CS162
Operating Systems and Systems Programming
Lecture 11

Scheduling (Finished), Deadlock, Address Translation

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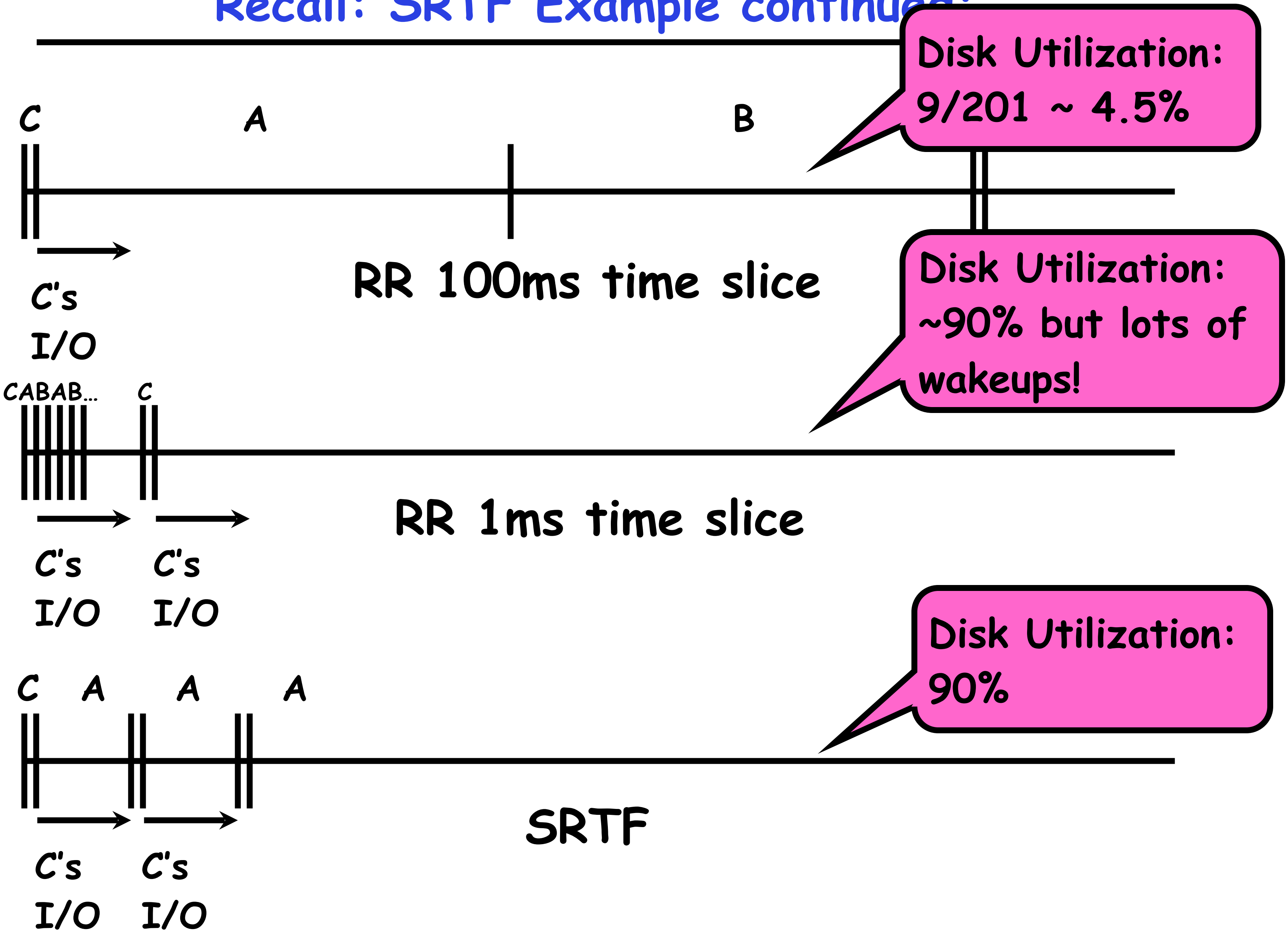
Acknowledgments: Lecture slides are from the Operating Systems course taught by John Kubiatowicz at Berkeley, with few minor updates/changes*. When slides are obtained from other sources, a a reference will be noted on the bottom of that slide, in which case a full list of references is provided on the last slide.*

Recall: SRTF Example continued:



Recall: Multi-Level Feedback Scheduling

Long-Running Compute Tasks Demoted to Low Priority

- Another method for exploiting past behavior
  - First used in CTSS
  - Multiple queues, each with different priority
    - » Higher priority queues often considered "foreground" tasks
  - Each queue has its own scheduling algorithm
    - » e.g. foreground – RR, background – FCFS
    - » Sometimes multiple RR priorities with quantum increasing exponentially (highest:1ms, next:2ms, next: 4ms, etc)
- Adjust each job's priority as follows (details vary)
  - Job starts in highest priority queue
  - If timeout expires, drop one level
  - If timeout doesn't expire, push up one level (or to top)

Recall: Linux Completely Fair Scheduler (CFS)

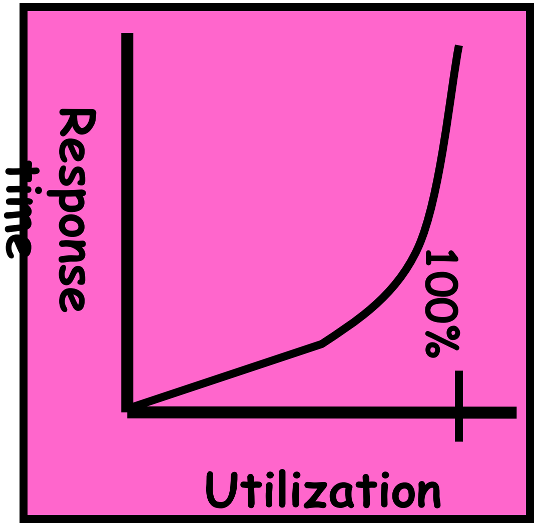
- First appeared in 2.6.23, modified in 2.6.24
- Inspired by Networking "Fair Queueing"
  - Each process given their fair share of resources
  - Models an "ideal multitasking processor" in which N processes execute simultaneously as if they truly got 1/N of the processor
- Idea: Track amount of "virtual time" received by each process when it is executing
  - Take real execution time, scale by a factor to reflect time it would have gotten on ideal multiprocessor
    - » So for instance, multiply real time by N
  - Keep virtual time for every process advancing at same rate
    - » Time sliced to achieve multiplexing
  - Uses a red-black tree to always find process which has gotten least amount of virtual time
- Automatically track interactivity:
  - Interactive process runs less frequently => lower registered virtual time => will run immediately when ready to run

Recall: Real-Time Scheduling (RTS)

- Efficiency is important but predictability is essential:
  - Real-time is about enforcing predictability, and does not equal to fast computing!!!
- Hard Real-Time
  - Attempt to meet all deadlines
  - EDF (Earliest Deadline First), LLF (Least Laxity First), RMS (Rate-Monotonic Scheduling), DM (Deadline Monotonic Scheduling)
- 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)

