CS 422/522 Design & Implementation
of Operating Systems

Lecture 10: Multi-Object Synchronization

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Multi-object programs

- What happens when we try to synchronize across multiple objects in a large program?
  - Each object with its own lock, condition variables
  - Is locking modular?
- Performance
- Semantics/correctness
- Deadlock
- Eliminating locks

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Synchronization performance

- A program with lots of concurrent threads can still have poor performance on a multiprocessor:
  - Overhead of creating threads, if not needed
  - Lock contention: only one thread at a time can hold a given lock
  - Shared data protected by a lock may ping back and forth between cores
  - False sharing: communication between cores even for data that is not shared

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Topics

- Multiprocessor cache coherence
- MCS locks (if locks are mostly busy)
- RCU locks (if locks are mostly busy, and data is mostly read-only)

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Multiprocessor cache coherence

- Scenario:
  - Thread A modifies data inside a critical section & releases lock
  - Thread B acquires lock and reads data
- Easy if all accesses go to main memory
  - Thread A changes main memory; thread B reads it
- What if new data is cached at processor A?
- What if old data is cached at processor B

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Write-back cache coherence

- Cache coherence = system behaves as if there is one copy of the data
  - If data is only being read, any number of caches can have a copy
  - If data is being modified, at most one cached copy
- On write: (get ownership)
  - Invalidate all cached copies, before doing write
  - Modified data stays in cache ("write back")
- On read:
  - Fetch value from owner or from memory

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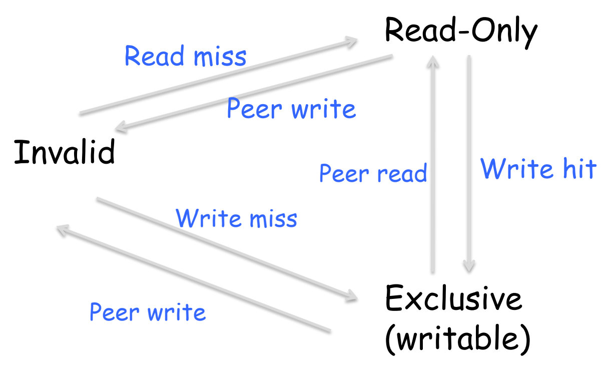
Cache state machine



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Directory-based cache coherence

- How do we know which cores have a location cached?
  - Hardware keeps track of all cached copies
  - On a read miss, if held exclusive, fetch latest copy and invalidate that copy
  - On a write miss, invalidate all copies
- Read-modify-write instructions
  - Fetch cache entry exclusive, prevent any other cache from reading the data until instruction completes

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A simple critical section

```
// A counter protected by a spinlock
Counter::Increment() {
   while (test_and_set(&lock))
      ;
   value++;
   lock = FREE;
   memory_barrier();
}
```

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A simple test of cache Behavior

Array of 1K counters, each protected by a separate spinlock
- Array small enough to fit in cache

- Test 1: one thread loops over array
- Test 2: two threads loop over different arrays
- Test 3: two threads loop over single array
- Test 4: two threads loop over alternate elements in single array

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Results (64 core AMD Opteron)

One thread, one array	51 cycles
Two threads, two arrays	52 cycles
Two threads, one array	197 cycles
Two threads, odd/even	127 cycles

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Reducing lock contention

- Fine-grained locking
  - Partition object into subsets, each protected by its own lock
  - Example: hash table buckets
- Per-processor data structures
  - Partition object so that most/all accesses are made by one processor
  - Example: per-processor heap
- Ownership/staged architecture
  - Only one thread at a time accesses shared data
  - Example: pipeline of threads

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What if locks are still mostly busy?

- MCS Locks
  - Optimize lock implementation for when lock is contended
- RCU (read-copy-update)
  - Efficient readers/writers lock used in Linux kernel
  - Readers proceed without first acquiring lock
  - Writer ensures that readers are done
- Both rely on atomic read-modify-write instructions

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The problem with test-and-set

```
Counter::Increment() {
   while (test_and_set(&lock))
      ;
   value++;
   lock = FREE;
   memory_barrier();
}
```

What happens if many processors try to acquire the lock at the same time?

