

CS162 Operating Systems and Systems Programming Lecture 11

Thread Scheduling (con't) Protection: Address Spaces

October 6, 2008
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Review: Banker's Algorithm for Preventing Deadlock

- Banker's algorithm:
 - 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!)
 - » Keeps system in a "SAFE" state, i.e. there exists a sequence $\{T_1, T_2, \dots, T_n\}$ 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



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Review: Last Time

- **Scheduling:** selecting a waiting process from the ready queue and allocating the CPU to it
- **FCFS Scheduling:**
 - Run threads to completion in order of submission
 - Pros: Simple (+)
 - Cons: Short jobs get stuck behind long ones (-)
- **Round-Robin Scheduling:**
 - Give each thread a small amount of CPU time when it executes; cycle between all ready threads
 - Pros: Better for short jobs (+)
 - Cons: Poor when jobs are same length (-)

Review: FCFS and RR Example with Different Quantum

Best FCFS:

P ₂ [8]	P ₄ [24]	P ₁ [53]	P ₃ [68]
0	8	32	85
			153

	Quantum	P ₁	P ₂	P ₃	P ₄	Average
Wait Time	Best FCFS	32	0	85	8	31½
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	61½
	Q = 8	80	8	85	56	57½
	Q = 10	82	10	85	68	61½
	Q = 20	72	20	85	88	66½
Completion Time	Worst FCFS	68	145	0	121	83½
	Best FCFS	85	8	153	32	69½
	Q = 1	137	30	153	81	100½
	Q = 5	135	28	153	82	99½
	Q = 8	133	16	153	80	95½
	Q = 10	135	18	153	92	99½
Q = 20	125	28	153	112	104½	
Worst FCFS	121	153	68	145	121½	

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Goals for Today

- Finish discussion of Scheduling
- Kernel vs User Mode
- What is an Address Space?
- How is it Implemented?

Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne

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What if we Knew the Future?

- Could we always mirror best FCFS?
- **Shortest Job First (SJF):**
 - Run whatever job has the least amount of computation to do
 - Sometimes called "Shortest Time to Completion First" (STCF)
- **Shortest Remaining Time First (SRTF):**
 - Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
 - Sometimes called "Shortest Remaining Time to Completion First" (SRTCF)
- These can be applied either to a whole program or the current CPU burst of each program
 - Idea is to get short jobs out of the system
 - Big effect on short jobs, only small effect on long ones
 - Result is better average response time



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Discussion

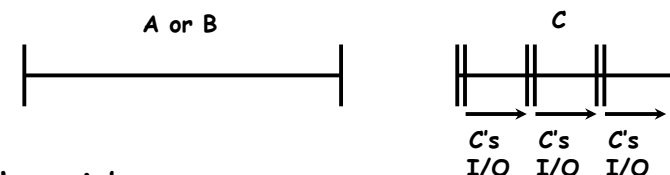
- SJF/SRTF are the best you can do at minimizing average response time
 - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
 - Since SRTF is always at least as good as SJF, focus on SRTF
- Comparison of SRTF with FCFS and RR
 - What if all jobs the same length?
 - » SRTF becomes the same as FCFS (i.e. FCFS is best can do if all jobs the same length)
 - What if jobs have varying length?
 - » SRTF (and RR): short jobs not stuck behind long ones

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Example to illustrate benefits of SRTF



