CS162
Operating Systems and Systems Programming
Lecture 13

Scheduling 4: Deadlock (Finished)

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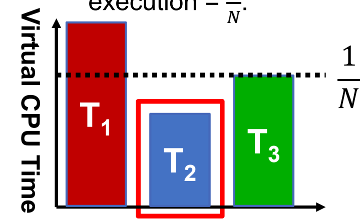
Recall: Linux Completely Fair Scheduler (CFS)

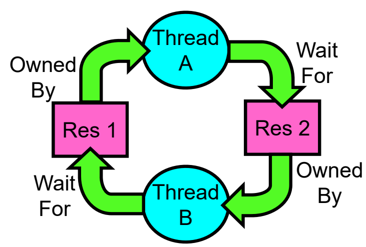
- Basic Idea: track CPU time per thread and schedule threads to match up average rate of execution
- **Scheduling Decision:**
  - "Repair" illusion of complete fairness
  - Choose thread with minimum CPU time
  - Closely related to Fair Queueing
- Use a heap-like scheduling queue for this…
  - O(log N) to add/remove threads
- Sleeping threads don't advance their CPU time, so they get a boost when they wake
  - Get interactivity automatically!
- Differentiation: Use weights! Key Idea: Assign a weight w_i to each process *I* to compute the switching quanta Q_i
  - Basic equal share: $Q_i = \text{Target Latency} \cdot \frac{1}{N}$
  - Weighted Share: $Q_i = \left({}^{w_i}/_{\sum_p w_p}\right) \cdot \text{Target Latency}$

CFS: Average rate of execution = $\frac{1}{N}$:

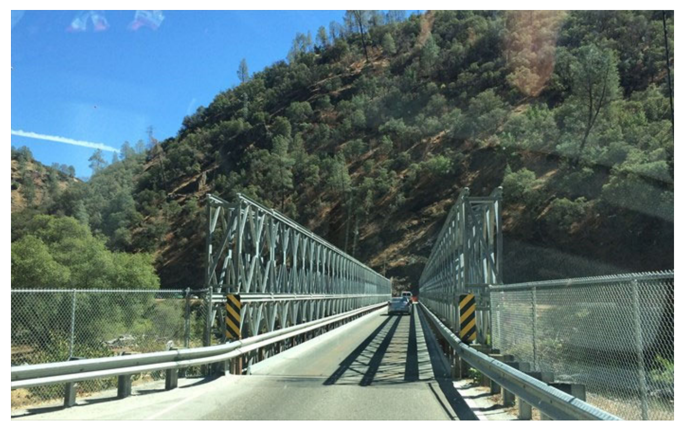


Deadlock: A Deadly type of Starvation

- Starvation: thread waits indefinitely
  - Example, low-priority thread waiting for resources constantly in use by high-priority threads
- Deadlock: circular waiting for resources
  - Thread A owns Res 1 and is waiting for Res 2
    Thread B owns Res 2 and is waiting for Res 1
- Deadlock ⇒ Starvation but not vice versa
  - Starvation can end (but doesn't have to)
  - Deadlock can't end without external intervention



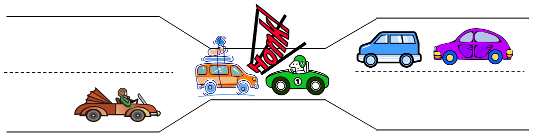
Example: Single-Lane Bridge Crossing

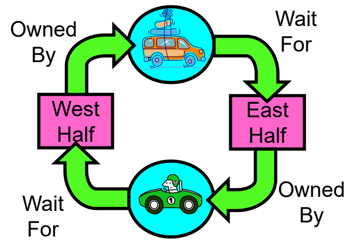


CA 140 to Yosemite National Park

Bridge Crossing Example

- Each segment of road can be viewed as a resource
  - Car must own the segment under them
  - Must acquire segment that they are moving into
- For bridge: must acquire both halves
  - Traffic only in one direction at a time

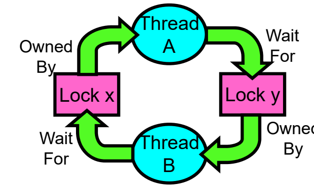




- Deadlock: Shown above when two cars in opposite directions meet in middle
  - Each acquires one segment and needs next
  - Deadlock resolved if one car backs up (preempt resources and rollback)
    - » Several cars may have to be backed up
- Starvation (not Deadlock):
  - East-going traffic really fast ⇒ no one gets to go west

