CS162
Operating Systems and Systems Programming
Lecture 12

Scheduling 3: Deadlock

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Recall: Real-Time Scheduling

- Goal: Predictability of Performance!
  - We need to predict with confidence worst case response times for systems!
  - In RTS, performance guarantees are:
    - Task- and/or class centric and often ensured a priori
  - In conventional systems, performance is:
    - System/throughput oriented with post-processing (… wait and see …)
  - Real-time is about enforcing predictability, and does not equal fast computing!!!
- Hard real-time: for time-critical safety-oriented systems
  - Meet all deadlines (if at all possible)
  - Ideally: determine in advance if this is possible
  - Earliest Deadline First (EDF), Least Laxity First (LLF), Rate-Monitonic Scheduling (RMS), Deadline Monotonic Scheduling (DM)
- Soft real-time: for multimedia
  - Attempt to meet deadlines with high probability
  - Constant Bandwidth Server (CBS)

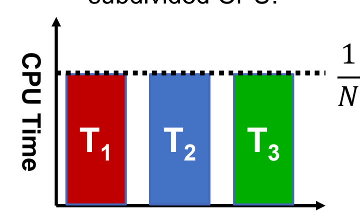
Recall: Stride Scheduling

- Achieve proportional share scheduling without resorting to randomness, and overcome the "law of small numbers" problem.
- "Stride" of each job is $\frac{big\#W}{N_i}$
  - The larger your share of tickets, the smaller your stride
  - Ex: W = 10,000, A=100 tickets, B=50, C=250
  - A stride: 100, B: 200, C: 40
- Each job as a "pass" counter
- Scheduler: pick job with lowest *pass*, runs it, add its *stride* to its *pass*
- Low-stride jobs (lots of tickets) run more often
  - Job with twice the tickets gets to run twice as often
- Some messiness of counter wrap-around, new jobs, …

Recall: Linux Completely Fair Scheduler (CFS)

- Goal: Each process gets an equal share of CPU
  - *N* threads "simultaneously" execute on $\frac{1}{N}$ of CPU
  - The *model* is somewhat like simultaneous multithreading – each thread gets $\frac{1}{N}$ of the cycles
- In general, can't do this with real hardware
  - OS needs to give out full CPU in time slices
  - Thus, we must use something to keep the threads roughly in sync with one another

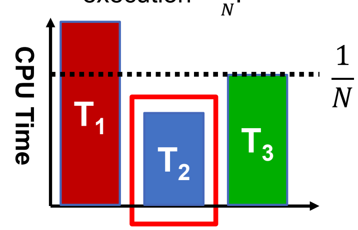
Model: "Perfectly" subdivided CPU:



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, where N is number of threads
- Sleeping threads don't advance their CPU time, so they get a boost when they wake up again…
  - Get interactivity automatically!

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



Linux CFS: Responsiveness/Starvation Freedom

- In addition to fairness, we want **low response time** and starvation freedom
  - Make sure that everyone gets to run at least a bit!
- Constraint 1: *Target Latency*
  - Period of time over which every process gets service
  - Quanta = Target_Latency / n
- Target Latency: 20 ms, 4 Processes
  - Each process gets 5ms time slice
- Target Latency: 20 ms, 200 Processes
  - Each process gets 0.1ms time slice (!!!)
  - Recall Round-Robin: large context switching overhead if slice gets to small

Linux CFS: Throughput

- Goal: Throughput
  - Avoid excessive overhead
- Constraint 2: Minimum Granularity
  - Minimum length of any time slice

- Target Latency 20 ms, Minimum Granularity 1 ms, 200 processes
  - Each process gets 1 ms time slice

Aside: Priority in Unix – Being Nice

- The industrial operating systems of the 60s and 70's provided priority to enforced desired usage policies.
  - When it was being developed at Berkeley, instead it provided ways to "be nice".
- `nice` values range from -20 to 19
  - Negative values are "not nice"
  - If you wanted to let your friends get more time, you would nice up your job
- Scheduler puts higher nice-value tasks (lower priority) to sleep more …
  - In O(1) scheduler, this translated fairly directly to priority (and time slice)
- How does this idea translate to CFS?
  - Change the rate of CPU cycles given to threads to change relative priority