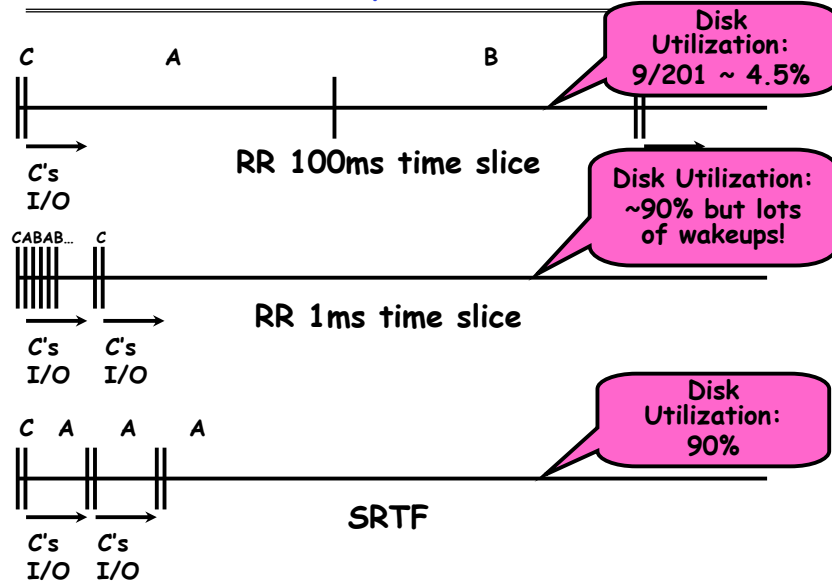
- Three jobs:
 - A, B: both CPU bound, run for week
 - C: I/O bound, loop 1ms CPU, 9ms disk I/O
 - If only one at a time, C uses 90% of the disk, A or B could use 100% of the CPU
- With FIFO:
 - Once A or B get in, keep CPU for two weeks
- What about RR or SRTF?
 - Easier to see with a timeline

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SRTF Example continued:



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SRTF Further discussion

- Starvation
 - SRTF can lead to starvation if many small jobs!
 - Large jobs never get to run
- Somehow need to predict future
 - How can we do this?
 - Some systems ask the user
 - » When you submit a job, have to say how long it will take
 - » To stop cheating, system kills job if takes too long
 - But: Even non-malicious users have trouble predicting runtime of their jobs
- Bottom line, can't really know how long job will take
 - However, can use SRTF as a yardstick for measuring other policies
 - Optimal, so can't do any better
- SRTF Pros & Cons
 - Optimal (average response time) (+)
 - Hard to predict future (-)
 - Unfair (-)



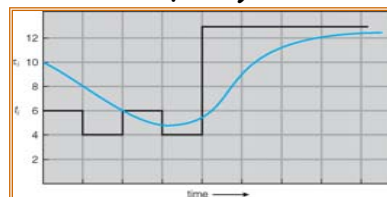
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Predicting the Length of the Next CPU Burst

- **Adaptive:** Changing policy based on past behavior
 - CPU scheduling, in virtual memory, in file systems, etc
 - Works because programs have predictable behavior
 - » If program was I/O bound in past, likely in future
 - » If computer behavior were random, wouldn't help
- Example: SRTF with estimated burst length
 - Use an estimator function on previous bursts:
 - Let $t_{n-1}, t_{n-2}, t_{n-3}, \dots$ be previous CPU burst lengths.
 - Estimate next burst $\tau_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \dots)$
 - Function f could be one of many different time series estimation schemes (Kalman filters, etc)
 - For instance,
 - exponential averaging**
 - $\tau_n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$
 - with $(0 < \alpha \leq 1)$

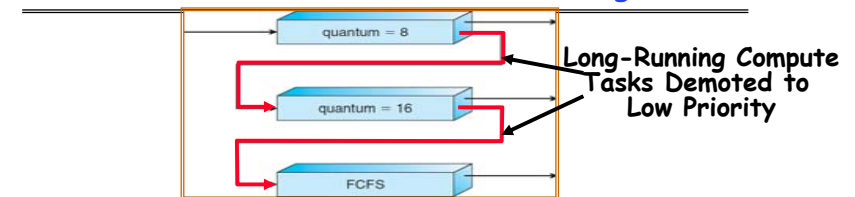


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Multi-Level Feedback Scheduling



- 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)

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Scheduling Details

- Result approximates SRTF:
 - CPU bound jobs drop like a rock
 - Short-running I/O bound jobs stay near top
- Scheduling must be done between the queues
 - **Fixed priority scheduling:**
 - » serve all from highest priority, then next priority, etc.
 - **Time slice:**
 - » each queue gets a certain amount of CPU time
 - » e.g., 70% to highest, 20% next, 10% lowest
- **Countermeasure:** user action that can foil intent of the OS designer
 - For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
 - Of course, if everyone did this, wouldn't work!
- Example of Othello program:
 - Playing against competitor, so key was to do computing at higher priority the competitors.
 - » Put in printf's, ran much faster!