- Hardware doesn’t prioritize FREE

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The problem with test-&-test-and-set

```
Counter::Increment() {
   while (lock == BUSY || test_and_set(&lock))
      ;
   value++;
   lock = FREE;
   memory_barrier();
}
```

What happens if many processors try to acquire the lock?
- Lock value pings between caches

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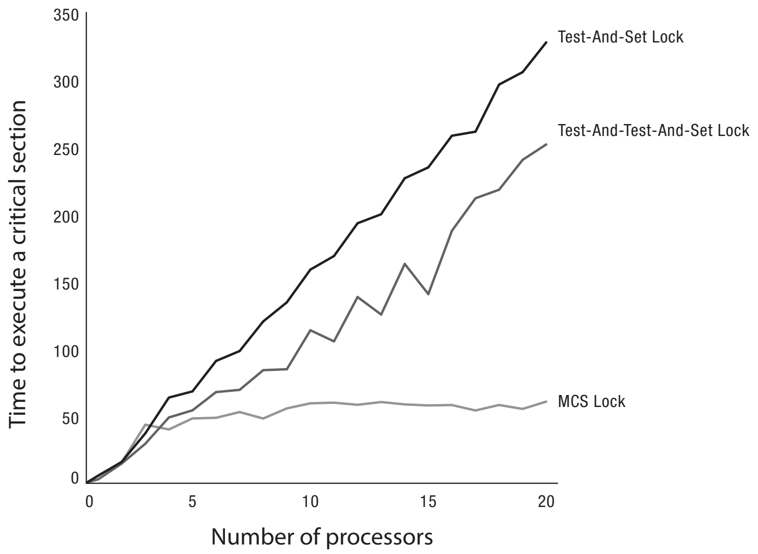
Test (and test) and set performance



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Some Approaches

- Insert a delay in the spin loop
  - Helps but acquire is slow when not much contention
- Spin adaptively
  - No delay if few waiting
  - Longer delay if many waiting
  - Guess number of waiters by how long you wait
- MCS
  - Create a linked list of waiters using compareAndSwap
  - Spin on a per-processor location

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Atomic CompareAndSwap

- Operates on a memory word
- Check that the value of the memory word hasn't changed from what you expect
  - E.g., no other thread did compareAndSwap first
- If it has changed, return an error (and loop)
- If it has not changed, set the memory word to a new value

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MCS Lock

- Maintain a list of threads waiting for the lock
  - Front of list holds the lock
  - MCSLock::tail is last thread in list
  - New thread uses CompareAndSwap to add to the tail
- Lock is passed by setting next->needToWait = FALSE;
  - Next thread spins while its needToWait is TRUE

```
TCB {
        TCB *next;              // next in line
         bool needToWait;
}
MCSLock {
        Queue *tail = NULL; // end of line
}
```

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MCS Lock implementation

```
class MCSLock {
  private Queue *tail = NULL;
}

MCSLock::release() {

   if (compareAndSwap(&tail,
            myTCB, NULL)) {

         // if tail == myTCB, no one is waiting.
         // MCSLock is now free.

   } else {
      // someone  is waiting
      while (myTCB->next == NULL)
         ;  // spin until next is set

      // Tell next thread to proceed
      myTCB->next->needToWait=FALSE;
   }
}
```

```
MCSLock::acquire() {

   Queue *oldTail = tail;

   myTCB->next = NULL;

   while (!compareAndSwap(&tail,
            oldTail, &myTCB)) {
      // try again if someone changed tail
      oldTail = tail;
   }

   if (oldTail != NULL) {
      // Need to wait
      myTCB->needToWait = TRUE;
      memory_barrier();
      oldTail->next = myTCB;
      while (myTCB->needToWait)
         ; // spin
   }
}
```