Deadlock with Locks

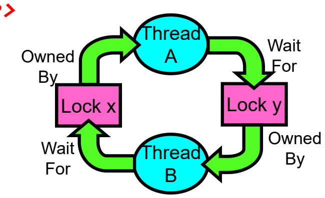
```
Thread A:          Thread B:
x.Acquire();       y.Acquire();
y.Acquire();       x.Acquire();
…                  …
y.Release();       x.Release();
x.Release();       y.Release();
```



- This lock pattern exhibits *non-deterministic deadlock*
  - Sometimes it happens, sometimes it doesn't!
- This is really hard to debug!

Deadlock with Locks: "Unlucky" Case

```
Thread A:                     Thread B:
x.Acquire();
                              y.Acquire();
y.Acquire(); <stalled>
<unreachable>                 x.Acquire(); <stalled>
…                             <unreachable>
y.Release();                  …
x.Release();                  x.Release();
                              y.Release();
```



Neither thread will get to run ⇒ Deadlock

Deadlock with Locks: "Lucky" Case

```
Thread A:                     Thread B:
x.Acquire();
y.Acquire();
…                             y.Acquire();
y.Release();
x.Release();
                              x.Acquire();
                              …
                              x.Release();
                              y.Release();
```

Sometimes, schedule won't trigger deadlock!

Other Types of Deadlock

- Threads often block waiting for resources
  - Locks
  - Terminals
  - Printers
  - CD drives
  - Memory
- Threads often block waiting for other threads
  - Pipes
  - Sockets
- You can deadlock on any of these!

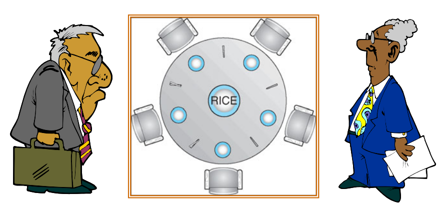
Deadlock with Space

Thread A:	**Thread B**
`AllocateOrWait(1 MB)`	`AllocateOrWait(1 MB)`
`AllocateOrWait(1 MB)`	`AllocateOrWait(1 MB)`
`Free(1 MB)`	`Free(1 MB)`
`Free(1 MB)`	`Free(1 MB)`

If only 2 MB of space, we get same deadlock situation

Dining Lawyers Problem

- Five chopsticks/Five lawyers (really cheap restaurant)
  - Free-for all: Lawyer will grab any one they can
  - Need two chopsticks to eat



- What if all grab at same time?
  - Deadlock!
- How to fix deadlock?
  - Make one of them give up a chopstick (Hah!)
  - Eventually everyone will get chance to eat
- How to prevent deadlock?
  - Never let lawyer take last chopstick if no hungry lawyer has two chopsticks afterwards
  - Can we formalize this requirement somehow?

Four requirements for occurrence of Deadlock

- Mutual exclusion
  - Only one thread at a time can use a resource.
- Hold and wait
  - Thread holding at least one resource is waiting to acquire additional resources held by other threads
- No preemption
  - Resources are released only voluntarily by the thread holding the resource, after thread is finished with it
- Circular wait
  - There exists a set $\{T_1, \ldots, T_n\}$ of waiting threads
    - » T_1 is waiting for a resource that is held by T_2
    - » T_2 is waiting for a resource that is held by T_3
    - » …
    - » T_n is waiting for a resource that is held by T_1

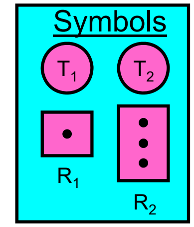
Administrivia

- Welcome to Project 2
  - Please get started earlier than last time!
- Midterm 2
  - Coming up in < 2 weeks! (3/15)
  - Everything up to the midterm is fair game (perhaps deemphasizing the lecture on the day before….)