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%



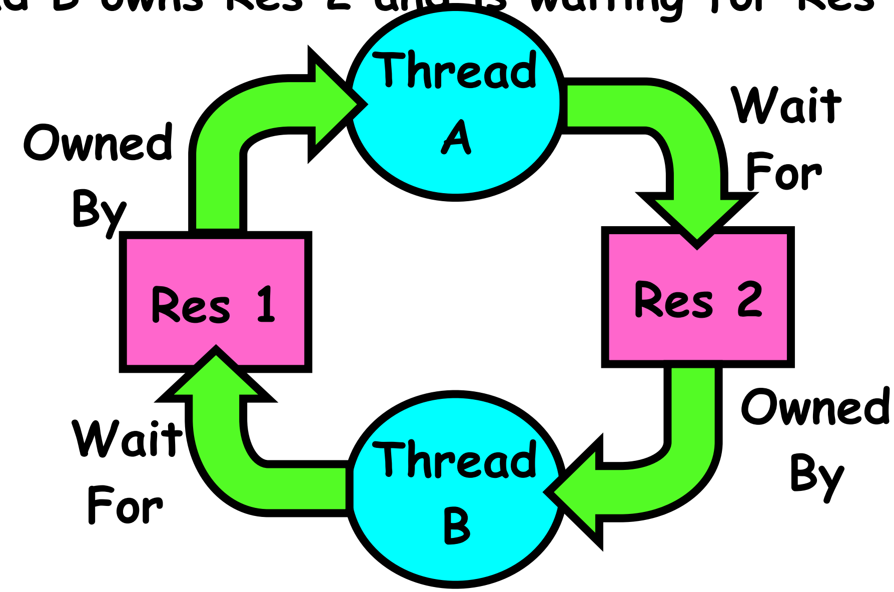
- An interesting implication of this curve:
  - Most scheduling algorithms work fine in the "linear" portion of the load curve, fail otherwise
  - Argues for buying a faster X when hit "knee" of curve

Resources

- Resources - passive entities needed by threads to do their work
  - CPU time, disk space, memory
- Two types of resources
  - Preemptable - can take it away
    - » CPU
  - Non-preemptable - must leave it with the thread
    - » Disk space, plotter, chunk of virtual address space
    - » Mutual exclusion - the right to enter a critical section
- Resources may require exclusive access or may be sharable
  - Read-only files are typically sharable
  - Printers are not sharable during time of printing
- One of the major tasks of an operating system is to manage resources

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

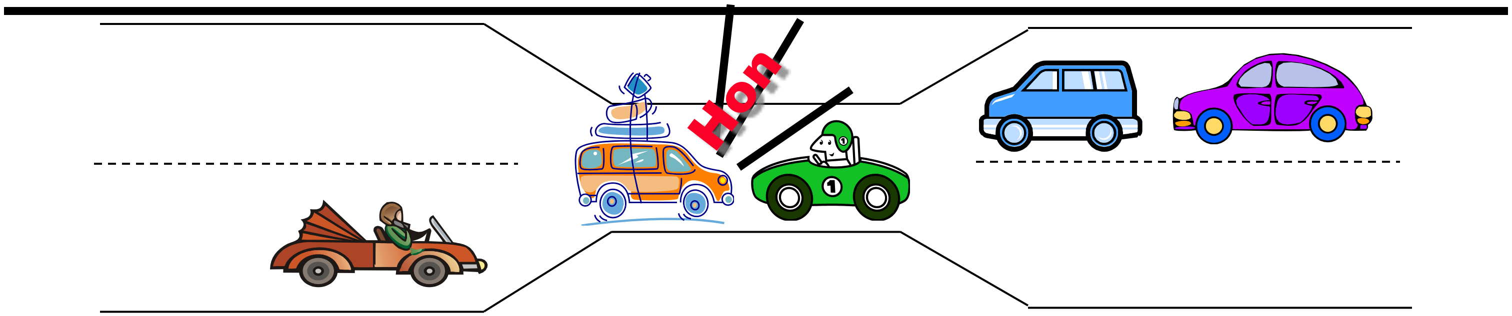
Conditions for Deadlock

- 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 $\Rightarrow$ no one goes west

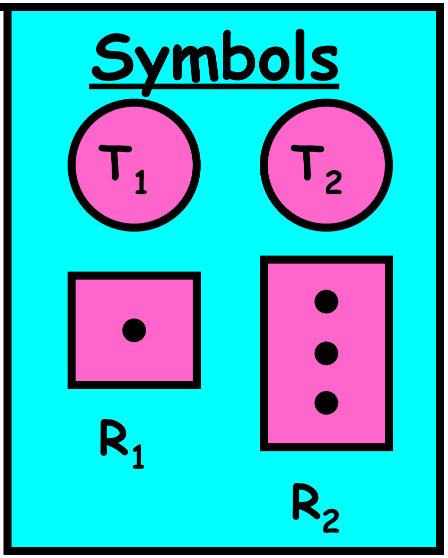
Dining Lawyers Problem

- 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

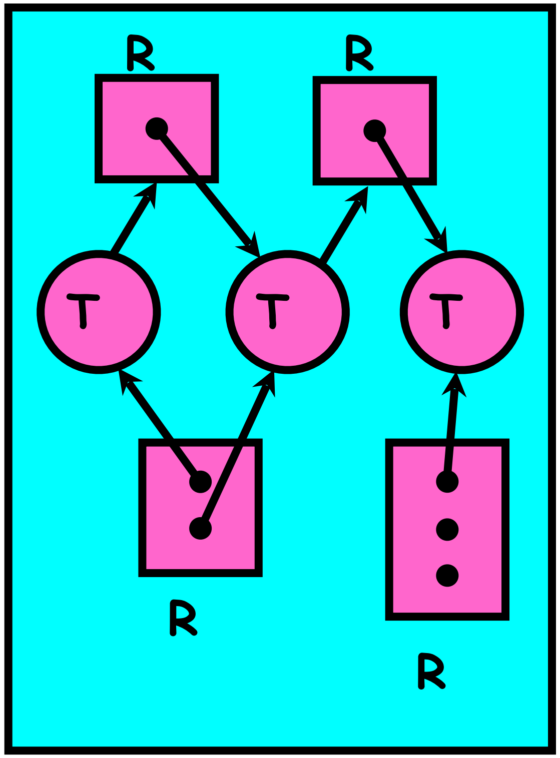


- System Model
  - A set of Threads $T_1, T_2, \ldots, T_n$
  - Resource types $R_1, R_2, \ldots, R_m$

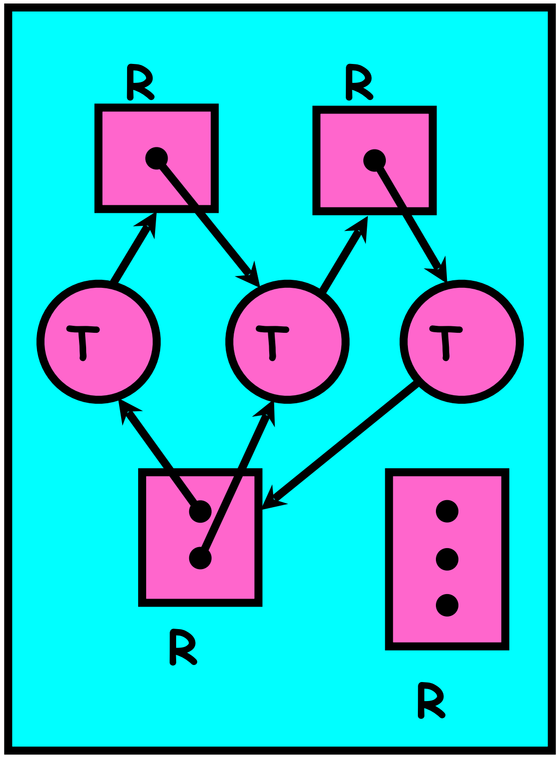
    CPU cycles, memory space, I/O devices
  - Each resource type R_i has W_i instances.
  - Each thread utilizes a resource as follows:
    - » `Request() / Use() / Release()`
- Resource-Allocation Graph:
  - V is partitioned into two types:
    - » $T = \{T_1, T_2, \ldots, T_n\}$, the set threads in the 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