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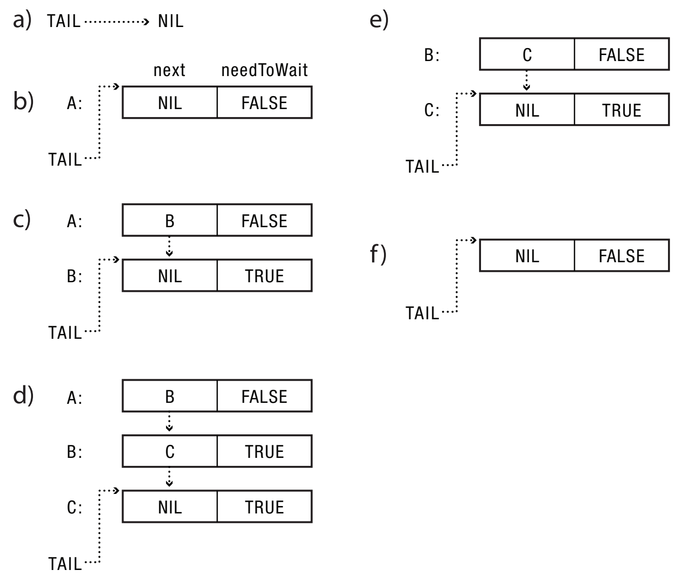
MCSLock in operation


a) TAIL NIL
b) A: next needToWait NIL FALSE TAIL
c) A: B FALSE B: NIL TRUE TAIL
d) A: B FALSE B: C TRUE C: NIL TRUE TAIL
e) B: C FALSE C: NIL TRUE TAIL
f) NIL FALSE TAIL

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Read-Copy-Update

- Goal: very fast reads to shared data
  - Reads proceed without first acquiring a lock
  - OK if write is (very) slow
- Restricted update
  - Writer computes new version of data structure
  - Publishes new version with a single atomic instruction
- Multiple concurrent versions
  - Readers may see old or new version
- Integration with thread scheduler
  - Guarantee all readers complete within grace period, and then garbage collect old version

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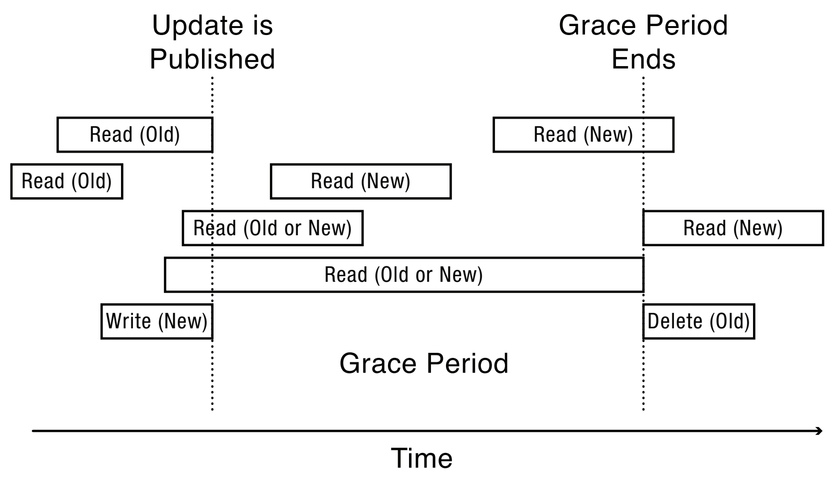
Read-Copy-Update



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Read-Copy-Update implementation

- Readers disable interrupts on entry
  - Guarantees they complete critical section in a timely fashion
  - No read or write lock
- Writer
  - Acquire write lock
  - Compute new data structure
  - Publish new version with atomic instruction
  - Release write lock
  - Wait for time slice on each CPU
  - Only then, garbage collect old version of data structure

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Non-blocking synchronization

- Goal: data structures that can be read/modified without acquiring a lock
  - No lock contention!
  - No deadlock!
- General method using compareAndSwap
  - Create copy of data structure
  - Modify copy
  - Swap in new version iff no one else has
  - Restart if pointer has changed

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Deadlock definition

- Resource: any (passive) thing needed by a thread to do its job (CPU, disk space, memory, lock)
  - Preemptable: can be taken away by OS
  - Non-preemptable: must leave with thread
- Starvation: thread waits indefinitely
- Deadlock: circular waiting for resources
  - Deadlock => starvation, but not vice versa

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Example: two locks

Thread A

```
lock1.acquire();
lock2.acquire();
lock2.release();
lock1.release();
```

Thread B

```
lock2.acquire();
lock1.acquire();
lock1.release();
lock2.release();
```

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Bidirectional bounded buffer

Thread A

```
buffer1.put(data);
buffer1.put(data);

buffer2.get();
buffer2.get();
```

Thread B

```
buffer2.put(data);
buffer2.put(data);

buffer1.get();
buffer1.get();
```

Suppose buffer1 and buffer2 both start almost full.