Detecting Deadlock: Resource-Allocation Graph

- System Model
  - A set of Threads $T_1, T_2, \ldots, T_n$
  - Resource types $R_1, R_2, \ldots, R_m$

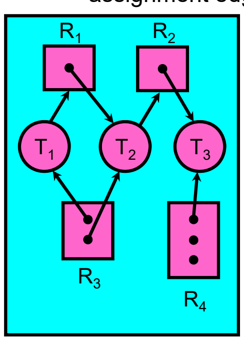
    CPU cycles, memory space, I/O devices
  - Each resource type R_i has W_i instances
  - Each thread utilizes a resource as follows:
    - » `Request() / Use() / Release()`



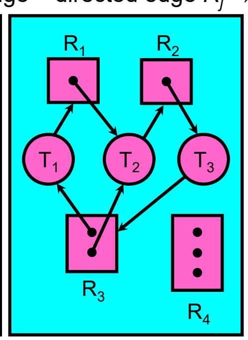
- Resource-Allocation Graph:
  - V is partitioned into two types:
    - » $T = \{T_1, T_2, \ldots, T_n\}$, the set threads in the system.
    - » $R = \{R_1, R_2, \ldots, R_m\}$, the set of resource types in system
  - request edge – directed edge $T_1 \rightarrow R_j$
  - assignment edge – directed edge $R_j \rightarrow T_i$

Resource-Allocation Graph Examples

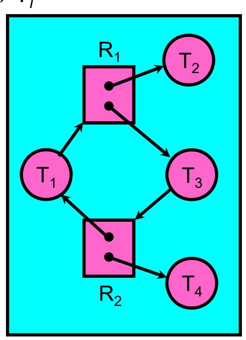
- Model:
  - request edge – directed edge $T_1 \rightarrow R_j$
  - assignment edge – directed edge $R_j \rightarrow T_i$



Simple Resource Allocation Graph



Allocation Graph With Deadlock



Allocation Graph With Cycle, but No Deadlock

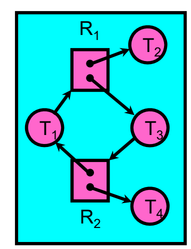
Deadlock Detection Algorithm

- Let [X] represent an m-ary vector of non-negative integers (quantities of resources of each type):

`[FreeResources]:`	Current free resources each type
`[Request_X]:`	Current requests from thread X
`[Alloc_X]:`	Current resources held by thread X

- See if tasks can eventually terminate on their own

```
[Avail] = [FreeResources]
Add all nodes to UNFINISHED
do {
   done = true
   Foreach node in UNFINISHED {
      if ([Request_node] <= [Avail]) {
         remove node from UNFINISHED
         [Avail] = [Avail] + [Alloc_node]
         done = false
      }
   }
} until(done)
```



- Nodes left in `UNFINISHED` $\Rightarrow$ deadlocked

How should a system deal with deadlock?

- Four different approaches:

1. Deadlock prevention: write your code in a way that it isn't prone to deadlock
2. Deadlock recovery: let deadlock happen, and then figure out how to recover from it
3. Deadlock avoidance: dynamically delay resource requests so deadlock doesn't happen
4. Deadlock denial: ignore the possibility of deadlock

- Modern operating systems:
  – Make sure the *system* isn't involved in any deadlock
  – Ignore deadlock in applications
    » "Ostrich Algorithm"

Techniques for Preventing Deadlock

- Infinite resources
  – Include enough resources so that no one ever runs out of resources. Doesn't have to be infinite, just large
  – Give illusion of infinite resources (e.g. virtual memory)
  – Examples:
    » Bay bridge with 12,000 lanes. Never wait!
    » Infinite disk space (not realistic yet?)
- No Sharing of resources (totally independent threads)
  – Not very realistic
- Don't allow waiting
  – How the phone company avoids deadlock
    » Call Mom in Toledo, works way through phone network, but if blocked get busy signal.
  – Technique used in Ethernet/some multiprocessor nets
    » Everyone speaks at once. On collision, back off and retry
  – Inefficient, since have to keep retrying
    » Consider: driving to San Francisco; when hit traffic jam, suddenly you're transported back home and told to retry!

(Virtually) Infinite Resources

```
Thread A                Thread B
AllocateOrWait(1 MB)    AllocateOrWait(1 MB)
AllocateOrWait(1 MB)    AllocateOrWait(1 MB)
Free(1 MB)              Free(1 MB)
Free(1 MB)              Free(1 MB)
```

- With virtual memory we have "infinite" space so everything will just succeed, thus above example won't deadlock
  – Of course, it isn't actually infinite, but certainly larger than 2MB!