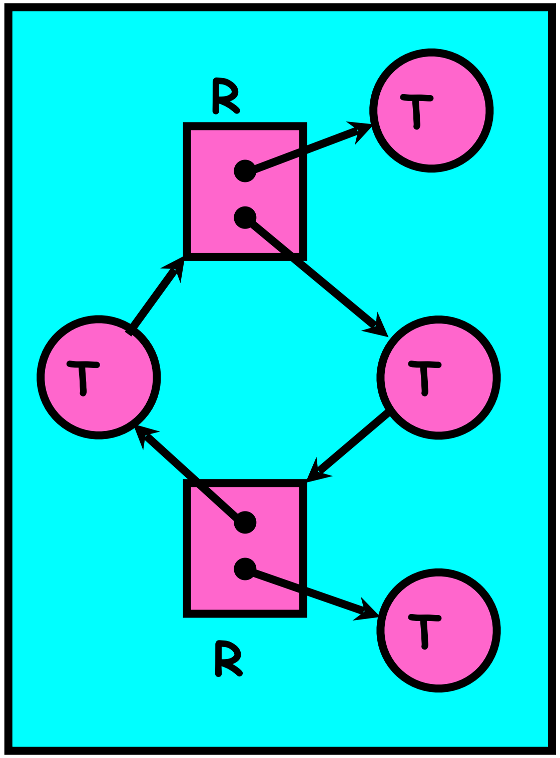
- **Recall:**
  - request edge – directed edge $T_1 \rightarrow R_j$
  - assignment edge – directed edge $R_j \rightarrow T_i$



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

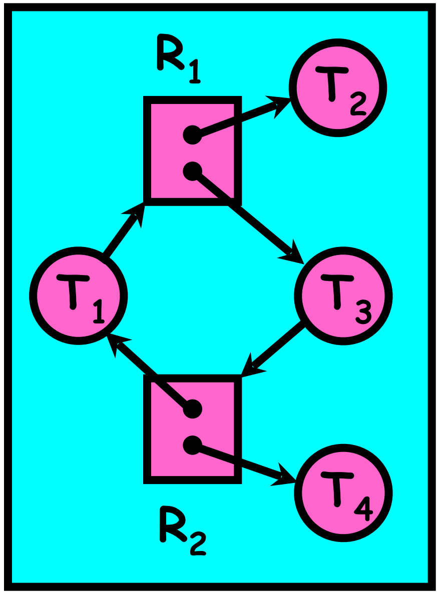
Deadlock Detection Algorithm

- Only one of each type of resource ⇒ look for loops
- More General Deadlock Detection Algorithm
  - Let [X] represent an m-aray 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

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 (con't)

- 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 city center by requiring everyone to go clockwise

Banker's Algorithm for Preventing Deadlock

- Toward right idea:
  - State maximum resource needs in advance
  - Allow particular thread to proceed if:

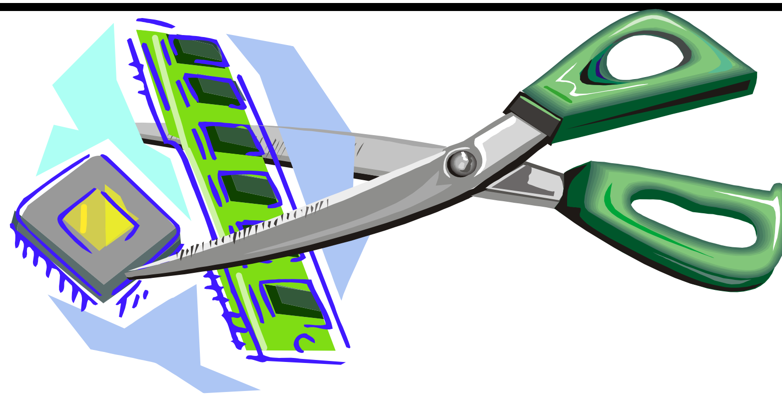
    (available resources - #requested) ≥ max remaining that might be needed by any thread

- 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
    - » Keeps system in a "SAFE" state, i.e. 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..
  - 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
    - » …