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Administrivia

- Midterm I coming up in next week!
 - Wednesday, 10/15, 5:30-8:30
 - Should be 2 hour exam with extra time
 - Closed book, one page of hand-written notes (both sides)
- No class on day of Midterm
 - I will post extra office hours for people who have questions about the material (or life, whatever)
- Review Session
 - 7:00pm Sunday 10/12
 - 306 Soda Hall
- Midterm Topics
 - Topics: Everything up to (and including) next Monday (10/13)
 - History, Concurrency, Multithreading, Synchronization, Protection/Address Spaces

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Scheduling Fairness

- What about fairness?
 - Strict fixed-priority scheduling between queues is unfair (run highest, then next, etc):
 - » long running jobs may never get CPU
 - » In Multics, shut down machine, found 10-year-old job
 - Must give long-running jobs a fraction of the CPU even when there are shorter jobs to run
 - **Tradeoff: fairness gained by hurting avg response time!**
- How to implement fairness?
 - Could give each queue some fraction of the CPU
 - » What if one long-running job and 100 short-running ones?
 - » Like express lanes in a supermarket—sometimes express lanes get so long, get better service by going into one of the other lines
 - Could increase priority of jobs that don't get service
 - » What is done in UNIX
 - » This is ad hoc—what rate should you increase priorities?
 - » And, as system gets overloaded, no job gets CPU time, so everyone increases in priority→Interactive jobs suffer

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Lottery Scheduling

- Yet another alternative: Lottery Scheduling
 - Give each job some number of lottery tickets
 - On each time slice, randomly pick a winning ticket
 - On average, CPU time is proportional to number of tickets given to each job
- How to assign tickets?
 - To approximate SRTF, short running jobs get more, long running jobs get fewer
 - To avoid starvation, every job gets at least one ticket (everyone makes progress)
- Advantage over strict priority scheduling: behaves gracefully as load changes
 - Adding or deleting a job affects all jobs proportionally, independent of how many tickets each job possesses



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Lottery Scheduling Example

Lottery Scheduling Example

- Assume short jobs get 10 tickets, long jobs get 1 ticket

# short jobs/ # long jobs	% of CPU each short jobs gets	% of CPU each long jobs gets
1/1	91%	9%
0/2	N/A	50%
2/0	50%	N/A
10/1	9.9%	0.99%
1/10	50%	5%

- What if too many short jobs to give reasonable response time?
 - » In UNIX, if load average is 100, hard to make progress
 - » One approach: log some user out

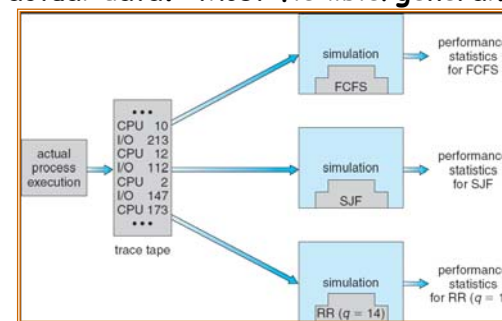
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How to Evaluate a Scheduling algorithm?

- Deterministic modeling
 - takes a predetermined workload and compute the performance of each algorithm for that workload
- Queueing models
 - Mathematical approach for handling stochastic workloads
- Implementation/Simulation:
 - Build system which allows actual algorithms to be run against actual data. Most flexible/general.



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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

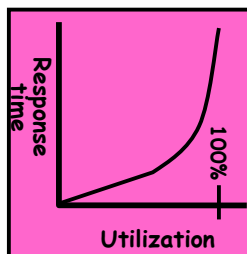
- When should you simply buy a faster computer?

- (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 \rightarrow 100%



- An interesting implication of this curve:

- Most scheduling algorithms work fine in the "linear" portion of the load curve, fail otherwise

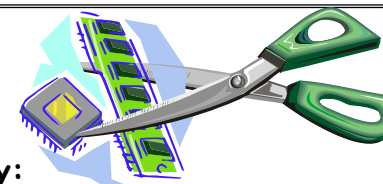
- Argues for buying a faster X when hit "knee" of curve

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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

