CS162
Operating Systems and Systems Programming
Lecture 11

Scheduling (finished), Deadlock, Address Translation

October 2nd, 2017
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Real-Time Scheduling (RTS)

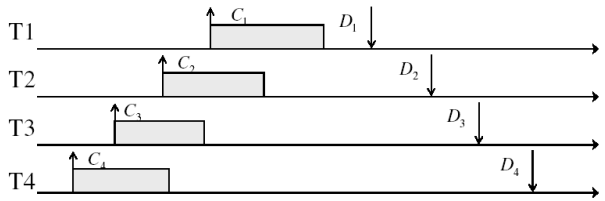
- Efficiency is important but predictability is essential:
  - We need to predict with confidence worst case response times for systems
  - In RTS, performance guarantees are:
    - » Task- and/or class centric and often ensured a priori
  - In conventional systems, performance is:
    - » System/throughput oriented with post-processing (… wait and see …)
  - Real-time is about enforcing predictability, and does not equal fast computing!!!

Real-Time Scheduling (RTS)

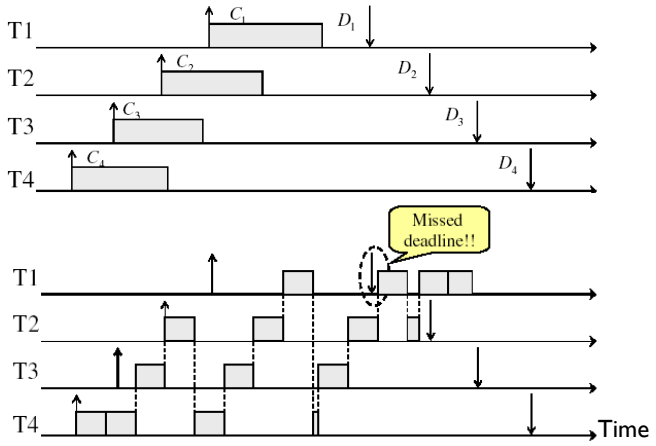
- Hard Real-Time
  - *Attempt to meet all deadlines*
  - EDF (Earliest Deadline First), LLF (Least Laxity First), RM (Rate-Monotonic), DM (Deadline Monotonic)
- Soft Real-Time
  - *Attempt to meet deadlines with high probability*
  - Minimize miss ratio / maximize completion ratio (firm real-time)
  - Important for multimedia applications
  - CBS (Constant Bandwidth Server)

Example: Workload Characteristics

- Tasks are preemptable, independent with arbitrary arrival (=release) times
- Tasks have deadlines (D) and known computation times (C)
- Example Setup:

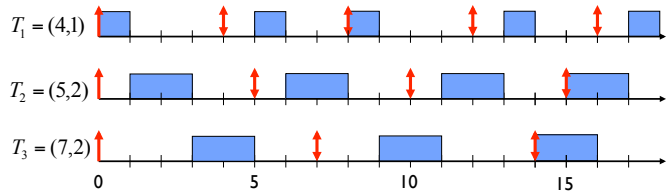


Example: Round-Robin Scheduling Doesn't Work



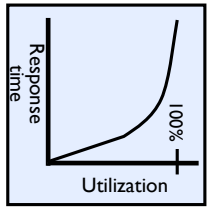
Earliest Deadline First (EDF)

- Tasks periodic with period P and computation C in each period: (P, C)
- Preemptive priority-based dynamic scheduling
- Each task is assigned a (current) priority based on how close the absolute deadline is
- The scheduler always schedules the active task with the closest absolute deadline



A Final Word On Scheduling

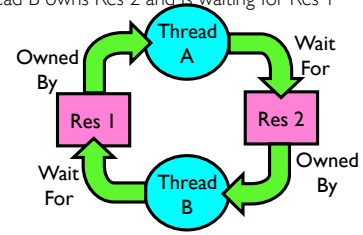
- When do the details of the scheduling policy and fairness really matter?
  - When there aren't enough resources to go around
- When should you simply buy a faster computer?
  - (Or network link, or expanded highway, or …)
  - One approach: Buy it when it will pay for itself in improved response time
    - » Assuming 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

Starvation vs Deadlock

- Starvation vs. Deadlock
  - 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

Conditions for Deadlock

- Deadlock not always deterministic – Example 2 mutexes:

Thread A	Thread B
x.P();	y.P();
y.P();	x.P();
y.V();	x.V();
x.V();	y.V();