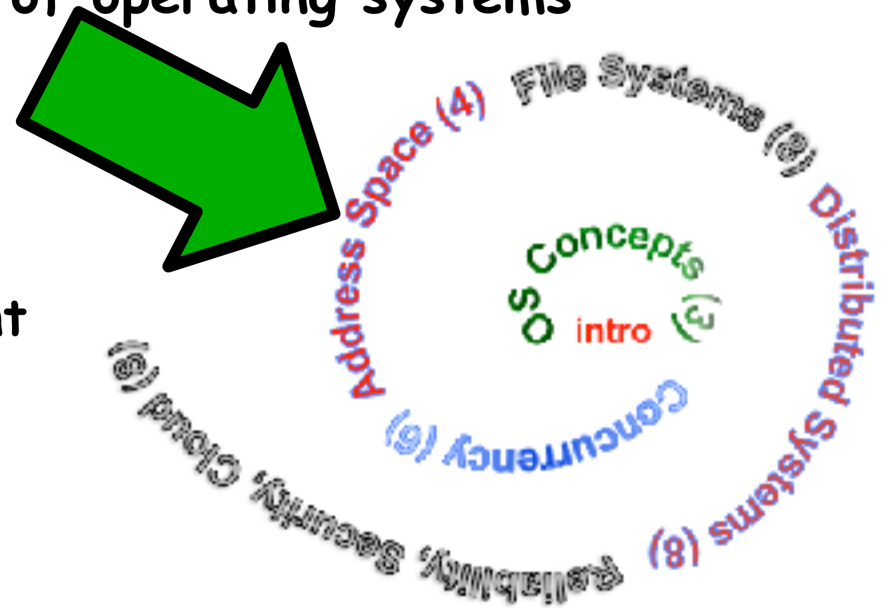
Virtualizing Resources



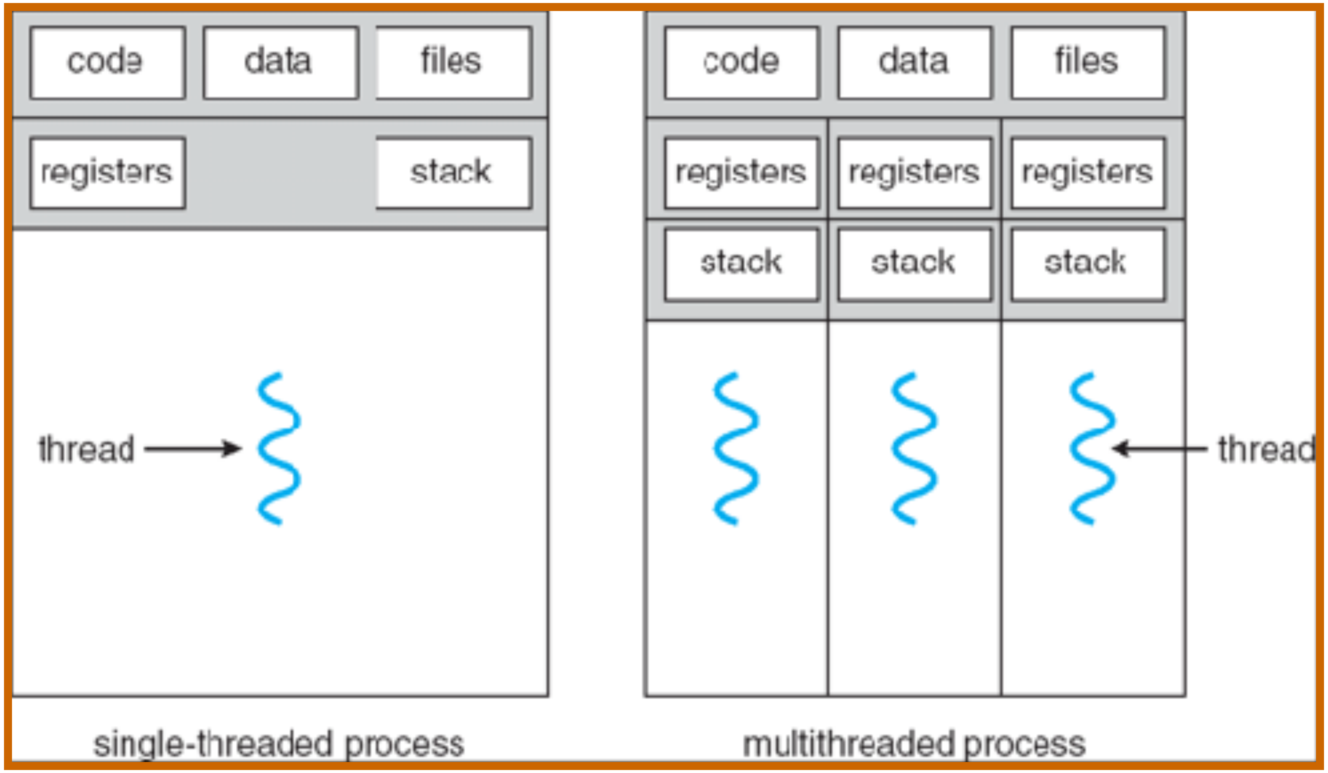
- Physical Reality:
  Different Processes/Threads share the same hardware
  - Need to multiplex CPU (Just finished: scheduling)
  - Need to multiplex use of Memory (Today)
  - Need to multiplex disk and devices (later in term)
- Why worry about memory sharing?
  - The complete working state of a process 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: Linking, Segmentation, Paged Virtual Address



Recall: Single and Multithreaded Processes

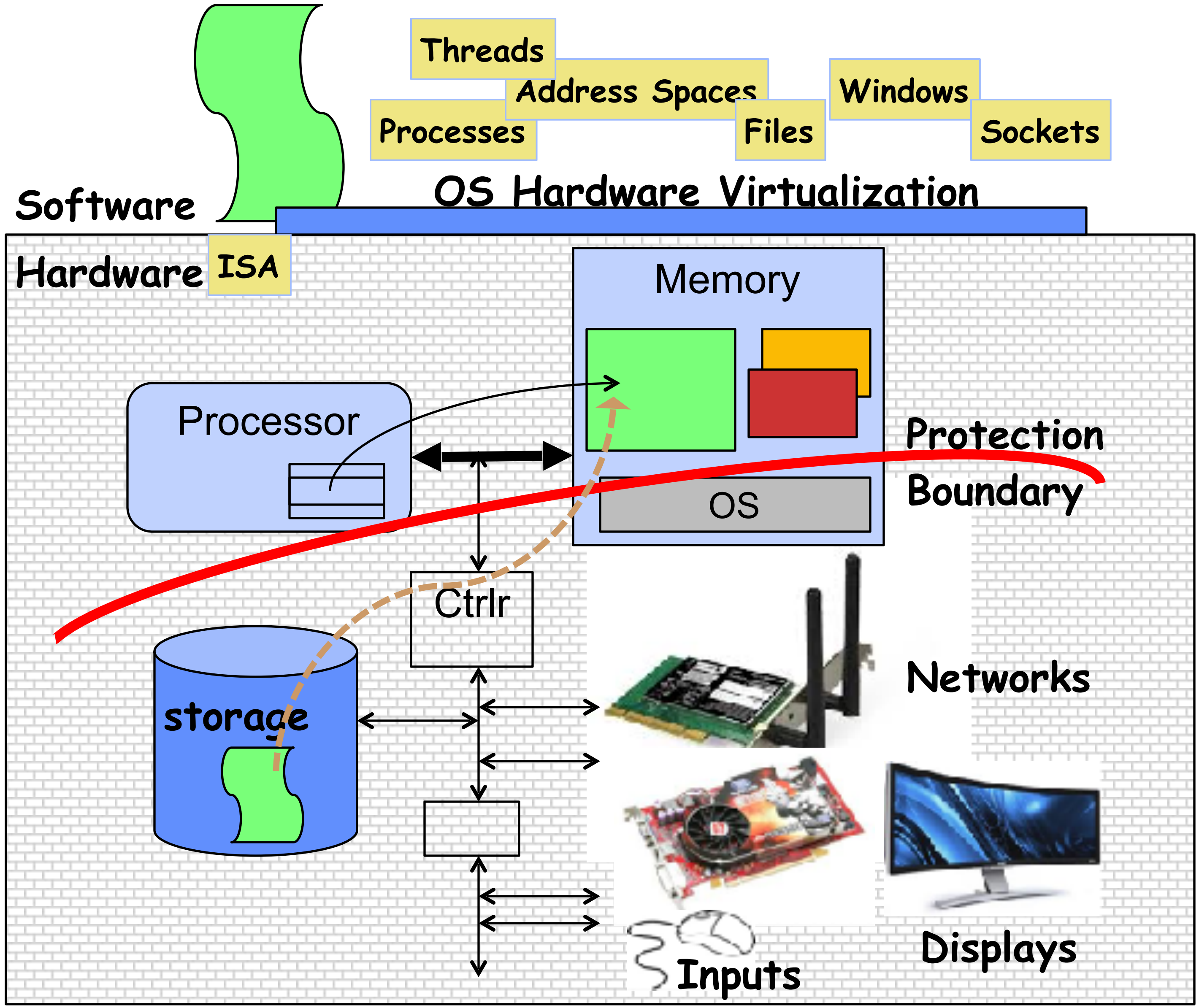


- Threads encapsulate concurrency
  - "Active" component of a process
- Address spaces encapsulate protection
  - Keeps buggy program from trashing the system
  - "Passive" component of a process

Important Aspects of Memory Multiplexing

- **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
- **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