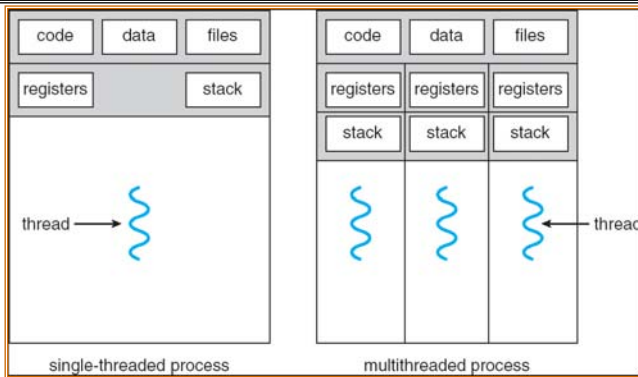
- Probably don't want different threads to even have access to each other's memory (protection)

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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

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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

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Binding of Instructions and Data to Memory

- Binding of instructions and data to addresses:
 - Choose addresses for instructions and data from the standpoint of the processor
- ```

data1: dw 32 0x300 00000020
 ...
start: lw r1,0(data1) 0x900 8C2000C0
 jal checkit 0x904 0C000340
loop: addi r1, r1, -1 0x908 2021FFFF
 bnz r1, r0, loop 0x90C 1420FFFF
 ...
checkit: ... 0xD00 ...

```
- 
- Could we place data1, start, and/or checkit at different addresses?
    - » Yes
    - » When? Compile time/Load time/Execution time
  - Related: which physical memory locations hold particular instructions or data?

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## Multi-step Processing of a Program for Execution

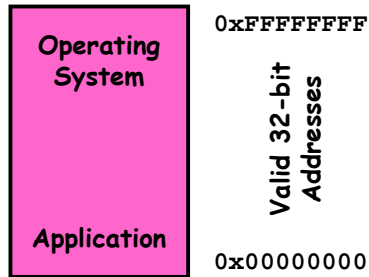
- Preparation of a program for execution involves components at:
    - Compile time (i.e. "gcc")
    - Link/Load time (unix "ld" does link)
    - Execution time (e.g. dynamic libs)
  - Addresses can be bound to final values anywhere in this path
    - Depends on hardware support
    - Also depends on operating system
  - Dynamic Libraries
    - Linking postponed until execution
    - Small piece of code, *stub*, used to locate the appropriate memory-resident library routine
    - Stub replaces itself with the address of the routine, and executes routine
- 
- The flowchart illustrates the process of preparing a program for execution. It starts with a 'source program' which goes through a 'compiler or assembler' (labeled as 'compile time') to produce an 'object module'. The 'object module' then goes through a 'linkage editor' to produce a 'load module'. The 'load module' goes through a 'loader' to produce an 'in-memory binary memory image' (labeled as 'execution time (run time)'). The 'linkage editor' and 'loader' steps are grouped as 'load time'. The 'in-memory binary memory image' is linked with 'other object modules', 'system library', and 'dynamically loaded system library' through 'dynamic linking'.

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## 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
- Of course, this doesn't help us with multithreading

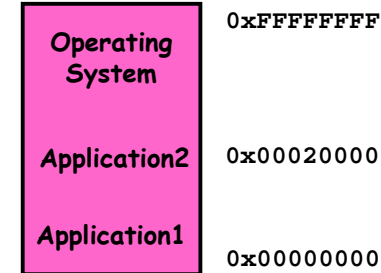
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## Multiprogramming (First Version)

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



- Trick: 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
  - » Was pretty common in early days
- With this solution, no protection: bugs in any program can cause other programs to crash or even the OS

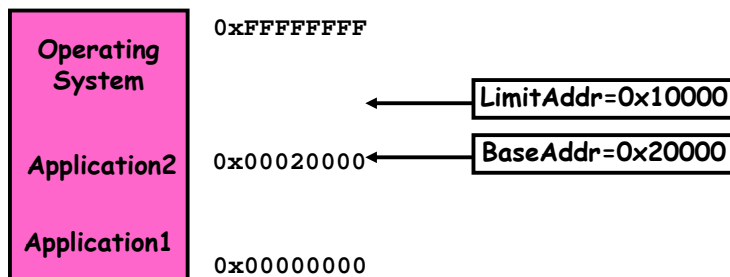
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## Multiprogramming (Version with Protection)

- Can we protect programs from each other without translation?