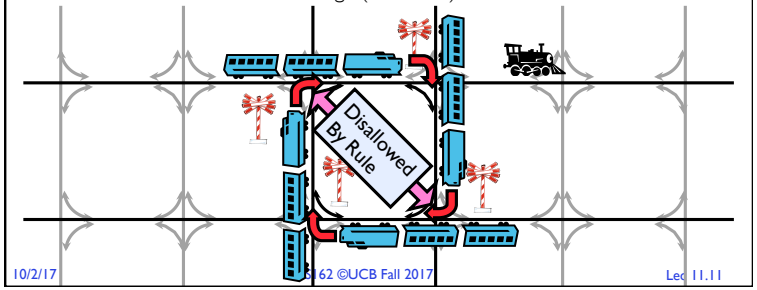
  - Deadlock won't always happen with this code
    - » Have to have exactly the right timing ("wrong" timing?)
    - » So you release a piece of software, and you tested it, and there it is, controlling a nuclear power plant…
- Deadlocks occur with multiple resources
  - Means you can't decompose the problem
  - Can't solve deadlock for each resource independently
- Example: System with 2 disk drives and two threads
  - Each thread needs 2 disk drives to function
  - Each thread gets one disk and waits for another one

Bridge Crossing Example

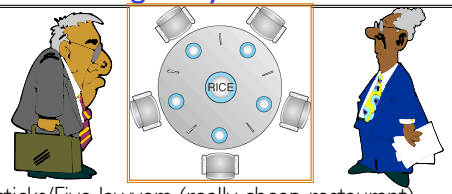
- Each segment of road can be viewed as a resource
  - Car must own the segment under them
  - Must acquire segment that they are moving into
- For bridge: must acquire both halves
  - Traffic only in one direction at a time
  - Problem occurs when two cars in opposite directions on bridge: each acquires one segment and needs next
- 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
- Starvation is possible
  - East-going traffic really fast ⇒ no one goes west

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)



Dining Lawyers Problem

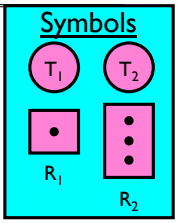


- Five chopsticks/Five lawyers (really cheap restaurant)
  - Free-for all: Lawyer will grab any one they can
  - Need two chopsticks to eat
- What if all grab at same time?
  - Deadlock!
- How to fix deadlock?
  - Make one of them give up a chopstick (Hah!)
  - Eventually everyone will get chance to eat
- How to prevent deadlock?
  - Never let lawyer take last chopstick if no hungry lawyer has two chopsticks afterwards

Four requirements for 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

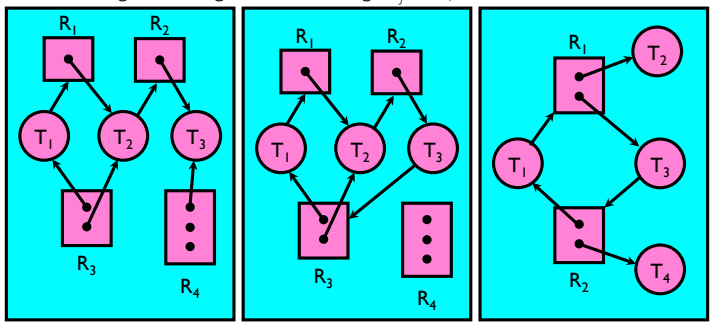
Resource-Allocation Graph



- 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

- Recall:
  - 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

Methods for Handling Deadlocks

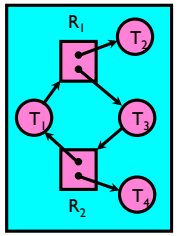
- Allow system to enter deadlock and then recover
  - Requires deadlock detection algorithm
  - Some technique for forcibly preempting resources and/or terminating tasks
- Ensure that system will *never* enter a deadlock
  - Need to monitor all lock acquisitions
  - Selectively deny those that *might* lead to deadlock
- Ignore the problem and pretend that deadlocks never occur in the system
  - Used by most operating systems, including UNIX

Deadlock Detection Algorithm

- Only one of each type of resource ⇒ look for loops
- More General 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

What to do when detect deadlock?

- Terminate thread, force it to give up resources
  - In Bridge example, Godzilla picks up a car, hurls it into the river. Deadlock solved!
  - Shoot a dining lawyer
  - 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

Administrivia

- Ion out next week (travelling to China):
  - 11/9: lecture will be given by Anthony Joseph (tentatively)
  - 11/11: lecture will be given by Neeraja

Deadline for 1st midterm regrades: Friday, 10/6

BREAK

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 to your Mom in Toledo, works its way through the phone lines, 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!