Recall: Loading



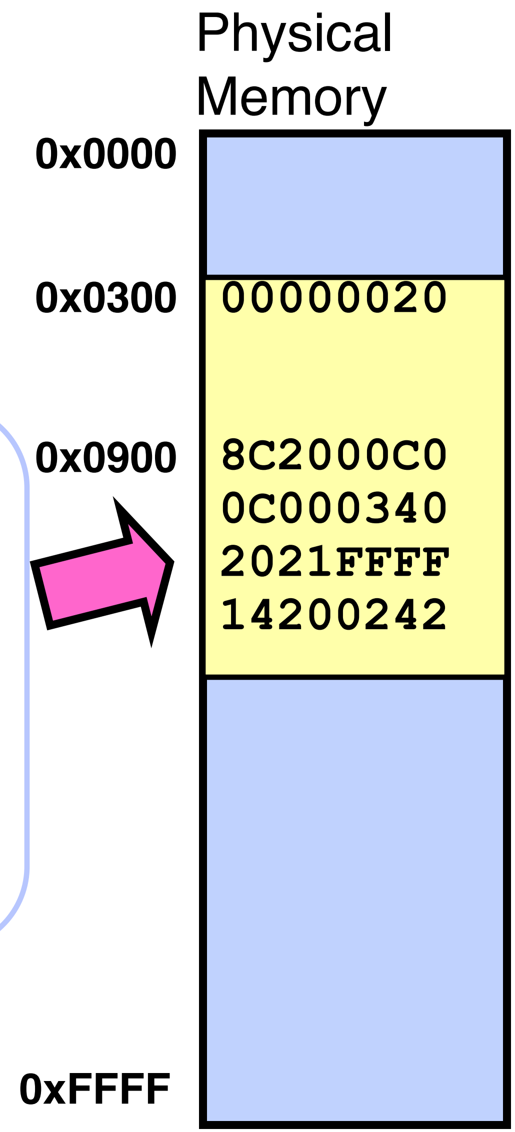
Binding of Instructions and Data to Memory

Process view of memory

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

Physical addresses

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



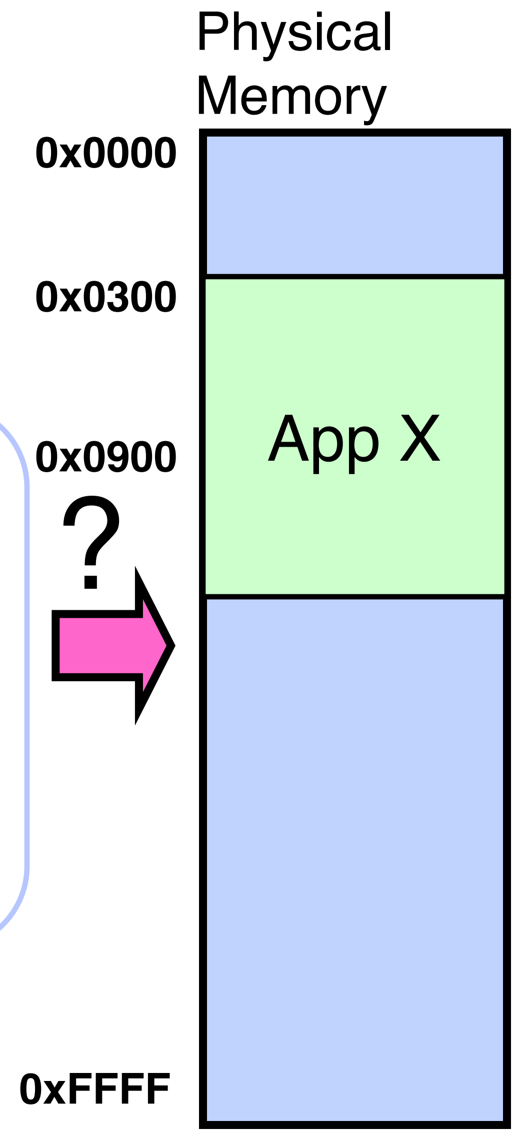
Second copy of program from previous example

Process view of memory

```
data1:   dw    32
               …
start:   lw    r1,0(data1)
         jal   checkit
loop:    addi r1, r1, -1
         bnz   r1, r0, loop
…
checkit: …
```

Physical addresses

```
0x300   00000020
   …       …
0x900   8C2000C0
0x904   0C000280
0x908   2021FFFF
0x90C   14200242
 …
0x0A00
```



Need address translation!

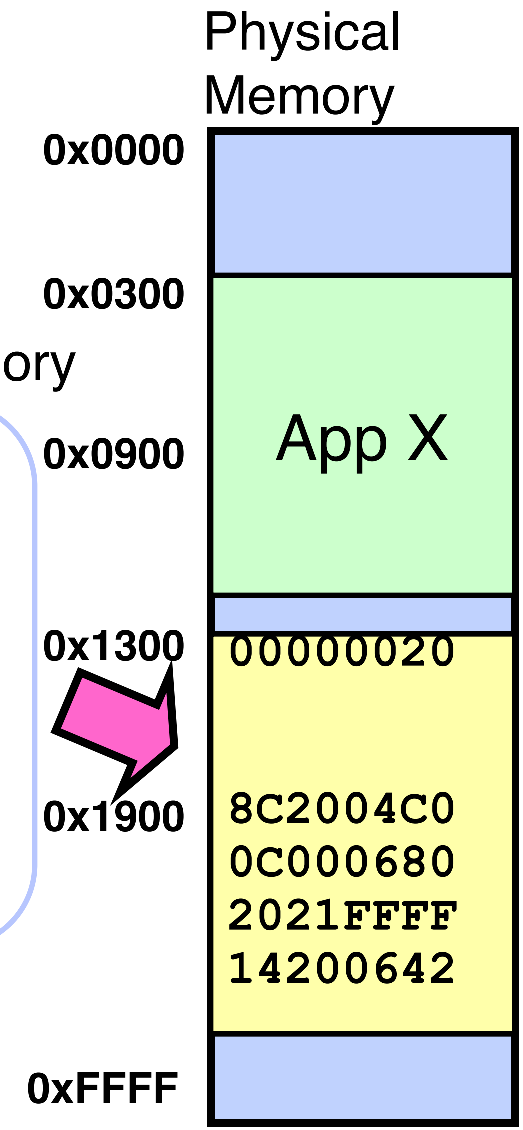
Second copy of program from previous example

Process view of memory

```
data1:   dw    32
               …
start:   lw    r1,0(data1)
         jal   checkit
loop:    addi r1, r1, -1
         bnz   r1, r0, loop
…
checkit: …
```

Processor view of memory

```
0x1300  00000020
    …        …
0x1900  8C2004C0
0x1904  0C000680
0x1908  2021FFFF
0x190C  14200642
  …
0x1A00
```