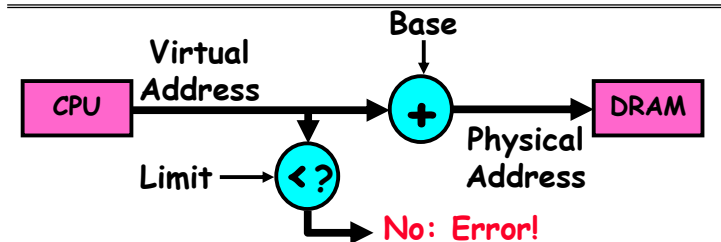
- Yes: use two special registers *BaseAddr* and *LimitAddr* to prevent user from straying outside designated area
  - » If user tries to access an illegal address, cause an error
- During switch, kernel loads new base/limit from TCB
  - » User not allowed to change base/limit registers

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## Segmentation with Base and Limit registers



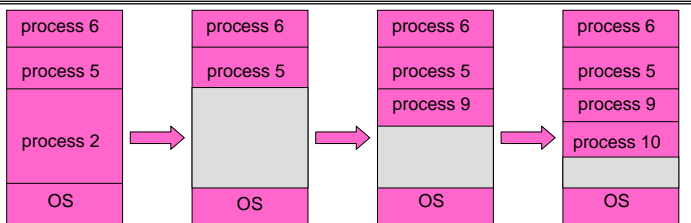
- Could use base/limit for **dynamic address translation** (often called "segmentation"):
  - Alter address of every load/store by adding "base"
  - User allowed to read/write within segment
    - » Accesses are relative to segment so don't have to be relocated when program moved to different segment
  - User may have multiple segments available (e.g x86)
    - » Loads and stores include segment ID in opcode: x86 Example: `mov [es:bx],ax`.
    - » Operating system moves around segment base pointers as necessary

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## Issues with simple segmentation method



- **Fragmentation problem**
  - Not every process is the same size
  - Over time, memory space becomes fragmented
- **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
- **Need enough physical memory for every process**

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## Multiprogramming (Translation and Protection version 2)

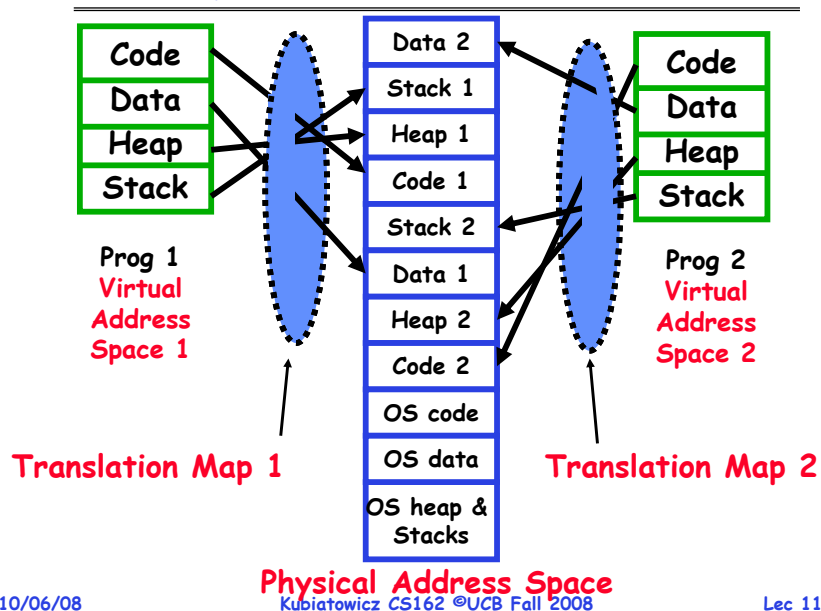
- **Problem:** Run multiple applications in such a way that they are protected from one another
- **Goals:**
  - Isolate processes and kernel from one another
  - Allow flexible translation that:
    - » Doesn't lead to fragmentation
    - » Allows easy sharing between processes
    - » Allows only part of process to be resident in physical memory
- **(Some of the required) Hardware Mechanisms:**
  - **General Address Translation**
    - » Flexible: Can fit physical chunks of memory into arbitrary places in users address space
    - » Not limited to small number of segments
    - » Think of this as providing a large number (thousands) of fixed-sized segments (called "pages")
  - **Dual Mode Operation**
    - » Protection base involving kernel/user distinction

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## Example of General Address Translation