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Two locks and a condition variable

Thread A

```
lock1.acquire();
…
lock2.acquire();
while (need to wait) {
    condition.wait(lock2);
}
lock2.release();
…
lock1.release();
```

Thread B

```
lock1.acquire();
…
lock2.acquire();
…
condition.signal(lock2);
…
lock2.release();
…
lock1.release();
```

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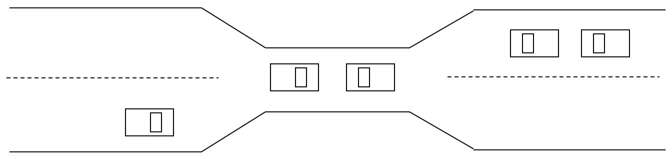
The bridge-crossing example



- Traffic only in one direction.
- Each section of a bridge can be viewed as a resource.
- If a deadlock occurs, it can be resolved if one car backs up (preempt resources and rollback).
- Several cars may have to be backed up if a deadlock occurs.
- Starvation is possible.

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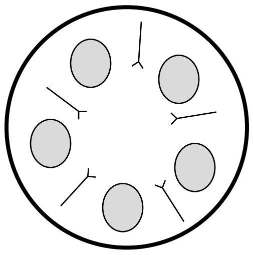
The dining philosophers problem

- Five philosophers around a table --- thinking or eating
- Five plates of spaghetti + five forks (placed between each plate)
- The spaghetti is so slippery that a philosopher needs two forks to eat it.

```
void philosopher (int i) {
   while (TRUE) {
       think();
       take_fork (i);
       take_fork ((i+1) % 5);
       eat();
       put_fork (i);
       put_fork ((i+1) % 5);
   }
}
```



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Necessary conditions for deadlock

- Limited access to resources
  - If infinite resources, no deadlock!
- No preemption
  - If resources are virtual, can break deadlock
- Multiple independent requests
  - “wait while holding”
- Circular chain of requests

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Question

- How does Dining Philosophers meet the necessary conditions for deadlock?
  - Limited access to resources
  - No preemption
  - Multiple independent requests (wait while holding)
  - Circular chain of requests
- How can we modify Dining Philosophers to prevent deadlock?

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Preventing deadlock

- Exploit or limit program behavior
  - Limit program from doing anything that might lead to deadlock
- Predict the future
  - If we know what program will do, we can tell if granting a resource might lead to deadlock
- Detect and recover
  - If we can rollback a thread, we can fix a deadlock once it occurs

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Exploit or limit behavior

- Provide enough resources
  - How many chopsticks are enough?
- Eliminate wait while holding
  - Release lock when calling out of module
  - Telephone circuit setup
- Eliminate circular waiting
  - Lock ordering: always acquire locks in a fixed order
  - Example: move file from one directory to another

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Example

Thread 1	Thread 2
1. Acquire A	1.
2.	2. Acquire B
3. Acquire C	3.
4.	4. Wait for A
5. If (maybe) Wait for B	

How can we make sure to avoid deadlock?

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System model

- Resource types $R_1, R_2, \ldots, R_m$
  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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Resource-allocation graph (1)

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 $P_1 \rightarrow R_j$
- assignment edge – directed edge $R_j \rightarrow P_i$

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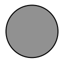
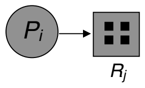
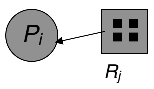
Resource-allocation graph (2)

- Process 
- Resource type with 4 instances

- P_i requests instance of R_j



- P_i is holding an instance of R_j



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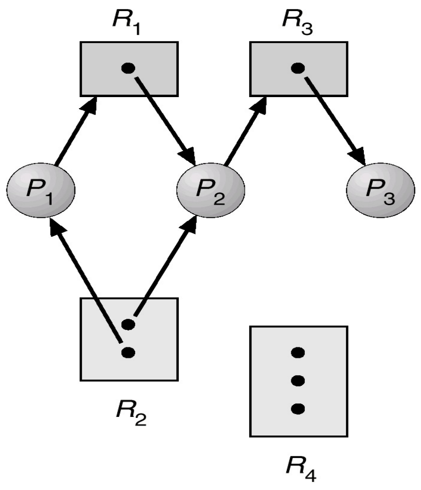
Example: resource-allocation graph