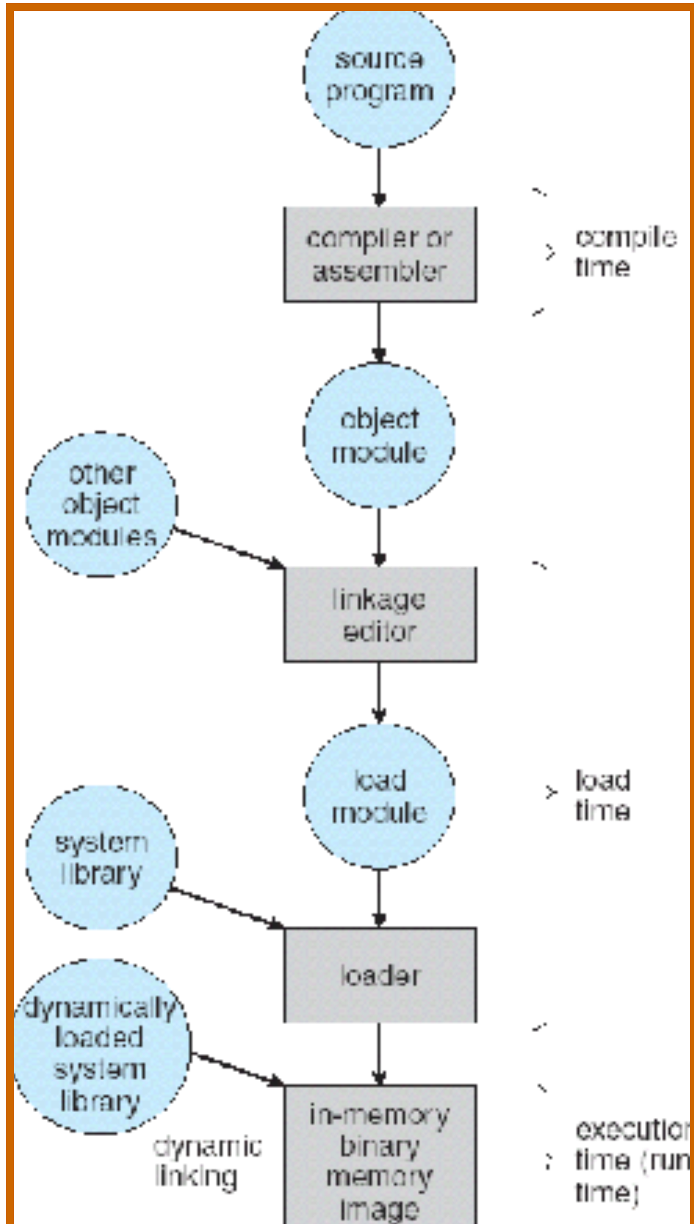


- **One of many possible translations!**
- **Where does translation take place?**

Compile time, Link/Load time, or Execution time?

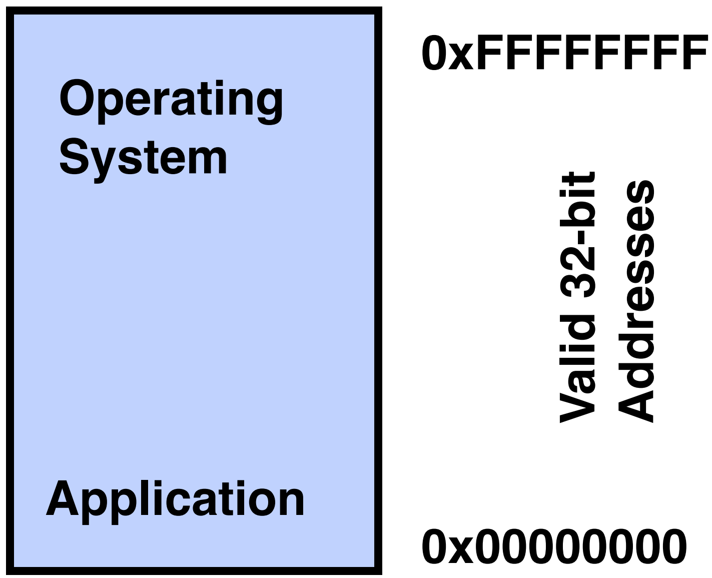
Multi-step Processing of a Program for Execution

- Preparation of a program for execution involves components at:
  - Compile time (i.e., "gcc")
  - Link/Load time (UNIX "ld" does link)
  - Execution time (e.g., dynamic libs)
- Addresses can be bound to final values anywhere in this path
  - Depends on hardware support
  - Also depends on operating system
- Dynamic Libraries
  - Linking postponed until execution
  - Small piece of code, stub, used to locate appropriate memory-resident library routine
  - Stub replaces itself with the address of the routine, and executes routine



Recall: Uniprogramming

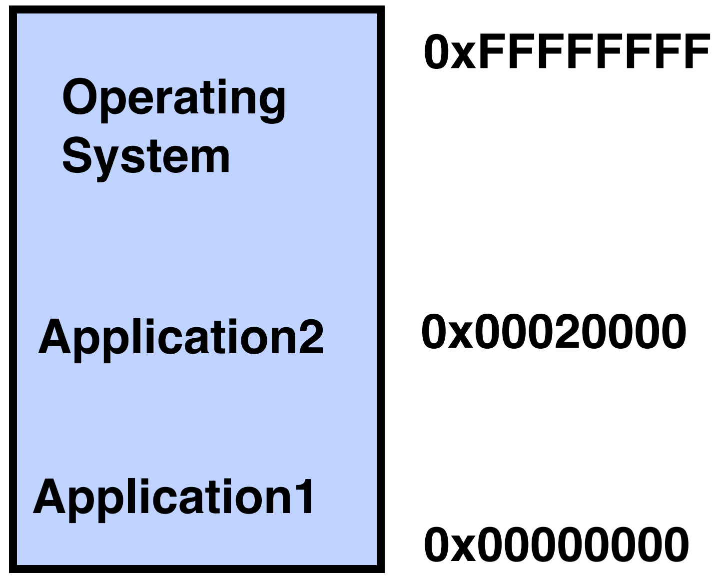
- Uniprogramming (no Translation or Protection)
  - Application always runs at same place in physical memory since only one application at a time
  - Application can access any physical address



  - Application given illusion of dedicated machine by giving it reality of a dedicated machine

Multiprogramming (primitive stage)

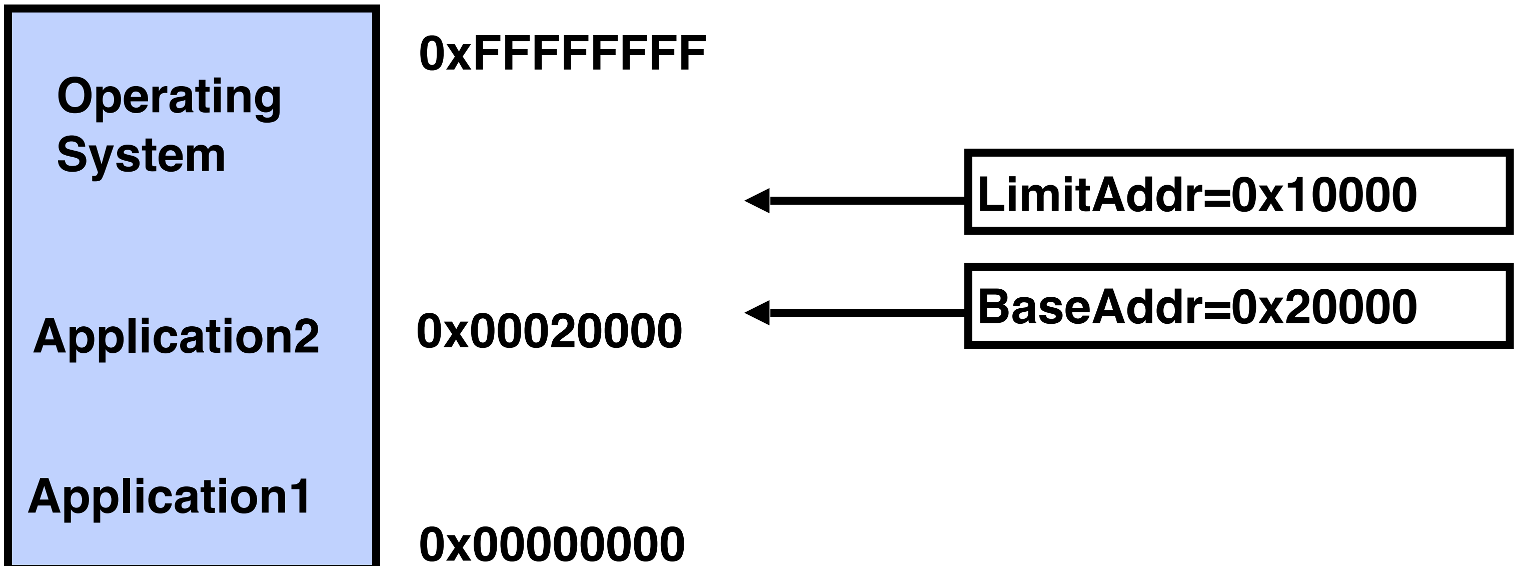
- Multiprogramming without Translation or Protection
  - Must somehow prevent address overlap between threads