Techniques for Preventing Deadlock (cont'd)

- 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.P, y.P, z.P,…)
    - » Make tasks request disk, then memory, then…
    - » Keep from deadlock on freeways around SF by requiring everyone to go clockwise

Review: Train Example (Wormhole-Routed Network)

- Circular dependency (Deadlock!)
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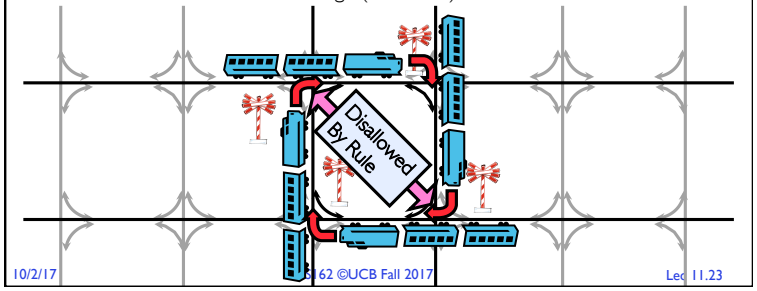

Banker's Algorithm for Preventing Deadlock

- 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
      $([Max_{node}]-[Alloc_{node}] \leq [Avail])$ for $([Request_{node}] \leq [Avail])$
      Grant request if result is deadlock free (conservative!)

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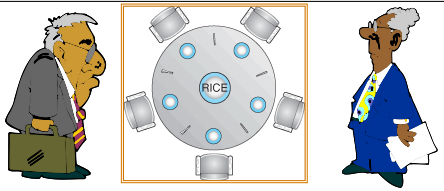
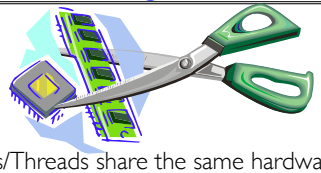
      ([Max_{node}]-[$Alloc_{node}$] ≤ [Avail]) for ([$Request_{node}$] ≤ [Avail])
      Grant request if result is deadlock free (conservative!)
    - » Keeps system in a "SAFE" state, i.e. there exists a sequence {T_1, T_2, … T_n} with T_1 requesting all remaining resources, finishing, then T_2 requesting all remaining resources, etc..
  - Algorithm allows the sum of maximum resource needs of all current threads to be greater than total resources

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
    - » …

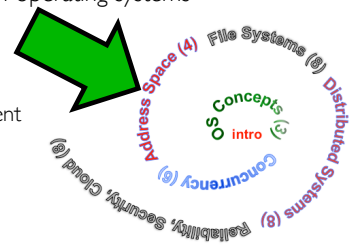
Virtualizing Resources



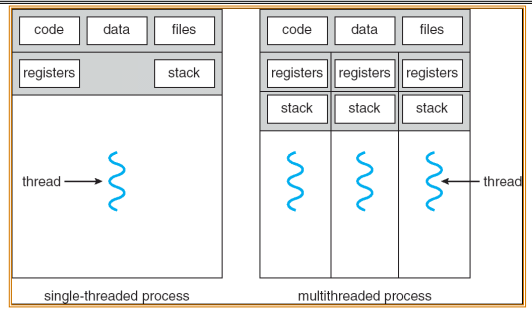
- Physical Reality:
  Different Processes/Threads share the same hardware
  - Need to multiplex CPU (Just finished: scheduling)
  - Need to multiplex use of Memory (starting today)
  - Need to multiplex disk and devices (later in term)
- Why worry about memory sharing?
  - The complete working state of a process and/or kernel is defined by its data in memory (and registers)
  - Consequently, cannot just let different threads of control use the same memory
    - » Physics: two different pieces of data cannot occupy the same locations in memory
  - Probably don't want different threads to even have access to each other's memory (protection)

Next Objective

- Dive deeper into the concepts and mechanisms of memory sharing and address translation
- Enabler of many key aspects of operating systems
  - Protection
  - Multi-programming
  - Isolation
  - Memory resource management
  - I/O efficiency
  - Sharing
  - Inter-process communication
  - Debugging
  - Demand paging
- Today: Translation



Recall: Single and Multithreaded Processes

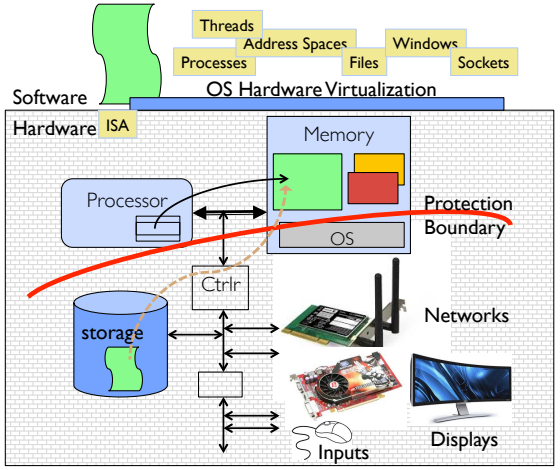


- Threads encapsulate concurrency
  - "Active" component of a process
- Address spaces encapsulate protection
  - Keeps buggy program from trashing the system
  - "Passive" component of a process