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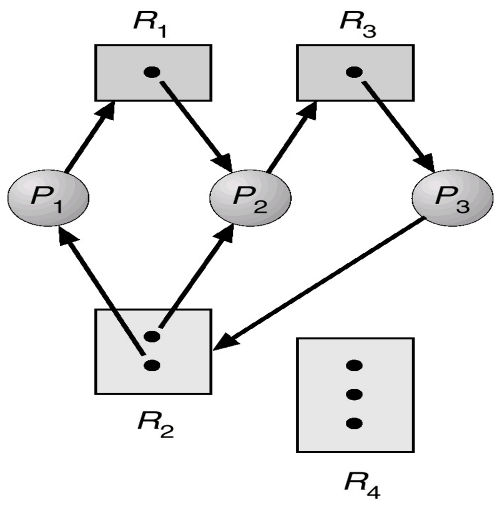
Resource-allocation graph with a deadlock



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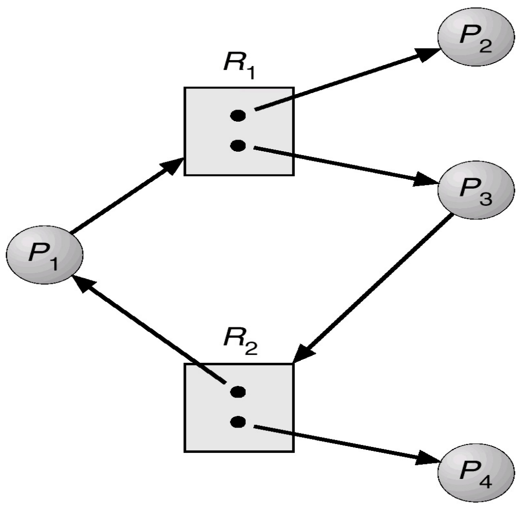
Resource-allocation graph with a cycle but no deadlock



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Resource allocation graph vs. deadlock?

- If graph contains no cycles ⇒ no deadlock.
- If graph contains a cycle ⇒
  - if only one instance per resource type, then deadlock.
  - if several instances per resource type, possibility of deadlock.

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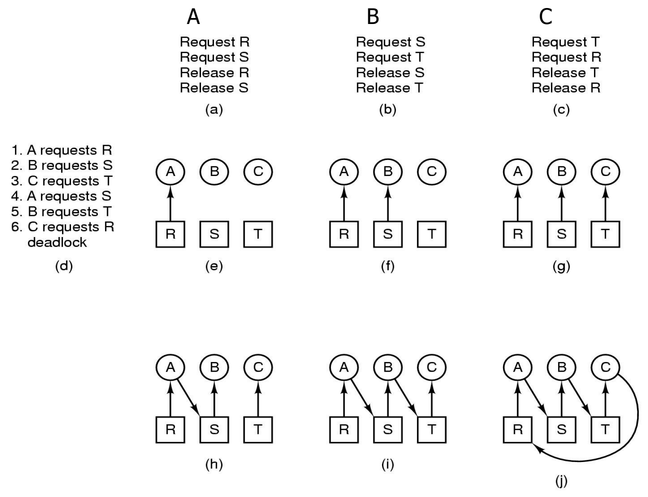
How deadlocks occur?



```
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
(a)            (b)            (c)
```

```
1. A requests R
2. B requests S
3. C requests T
4. A requests S
5. B requests T
6. C requests R
   deadlock
(d)
```

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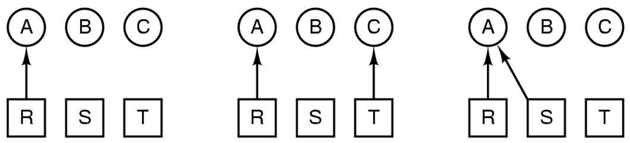
How deadlocks can be avoided

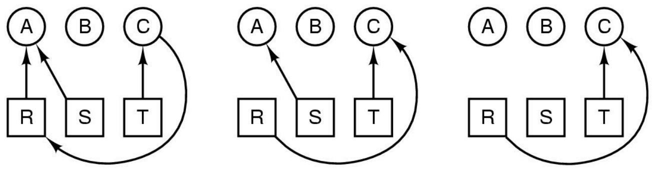
1. A requests R
2. C requests T
3. A requests S
4. C requests R
5. A releases R
6. A releases S
   no deadlock