  - Use Loader/Linker: Adjust addresses while program loaded into memory (loads, stores, jumps)
    - » Everything adjusted to memory location of program
    - » Translation done by a linker-loader (relocation)
    - » Common in early days (… till Windows 3.x, 95?)
- With this solution, no protection: bugs in any program can cause other programs to crash or even the OS

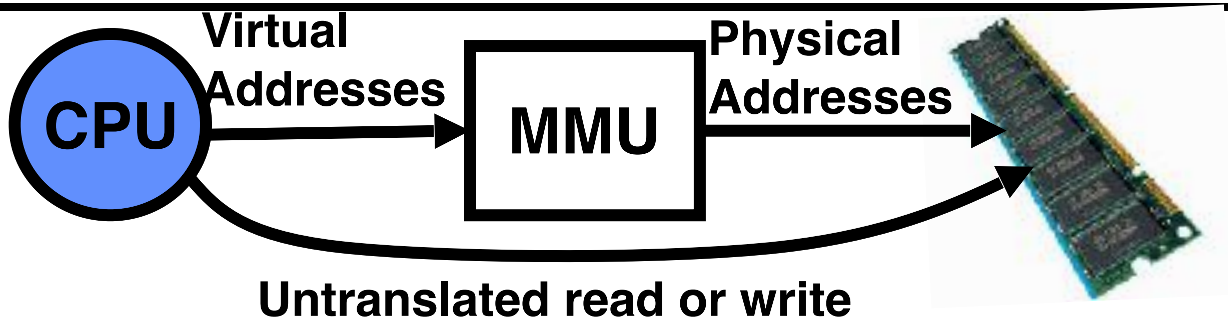
Multiprogramming (Version with Protection)

- Can we protect programs from each other without translation?



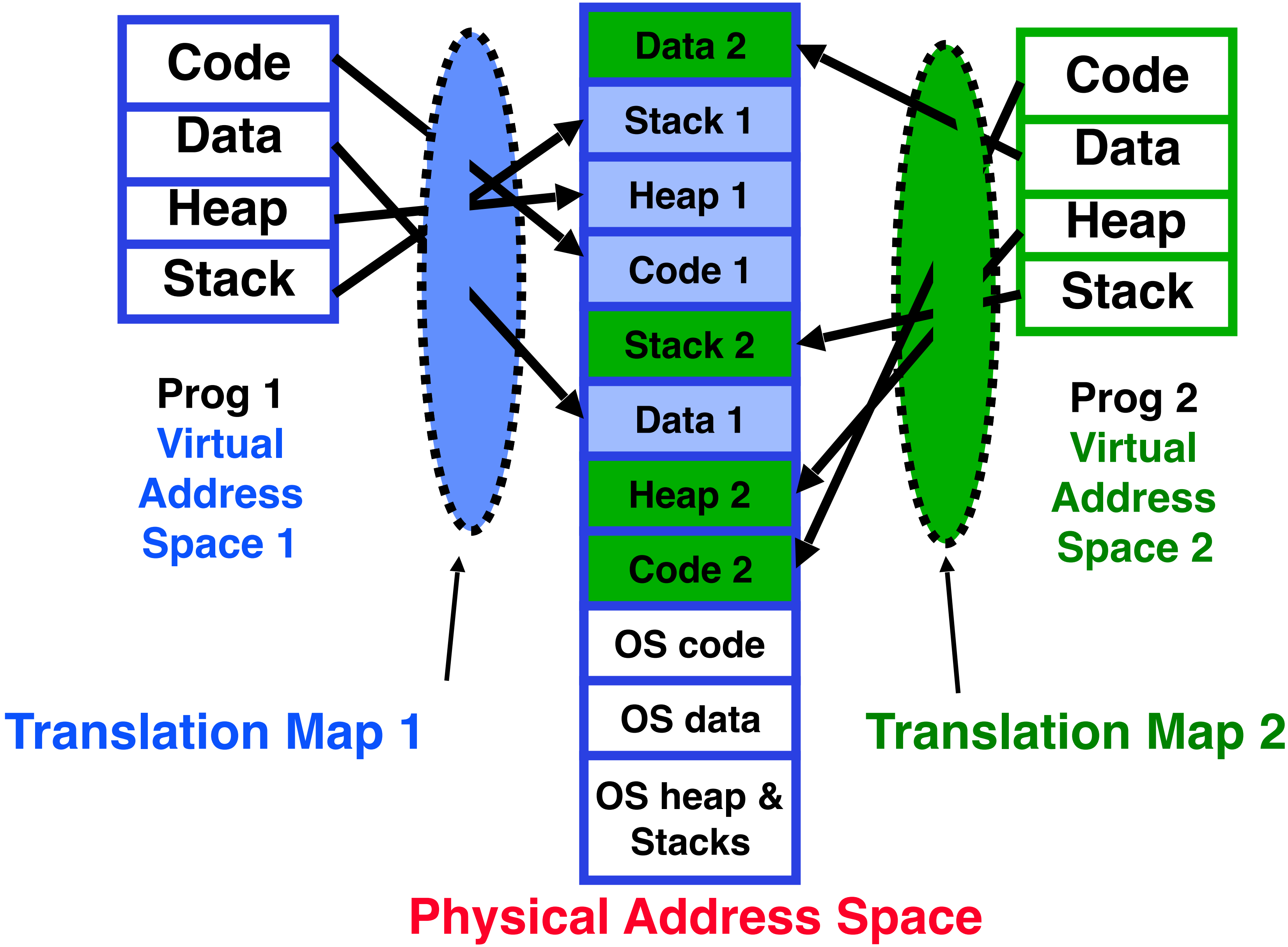
  - Yes: use two special registers BaseAddr and LimitAddr to prevent user from straying outside designated area
    - » If user tries to access an illegal address, cause an error
  - During switch, kernel loads new base/limit from PCB (Process Control Block)
    - » User not allowed to change base/limit registers