Techniques for Preventing Deadlock

- Make all threads request everything they'll need at the beginning.
  – Problem: Predicting future is hard, tend to over-estimate resources
  – Example:
    » If need 2 chopsticks, request both at same time
    » Don't leave home until we know no one is using any intersection between here and where you want to go; only one car on the Bay Bridge at a time
- Force all threads to request resources in a particular order preventing any cyclic use of resources
  – Thus, preventing deadlock
  – Example (`x.Acquire()`, `y.Acquire()`, `z.Acquire()`,…)
    » Make tasks request disk, then memory, then…
    » Keep from deadlock on freeways around SF by requiring everyone to go clockwise

Request Resources Atomically (1)

Rather than:

Thread A:	Thread B:
`x.Acquire();`	`y.Acquire();`
`y.Acquire();`	`x.Acquire();`
…	…
`y.Release();`	`x.Release();`
`x.Release();`	`y.Release();`

Consider instead:

Thread A:	Thread B:
`Acquire_both(x, y);`	`Acquire_both(y, x);`
…	…
`y.Release();`	`x.Release();`
`x.Release();`	`y.Release();`

Request Resources Atomically (2)

Or consider this:

Thread A	Thread B
`z.Acquire();`	`z.Acquire();`
`x.Acquire();`	`y.Acquire();`
`y.Acquire();`	`x.Acquire();`
`z.Release();`	`z.Release();`
…	…
`y.Release();`	`x.Release();`
`x.Release();`	`y.Release();`

Acquire Resources in Consistent Order

Rather than:

Thread A:	Thread B:
`x.Acquire();`	`y.Acquire();`
`y.Acquire();`	`x.Acquire();`
…	…
`y.Release();`	`x.Release();`
`x.Release();`	`y.Release();`

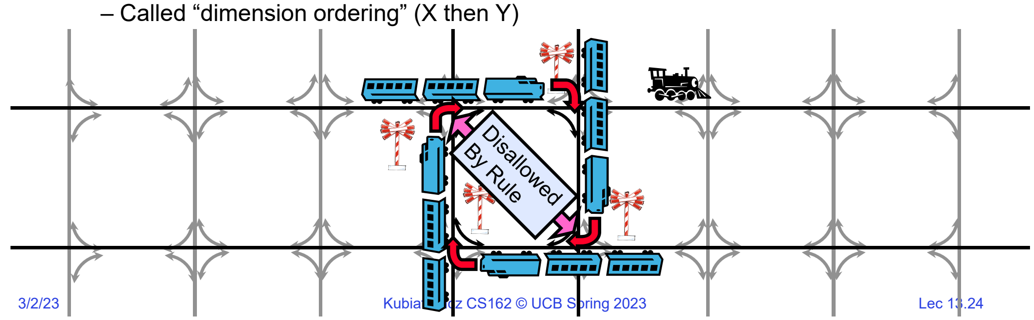
Consider instead:

Thread A:	Thread B:
`x.Acquire();`	`x.Acquire();`
`y.Acquire();`	`y.Acquire();`
…	…
`y.Release();`	`x.Release();`
`x.Release();`	`y.Release();`

Does it matter in which order the locks are released?

Train Example (Wormhole-Routed Network)

- Circular dependency (Deadlock!)
  - Each train wants to turn right, but is blocked by other trains
- Similar problem to multiprocessor networks
  - Wormhole-Routed Network: Messages trail through network like a "worm"
- Fix? Imagine grid extends in all four directions
  - Force ordering of channels (tracks)
    - Protocol: Always go east-west first, then north-south
  - Called "dimension ordering" (X then Y)



Techniques for Recovering from Deadlock

- Terminate thread, force it to give up resources
  - In Bridge example, Godzilla picks up a car, hurls it into the river. Deadlock solved!
  - Hold dining lawyer in contempt and take away in handcuffs
  - But, not always possible – killing a thread holding a mutex leaves world inconsistent
- Preempt resources without killing off thread
  - Take away resources from thread temporarily
  - Doesn't always fit with semantics of computation
- Roll back actions of deadlocked threads
  - Hit the rewind button on TiVo, pretend last few minutes never happened
  - For bridge example, make one car roll backwards (may require others behind him)
  - Common technique in databases (transactions)
  - Of course, if you restart in exactly the same way, may reenter deadlock once again
- Many operating systems use other options

Another view of virtual memory: Pre-empting Resources

Thread A:	**Thread B**:
`AllocateOrWait(1 MB)`	`AllocateOrWait(1 MB)`
`AllocateOrWait(1 MB)`	`AllocateOrWait(1 MB)`
`Free(1 MB)`	`Free(1 MB)`
`Free(1 MB)`	`Free(1 MB)`

- Before: With virtual memory we have "infinite" space so everything will just succeed, thus above example won't deadlock
  - Of course, it isn't actually infinite, but certainly larger than 2MB!
- Alternative view: we are "pre-empting" memory when paging out to disk, and giving it back when paging back in
  - This works because thread can't use memory when paged out

Techniques for Deadlock Avoidance

- Idea: When a thread requests a resource, OS checks if it would result in deadlock
  - If not, it grants the resource right away
  - If so, it waits for other threads to release resources

THIS DOES NOT WORK!!!!