(k)



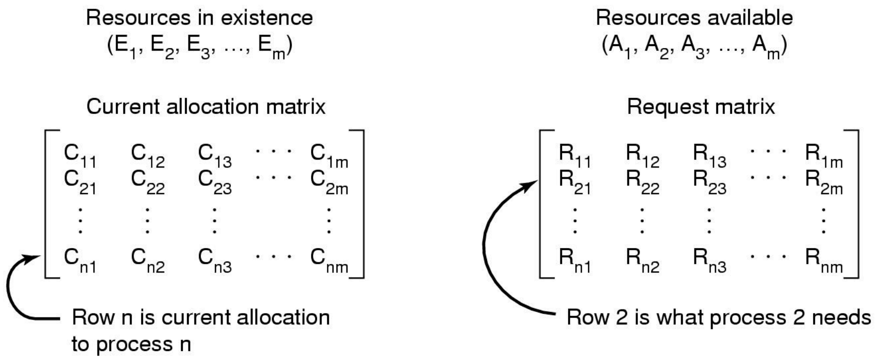
(l) (m) (n)

Block process B when it asks for S.



(o) (p) (q)

Deadlock detection: data structures



Resources in existence
$(E_1, E_2, E_3, \ldots, E_m)$

Current allocation matrix

$$\begin{bmatrix} C_{11} & C_{12} & C_{13} & \cdots & C_{1m} \\ C_{21} & C_{22} & C_{23} & \cdots & C_{2m} \\ \vdots & \vdots & \vdots & & \vdots \\ C_{n1} & C_{n2} & C_{n3} & \cdots & C_{nm} \end{bmatrix}$$

Row n is current allocation to process n

Resources available
$(A_1, A_2, A_3, \ldots, A_m)$

Request matrix

$$\begin{bmatrix} R_{11} & R_{12} & R_{13} & \cdots & R_{1m} \\ R_{21} & R_{22} & R_{23} & \cdots & R_{2m} \\ \vdots & \vdots & \vdots & & \vdots \\ R_{n1} & R_{n2} & R_{n3} & \cdots & R_{nm} \end{bmatrix}$$

Row 2 is what process 2 needs

Data structures needed by deadlock detection algorithm

Deadlock detection: example

$$E = \begin{array}{cccc} \text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms} \\ (4 & 2 & 3 & 1) \end{array} \qquad A = \begin{array}{cccc} \text{Tape drives} & \text{Plotters} & \text{Scanners} & \text{CD Roms} \\ (2 & 1 & 0 & 0) \end{array}$$

Current allocation matrix

$$C = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 2 & 0 & 0 & 1 \\ 0 & 1 & 2 & 0 \end{bmatrix}$$

Request matrix

$$R = \begin{bmatrix} 2 & 0 & 0 & 1 \\ 1 & 0 & 1 & 0 \\ 2 & 1 & 0 & 0 \end{bmatrix}$$

An example for the deadlock detection algorithm

Methods for handling deadlocks

- Ensure that the system will *never* enter a deadlock state. ***(deadlock prevention and avoidance)***
  - * problems: low device utilization, reduced throughput
  - * avoidance also requires prediction of resource needs
- Allow the system to enter a deadlock state and then recover. ***(deadlock detection and recovery)***
  - * costly; sometimes impossible to recover
- Ignore the problem and pretend that deadlocks never occur in the system; used by most operating systems, including UNIX.