Recall: General Address translation

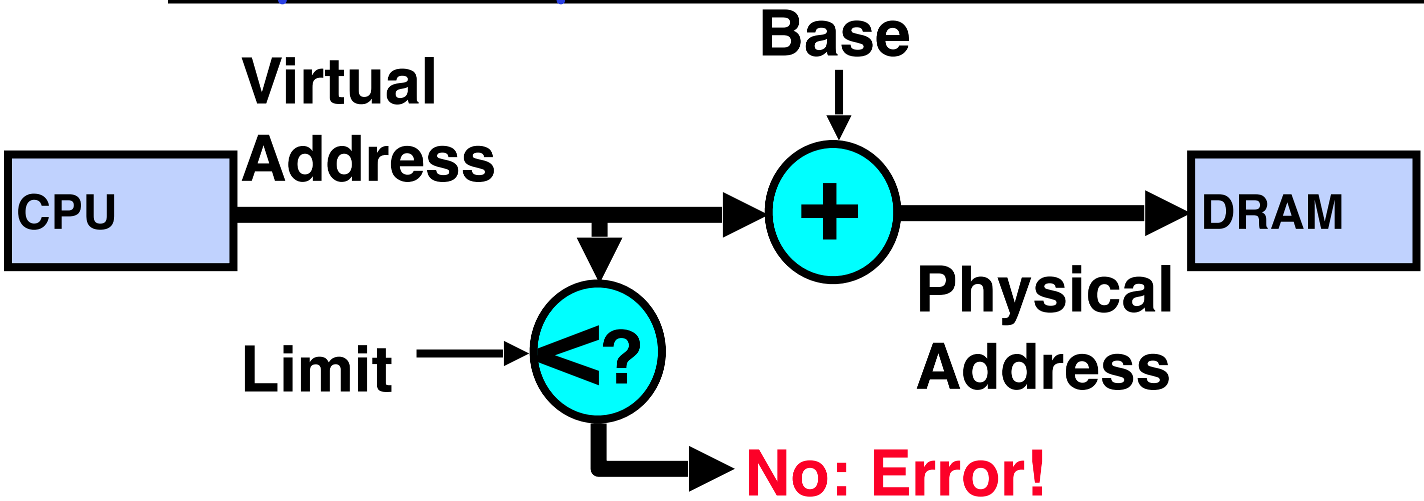


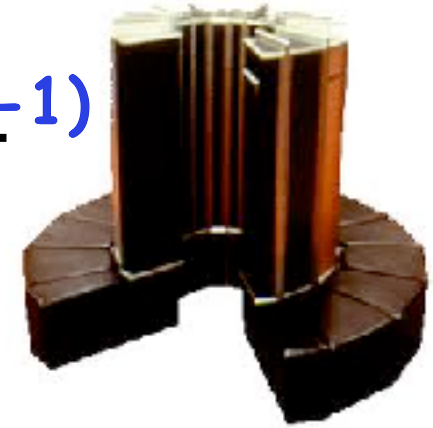
- Recall: Address Space:
  - All the addresses and state a process can touch
  - Each process and kernel has different address space
- Consequently, two views of memory:
  - View from the CPU (what program sees, virtual memory)
  - View from memory (physical memory)
  - Translation box (MMU) converts between the two views
- Translation makes it much easier to implement protection
  - If task A cannot even gain access to task B's data, no way for A to adversely affect B
- With translation, every program can be linked/loaded into same region of user address space

Example of General Address Translation



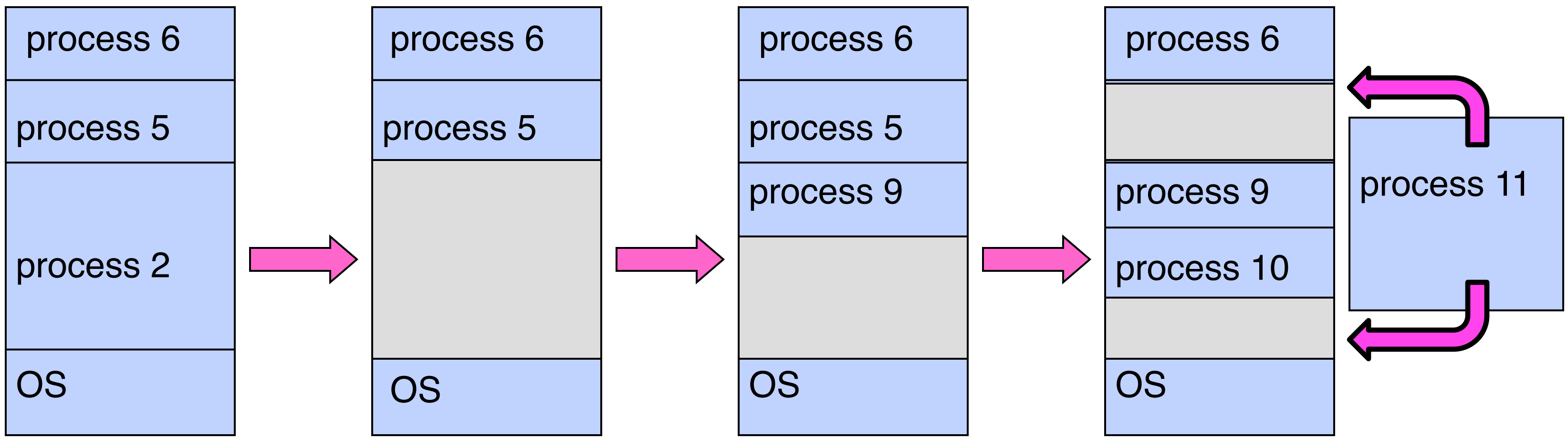
Simple Example: Base and Bounds (CRAY-1)





- Could use base/limit for dynamic address translation – translation happens at execution:
  - Alter address of every load/store by adding “base”
  - Generate error if address bigger than limit
- This gives program the illusion that it is running on its own dedicated machine, with memory starting at 0
  - Program gets continuous region of memory
  - Addresses within program do not have to be relocated when program placed in different region of DRAM

Issues with Simple B&B Method



- Fragmentation problem
  - Not every process is the same size
  - Over time, memory space becomes fragmented
- Missing support for sparse address space
  - Would like to have multiple chunks/program
  - E.g.: Code, Data, Stack
- Hard to do inter-process sharing
  - Want to share code segments when possible
  - Want to share memory between processes
  - Helped by providing multiple segments per process

Summary

- Starvation vs. Deadlock
  - Starvation: thread waits indefinitely
  - Deadlock: circular waiting for resources
- Four conditions for deadlocks
  - 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 threads
  - Circular wait
    - » ∃ set $\{T_1, \ldots, T_n\}$ of threads with a cyclic waiting pattern
- Techniques for addressing Deadlock
  - Allow system to enter deadlock and then recover
  - Ensure that system will never enter a deadlock
  - Ignore the problem and pretend that deadlocks never occur in the system

Summary (2)

- Memory is a resource that must be multiplexed
  - Controlled Overlap: only shared when appropriate
  - Translation: Change virtual addresses into physical addresses
  - Protection: Prevent unauthorized sharing of resources
- Simple Protection through segmentation
  - Base + Limit registers restrict memory accessible to user
  - Can be used to translate as well