- Example:

	Thread A:	**Thread B**:	
	`x.Acquire();`	`y.Acquire();`	
Blocks…	`y.Acquire();`	`x.Acquire();`	Wait?
	…	…	But it's already too late…
	`y.Release();`	`x.Release();`	
	`x.Release();`	`y.Release();`	

Deadlock Avoidance: Three States

- Safe state
  - System can delay resource acquisition to prevent deadlock
- Unsafe state
  - No deadlock yet…
  - But threads can request resources in a pattern that ***unavoidably*** leads to deadlock

Deadlock avoidance: prevent system from reaching an *unsafe* state

- Deadlocked state
  - There exists a deadlock in the system
  - Also considered "unsafe"

Deadlock Avoidance

- Idea: When a thread requests a resource, OS checks if it would result in ~~deadlock~~ an unsafe state
  - If not, it grants the resource right away
  - If so, it waits for other threads to release resources

- Example:

Thread A:	**Thread B:**	
`x.Acquire();`	`y.Acquire();`	
`y.Acquire();`	`x.Acquire();`	**Wait until Thread A releases mutex X**
…	…	
`y.Release();`	`x.Release();`	
`x.Release();`	`y.Release();`	

Banker's Algorithm for Avoiding Deadlock

- Toward right idea:
  - State maximum (max) resource needs in advance
  - Allow particular thread to proceed if:
    (available resources - #requested) ≥ max remaining that might be needed by any thread

- Banker's algorithm (less conservative):
  - Allocate resources dynamically
    - » Evaluate each request and grant if some ordering of threads is still deadlock free afterward
    - » Technique: pretend each request is granted, then run deadlock detection algorithm, substituting:
      ($[Max_{node}]$-$[Alloc_{node}]$ <= [Avail]) for ($[Request_{node}]$ <= [Avail])
      Grant request if result is deadlock free (conservative!)

Banker's Algorithm for Avoiding Deadlock

```
[Avail] = [FreeResources]
     Add all nodes to UNFINISHED
     do {
        done = true
        Foreach node in UNFINISHED {
           if ([Request_node] <= [Avail]) {
              remove node from UNFINISHED
              [Avail] = [Avail] + [Alloc_node]
              done = false
           }
        }
     } until(done)
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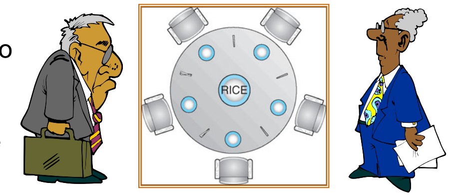
      ([Max_{node}]-[$Alloc_{node}$] <= [Avail]) for ([$Request_{node}$] <= [Avail])
      Grant request if result is deadlock free (conservative!)
  - Keeps system in a "SAFE" state: there exists a sequence {T_1, T_2, … T_n} with T_1 requesting all remaining resources, finishing, then T_2 requesting all remaining resources, etc..

Banker's Algorithm Example

- Banker's algorithm with dining lawyers
  - "Safe" (won't cause deadlock) if when try to grab chopstick either:
    - » Not last chopstick
    - » Is last chopstick but someone will have two afterwards



  - What if k-handed lawyers? Don't allow if:
    - » It's the last one, no one would have k
    - » It's 2nd to last, and no one would have k-1
    - » It's 3rd to last, and no one would have k-2
    - » …

Deadlock Summary

- Four conditions for deadlocks
  - Mutual exclusion
  - Hold and wait
  - No preemption
  - Circular wait
- Techniques for addressing Deadlock
  - Deadlock prevention:
    - » write your code in a way that it isn't prone to deadlock
  - Deadlock recovery:
    - » let deadlock happen, and then figure out how to recover from it
  - Deadlock avoidance:
    - » dynamically delay resource requests so deadlock doesn't happen
    - » Banker's Algorithm provides on algorithmic way to do this
  - Deadlock denial:
    - » ignore the possibility of deadlock