Deadlock dynamics

- Safe state:
  - For any possible sequence of future resource requests, it is possible to eventually grant all requests
  - May require waiting even when resources are available!
- Unsafe state:
  - Some sequence of resource requests can result in deadlock
  -
- Doomed state:
  - All possible computations lead to deadlock

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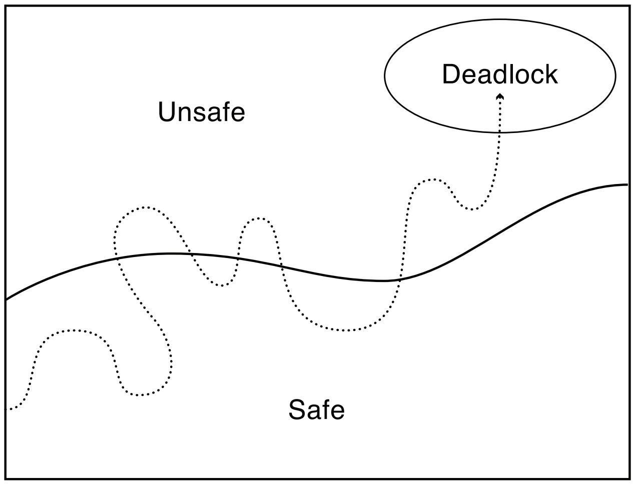
Possible system states



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Safe and unsafe states

(a)

	Has	Max
A	3	9
B	2	4
C	2	7

Free: 3

(b)

	Has	Max
A	3	9
B	4	4
C	2	7

Free: 1

(c)

	Has	Max
A	3	9
B	0	–
C	2	7

Free: 5

(d)

	Has	Max
A	3	9
B	0	–
C	7	7

Free: 0

(e)

	Has	Max
A	3	9
B	0	–
C	0	–

Free: 7

Demonstration that the state in **(a)** is safe

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Safe and unsafe states

(a)

	Has	Max
A	3	9
B	2	4
C	2	7

Free: 3

(b)

	Has	Max
A	4	9
B	2	4
C	2	7

Free: 2

(c)

	Has	Max
A	4	9
B	4	4
C	2	7

Free: 0

(d)

	Has	Max
A	4	9
B	—	—
C	2	7

Free: 4

Demonstration that the state in **(b)** is not safe

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Predict the future

- Banker's algorithm
  - State maximum resource needs in advance
  - Allocate resources dynamically when resource is needed -- wait if granting request would lead to deadlock
  - Request can be granted if some sequential ordering of threads is deadlock free

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Banker's algorithm

- Grant request iff result is a safe state
- Sum of maximum resource needs of current threads can be greater than the total resources
  - Provided there is some way for all the threads to finish without getting into deadlock
- Example: proceed iff
  - total available resources - # allocated >= max remaining that might be needed by this thread in order to finish
  - Guarantees this thread can finish

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Banker's algorithm for a single resource

	Has	Max
A	0	6
B	0	5
C	0	4
D	0	7

Free: 10

(a)

	Has	Max
A	1	6
B	1	5
C	2	4
D	4	7

Free: 2

(b)

	Has	Max
A	1	6
B	2	5
C	2	4
D	4	7

Free: 1

(c)

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Banker's algorithm for multiple resources

Process	Tape drives	Plotters	Scanners	CD ROMs
A	3	0	1	1
B	0	1	0	0
C	1	1	1	0
D	1	1	0	1
E	0	0	0	0

Resources assigned

Process	Tape drives	Plotters	Scanners	CD ROMs
A	1	1	0	0
B	0	1	1	2
C	3	1	0	0
D	0	0	1	0
E	2	1	1	0

Resources still needed

E = (6342)
P = (5322)
A = (1020)

Example of banker's algorithm with multiple resources

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Banker’s algorithm: data structures

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

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

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

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Banker’s algorithm

```
class ResourceMgr {
  private:
    Lock lock;
    CV cv;
    int r;          // Number of resources
    int t;          // Number of threads
    int avail[];    // avail[i]: instances of resource i available
    int max[][];    // max[i][j]: max of resource i needed by thread j
    int alloc[][];  // alloc[i][j]: current allocation of resource i to thread j
  ...
}

// Invariant: the system is in a safe state.
ResourceMgr::Request(int resourceID, int threadID) {
    lock.Acquire();
    assert(isSafe());
    while (!wouldBeSafe(resourceID, threadID)) {
        cv.Wait(&lock);
    }
    alloc[resourceID][threadID]++;
    avail[resourceID]--;
    assert(isSafe());
    lock.Release();
}
```

