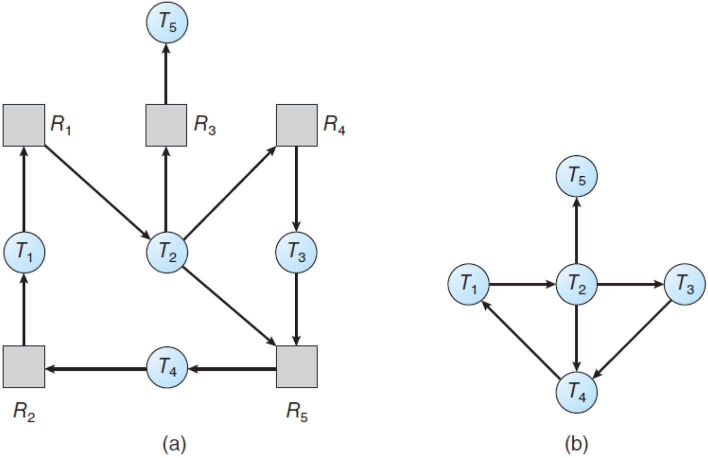

Figure: (a) Resource-allocation graph. (b) Corresponding wait-for graph.

Deadlock Detection in BCC Toolkit

See the example at:

https://github.com/iovisor/bcc/blob/master/tools/deadlock_example.txt

Matrix-based Deadlock Detection Algorithm

Using a variant of Banker's algorithm to detect whether there is a deadlock.

Data Structures

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.
- Allocation. An $n \times m$ matrix defines the number of resources of each type currently allocated to each thread.
- **Request**. An $n \times m$ matrix indicates the current request of each thread. If `Request[i][j]` equals `k`, then process P_i is requesting `k` more instances of resource type R_j. (Compare this with Need in the satety algorithm)

Deadlock Detection Algorithm

1. Let `Work` and `Finish` be vectors of length `m` and `n`, respectively. Do the following initialization,
   `Work = Available`
   For `i = 0, 1, ..., n-1`:
     if `Allocation[i]` $\neq$ 0, **then** `Finish[i] = false`
     else `Finish[i] = true`
2. Find an index `i` such that both
   2.1 `Finish[i] == false`
   2.2 `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, $0 \leq i < n$, then the system is in a deadlocked state. Moreover, if `Finish[i] == false`, then process P_i is deadlocked.

Examples of Deadlock Detection Algorithm

Let's examine a few examples ...

Banker's Algorithm: Example for Deadlock Detection

	Allocation	*Request*	*Available*
	A B C	A B C	A B C
T_0	0 1 0	0 0 0	0 0 0
T_1	2 0 0	2 0 2	
T_2	3 0 3	0 0 0	
T_3	2 1 1	1 0 0	
T_4	0 0 2	0 0 2	

Banker's Algorithm: Example for Deadlock Detection

What if the requests are modified as follows:

	Allocatio	Request	Available
	A B C	A B C	A B C
T_0	0 1 0	0 0 0	0 0 0
T_1	2 0 0	2 0 2	
T_2	3 0 3	0 0 1	
T_3	2 1 1	1 0 0	
T_4	0 0 2	0 0 2	

Outline

Events vs. Threads

There have been a recurrent discussion on how we should realize concurrency [2, 3, 4, 6, 5]

- Threads vs. events [2, 4, 6, 5]
- Theory vs. practice ([1, Section 9.1], [3])

Reference I

[1] Brian Goetz et al. *Java concurrency in practice*. Pearson Education, 2006.

[2] Hugh C Lauer and Roger M Needham. "On the duality of operating system structures". In: *ACM SIGOPS Operating Systems Review* 13.2 (1979), pp. 3–19.

[3] John Ousterhout. "Why threads are a bad idea (for most purposes)". In: *Presentation given at the 1996 Usenix Annual Technical Conference*. Vol. 5. San Diego, CA, USA. 1996.

[4] J Robert Von Behren, Jeremy Condit, and Eric A Brewer. "Why Events Are a Bad Idea (for High-Concurrency Servers).". In: *HotOS*. 2003, pp. 19–24.

Reference II

[5] Rob Von Behren et al. "Capriccio: scalable threads for internet services". In: *ACM SIGOPS Operating Systems Review* 37.5 (2003), pp. 268–281.

[6] Matt Welsh, David Culler, and Eric Brewer. "SEDA: an architecture for well-conditioned, scalable internet services". In: *ACM SIGOPS Operating Systems Review* 35.5 (2001), pp. 230–243.