Important Aspects of Memory Multiplexing

- Protection:
  - Prevent access to private memory of other processes
    - » Different pages of memory can be given special behavior (Read Only, Invisible to user programs, etc).
    - » Kernel data protected from User programs
    - » Programs protected from themselves
- Controlled overlap:
  - Separate state of threads should not collide in physical memory. Obviously, unexpected overlap causes chaos!
  - Conversely, would like the ability to overlap when desired (for communication)
- Translation:
  - Ability to translate accesses from one address space (virtual) to a different one (physical)
  - When translation exists, processor uses virtual addresses, physical memory uses physical addresses
  - Side effects:
    - » Can be used to avoid overlap
    - » Can be used to give uniform view of memory to programs

Recall: Loading



Binding of Instructions and Data to Memory

Process view of memory

```
data1:   dw    32
         …
start:   lw    r1,0(data1)
         jal   checkit
loop:    addi r1, r1, -1
         bnz   r1, loop
         …
checkit: …
```

Physic

```
0x0300  0…
  …
0x0900  8C2000C0
0x0904  0C000280
0x0908  2021FFFF
0x090C  14200242
 …
0x0A00
```

Assume 4byte words
0x300 = 4 * 0x0C0
0x0C0 = 0000 1100 0000
0x300 = 0011 0000 0000

Binding of Instructions and Data to Memory

Process view of memory

```
data1:   dw    32
         …
start:   lw    r1,0(data1)
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checkit: …
```

Physical addresses

```
0x0300  00000020
  …       …
0x0900  8C2000C0
0x0904  0C000280
0x0908  2021FFFF
0x090C  14200242
 …
0x0A00
```

Physical Memory

```
0x0000
0x0300  00000020
0x0900  8C2000C0
        0C000340
        2021FFFF
        14200242
0xFFFF
```


Second copy of program from previous example

Process view of memory

```
data1:   dw    32
         …
start:   lw    r1,0(data1)
         jal   checkit
loop:    addi r1, r1, -1
         bnz   r1, loop
         …
checkit: …
```

Physical addresses

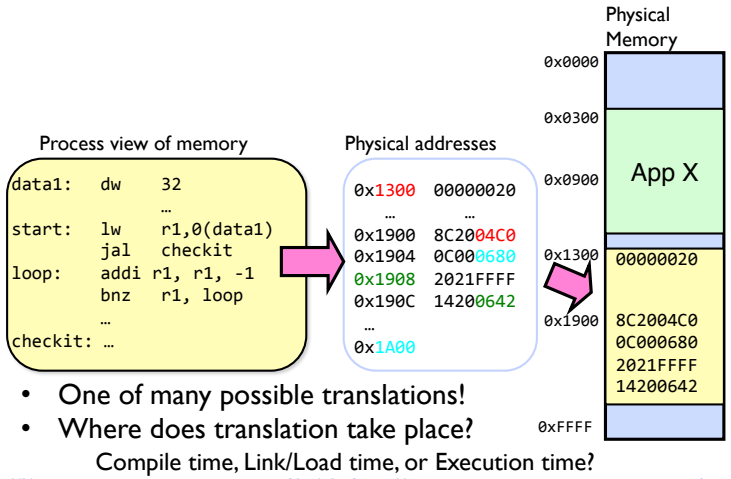
```
0x0300  00000020
  …       …
0x0900  8C2000C0
0x0904  0C000280
0x0908  2021FFFF
0x090C  14200242
 …
0x0A00
```

Physical Memory

```
0x0000
0x0300
0x0900  ?
        App X
0xFFFF
```

Need address translation!

Second copy of program from previous example



- One of many possible translations!
- Where does translation take place?
  Compile time, Link/Load time, or Execution time?

Summary

- Real-time scheduling
  - Need to meet a deadline, predictability essential
  - Earliest Deadline First (EDF) and Rate Monotonic (RM) scheduling
- Four requirements for deadlock:
  - Mutual exclusion
  - Hold and wait
  - No preemption
  - Circular wait
- Simple Protection through segmentation
  - Base + Limit registers restrict memory accessible to user
  - Can be used to translate as well