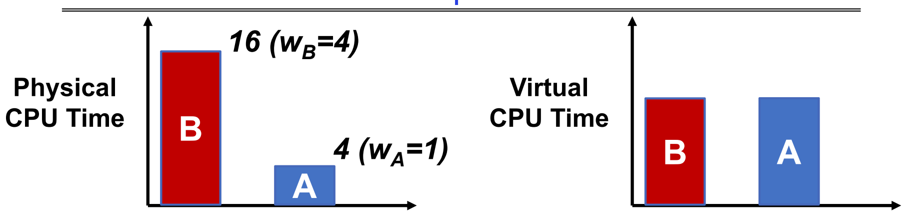
Linux CFS: Proportional Shares

- What if we want to give more CPU to some and less to others in CFS (proportional share) ?
  - Allow different threads to have different *rates* of execution (cycles/time)
- 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: $Q_i = \left({}^{w_i}/_{\sum_p w_p} \right) \cdot \text{Target Latency}$
- Reuse `nice` value to reflect share, rather than priority,
  - Remember that lower nice value ⇒ higher priority
  - CFS uses nice values to scale weights exponentially: Weight=1024/(1.25)^{nice}
    - » Two CPU tasks separated by nice value of 5 ⇒ Task with lower nice value has 3 times the weight, since $(1.25)^5 \approx 3$
- So, we use "Virtual Runtime" instead of CPU time

Example: Linux CFS: Proportional Shares

- Target Latency = 20ms
- Minimum Granularity = 1ms
- Example: Two CPU-Bound Threads
  - Thread A has weight 1
  - Thread B has weight 4
- Time slice for A? 4 ms
- Time slice for B? 16 ms

Linux CFS: Proportional Shares



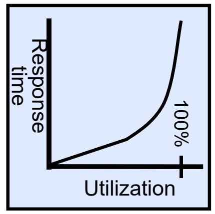
- Track a thread's *virtual* runtime rather than its true physical runtime
  - Higher weight: Virtual runtime increases more slowly
  - Lower weight: Virtual runtime increases more quickly
- Scheduler's Decisions are based on Virtual CPU Time
- Use of Red-Black tree to hold all runnable processes as sorted on vruntime variable
  - O(1) time to find next thread to run (top of heap!)
  - O(log N) time to perform insertions/deletions
    - » Cash the item at far left (item with earliest vruntime)
  - When ready to schedule, grab version with smallest vruntime (which will be item at the far left).

Choosing the Right Scheduler

I Care About:	Then Choose:
CPU Throughput	FCFS
Avg. Response Time	SRTF Approximation
I/O Throughput	SRTF Approximation
Fairness (CPU Time)	Linux CFS
Fairness – Wait Time to Get CPU	Round Robin
Meeting Deadlines	EDF
Favoring Important Tasks	Priority

A Final Word On Scheduling

- When do the details of the scheduling policy and fairness really matter?
  - When there aren't enough resources to go around
- When should you simply buy a faster computer?
  - (Or network link, or expanded highway, or …)
  - One approach: Buy it when it will pay for itself in improved response time
    - » Perhaps you're paying for worse response time in reduced productivity, customer angst, etc…
    - » Might think that you should buy a faster X when X is utilized 100%, but usually, response time goes to infinity as utilization⇒100%
- An interesting implication of this curve:
  - Most scheduling algorithms work fine in the "linear" portion of the load curve, fail otherwise
  - Argues for buying a faster X when hit "knee" of curve

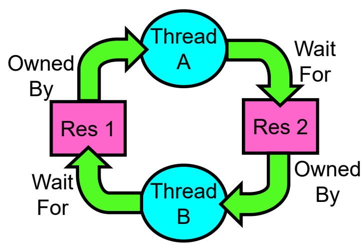


Administrivia

- Midterm 1: Still grading
- Group evaluations coming up for Project 1
  - Every person gets 20 pts/partner which they hand out as they wish
  - No points to yourself!
  - Projects are a zero-sum game: you must participate in your group!
    - » Some of you seem to have fallen off the earth and aren't responding to email
    - » This is a good way to get no points for your part in projects
- Make sure that your TA understands any issues that you might be having with your group
  - I'm happy to meet with groups that just want a bit of "fine-tuning"
- Group Coffee Hours
  - Look for opportunities to get extra points for a screen-shot with you and your team (with cameras turned on)!
- Don't forget to turn on camera for discussion sections!