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Banker's algorithm (cont'd)

```
// A state is safe iff there exists a safe sequence of grants that are sufficient
// to allow all threads to eventually receive their maximum resource needs.
bool ResourceMgr::isSafe() {
   int j;
   int toBeAvail[] = copy avail[];
   int need[][] = max[][] - alloc[][];  // need[i][j] is initialized to  max[i][j] - alloc[i][j]
   bool finish[] = [false, false, false, ...]; // finish[j] is true if thread j is guaranteed to finish
   while (true) {
      j = any threadID such that:
         (finish[j] == false) && forall i: need[i][j] <= toBeAvail[i];
      if (no such j exists) {
         if (forall j: finish[j] == true) {
            return true;
         } else {
            return false;
         }
      } else {  // Thread j will eventually finish and return its current allocation to the pool.
         finish[j] = true;
         forall i:  toBeAvail[i] = toBeAvail[i] + alloc[i][j];
      }
   }
}
```

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Banker's algorithm (cont'd)

```
// Hypothetically grant request and see if resulting state is safe.

bool
ResourceMgr::wouldBeSafe(int resourceID, int threadID) {
   bool result = false;

   avail[resourceID]--;
   alloc[resourceID][threadID]++;
   if (isSafe()) {
      result = true;
   }
   avail[resourceID]++;
   alloc[resourceID][threadID]--;
   return result;
}
```

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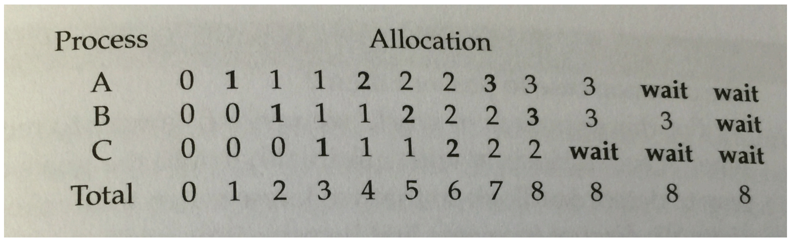
Why we need Banker's algorithm?

8 pages of memory available

Three processes: A, B, C which need 4, 5, 5 pages respectively

The following would leads to deadlock



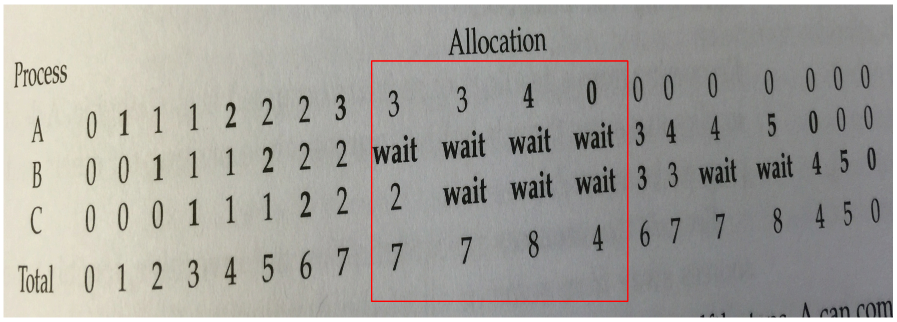
Process	Allocation											
A	0	**1**	1	1	**2**	2	2	**3**	3	3	**wait**	**wait**
B	0	0	**1**	1	1	**2**	2	2	**3**	3	3	**wait**
C	0	0	0	**1**	1	1	**2**	2	2	**wait**	**wait**	**wait**
Total	0	1	2	3	4	5	6	7	8	8	8	8

Why we need Banker's algorithm?

8 pages of memory available

Three processes: A, B, C which need 4, 5, 5 pages respectively

The following would work!



Process	Allocation																		
A	0	**1**	1	1	**2**	2	2	**3**	3	3	**4**	**0**	0	0	0	0	0	0	0
B	0	0	**1**	1	1	**2**	2	2	**wait**	**wait**	**wait**	**wait**	3	4	4	5	0	0	0
C	0	0	0	**1**	1	1	**2**	2	2	**wait**	**wait**	**wait**	3	3	wait	wait	4	5	0
Total	0	1	2	3	4	5	6	7	7	7	8	4	6	7	7	8	4	5	0

Detect and repair

- Algorithm
  - Scan wait for graph
  - Detect cycles
  - Fix cycles
- Proceed without the resource
  - Requires robust exception handling code
- Roll back and retry
  - Transaction: all operations are provisional until have all required resources to complete operation

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