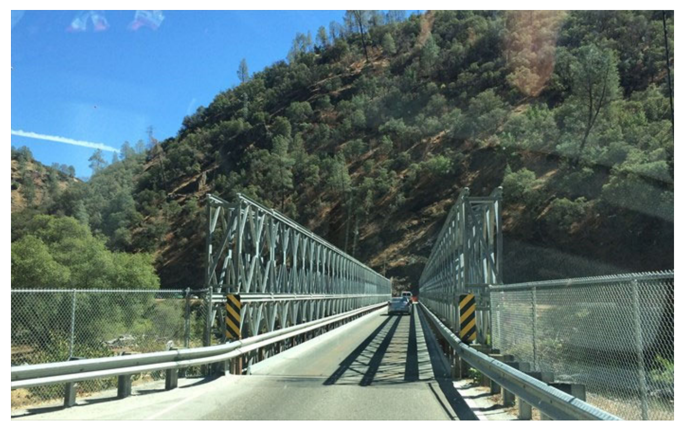
Deadlock: A Deadly type of Starvation

- 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

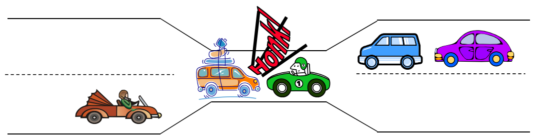
Example: Single-Lane Bridge Crossing

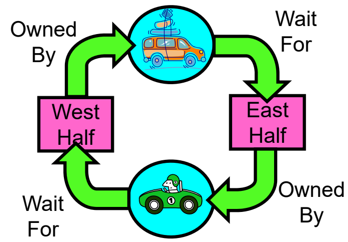


CA 140 to Yosemite National Park

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



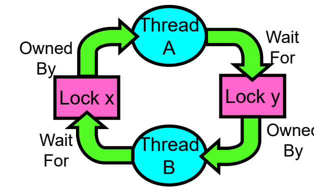


- Deadlock: Shown above when two cars in opposite directions meet in middle
  – Each acquires one segment and needs next
  – Deadlock resolved if one car backs up (preempt resources and rollback)
    » Several cars may have to be backed up
- Starvation (not Deadlock):
  – East-going traffic really fast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

Deadlock with Locks

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

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

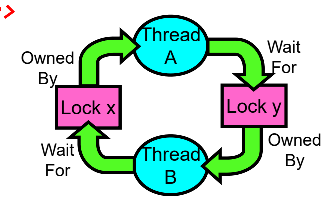
Thread A:
```
x.Acquire();

y.Acquire(); <stalled>
<unreachable>
…
y.Release();
x.Release();
```

Thread B:
```

y.Acquire();

x.Acquire(); <stalled>
<unreachable>
…
x.Release();
y.Release();
```



Neither thread will get to run ⇒ Deadlock

Deadlock with Locks: "Lucky" Case

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

Thread B:
```


y.Acquire();

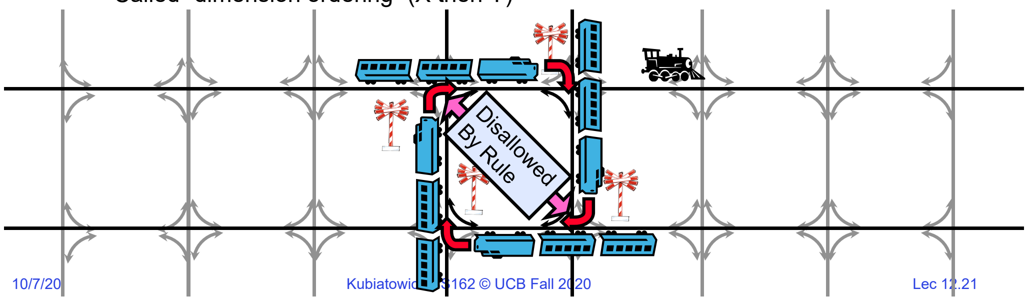


x.Acquire();
…
x.Release();
y.Release();
```

Sometimes, schedule won't trigger deadlock!

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)



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!

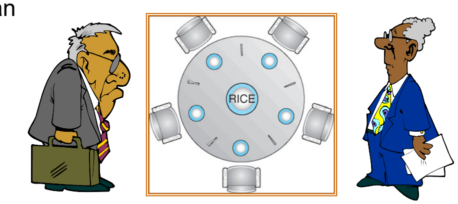
Deadlock with Space

<u>Thread A:</u>	<u>Thread B</u>
`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?

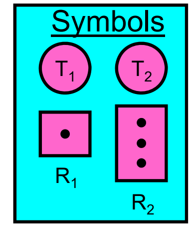


Four requirements for occurrence of Deadlock

- 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

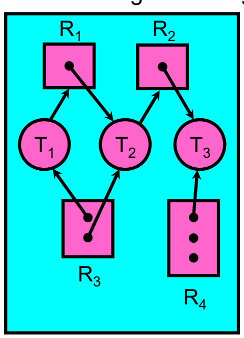
Detecting Deadlock: Resource-Allocation Graph

- 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 $R_j \rightarrow T_i$

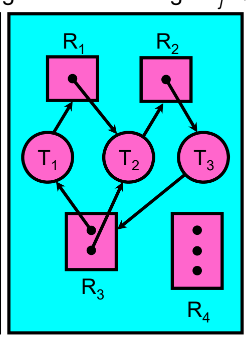


Resource-Allocation Graph Examples

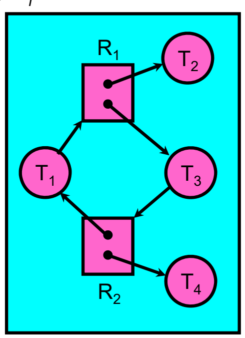
- Model:
  – request edge – directed edge $T_1 \rightarrow R_j$
  – assignment edge – directed edge $R_j \rightarrow T_i$



Simple Resource Allocation Graph



Allocation Graph With Deadlock



Allocation Graph With Cycle, but No Deadlock

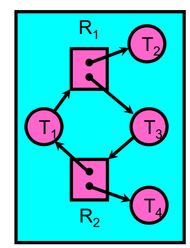
Deadlock Detection Algorithm

- 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` ⇒ 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:
```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

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

Consider instead:

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

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


Request Resources Atomically (2)

Or consider this:

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

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


Acquire Resources in Consistent Order

Rather than:

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

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

Consider instead:

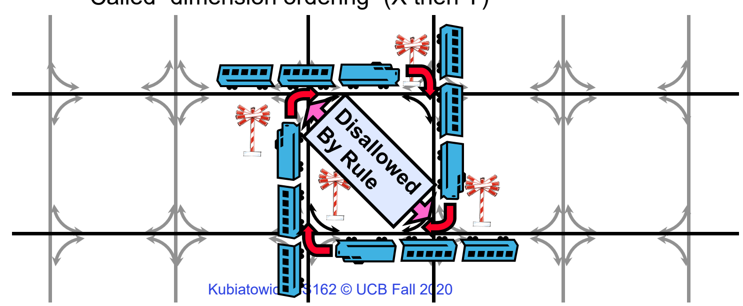
Thread A:
```
x.Acquire();
y.Acquire();
…
y.Release();
x.Release();
```

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

Does it matter in which order the locks are released?

Review: Train Example (Wormhole-Routed Network)

- Circular dependency (Deadlock!)
  - Each train wants to turn right
  - Blocked by other trains
  - Similar problem to multiprocessor networks
- 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:
      ($[\text{Max}_{node}]$-$[\text{Alloc}_{node}]$ <= [Avail]) for ($[\text{Request}_{node}]$ <= [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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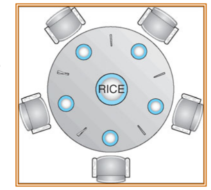
Banker's Algorithm for Avoiding Deadlock

- 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!)
  - Keeps system in a "SAFE" state: there exists a sequence $\{T_1, T_2, \ldots T_n\}$ 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 2^{nd} to last, and no one would have k-1
    - » It's 3^{rd} to last, and no one would have k-2
    - » …

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