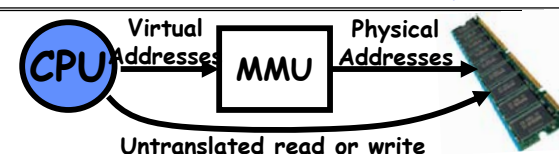


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## Two Views of Memory



- **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 converts between the two views
- **Translation helps 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**
  - Overlap avoided through translation, not relocation

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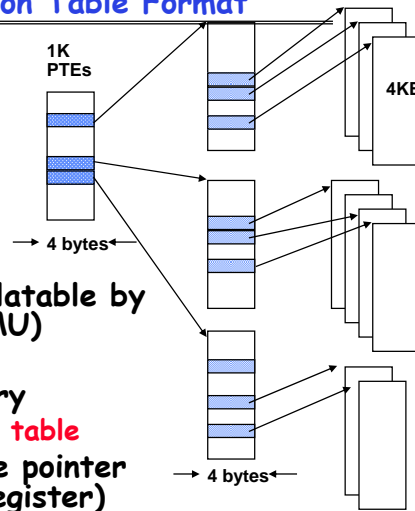
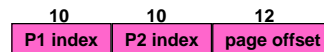
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## Example of Translation Table Format

### Two-level Page Tables

32-bit address:



- **Page:** a unit of memory translatable by memory management unit (MMU)
  - Typically 1K - 8K
- **Page table structure in memory**
  - **Each user has different page table**
- **Address Space switch:** change pointer to base of table (hardware register)
  - Hardware traverses page table (for many architectures)
  - MIPS uses software to traverse table

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## Dual-Mode Operation

- **Can Application Modify its own translation tables?**
  - If it could, could get access to all of physical memory
  - Has to be restricted somehow
- **To Assist with Protection, Hardware provides at least two modes (Dual-Mode Operation):**
  - "Kernel" mode (or "supervisor" or "protected")
  - "User" mode (Normal program mode)
  - Mode set with bits in special control register only accessible in kernel-mode
- **Intel processor actually has four "rings" of protection:**
  - PL (Privilege Level) from 0 - 3
    - » PLO has full access, PL3 has least
  - Privilege Level set in code segment descriptor (CS)
  - Mirrored "IOPL" bits in condition register gives permission to programs to use the I/O instructions
  - Typical OS kernels on Intel processors only use PLO ("user") and PL3 ("kernel")

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## For Protection, Lock User-Programs in Asylum

- **Idea:** Lock user programs in padded cell with no exit or sharp objects
  - Cannot change mode to kernel mode
  - User cannot modify page table mapping
  - Limited access to memory: cannot adversely effect other processes
    - » Side-effect: Limited access to memory-mapped I/O operations (I/O that occurs by reading/writing memory locations)
  - Limited access to interrupt controller
  - What else needs to be protected?
- **A couple of issues**
  - How to share CPU between kernel and user programs?
    - » Kinda like both the inmates and the warden in asylum are the same person. How do you manage this???
  - How do programs interact?
  - How does one switch between kernel and user modes?
    - » OS → user (kernel → user mode): getting into cell
    - » User → OS (user → kernel mode): getting out of cell



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## How to get from Kernel→User

- **What does the kernel do to create a new user process?**
  - Allocate and initialize address-space control block
  - Read program off disk and store in memory
  - Allocate and initialize translation table
    - » Point at code in memory so program can execute
    - » Possibly point at statically initialized data
  - Run Program:
    - » Set machine registers
    - » Set hardware pointer to translation table
    - » Set processor status word for user mode
    - » Jump to start of program
- **How does kernel switch between processes?**
  - Same saving/restoring of registers as before
  - Save/restore PSL (hardware pointer to translation table)

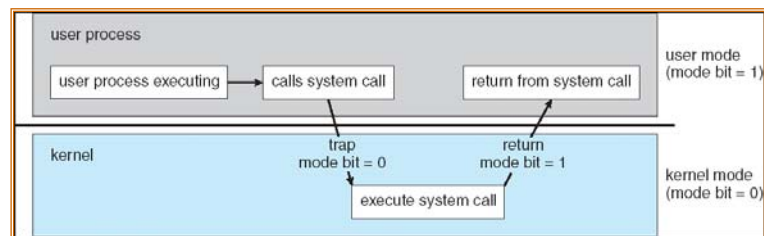
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## User→Kernel (System Call)

- Can't let inmate (user) get out of padded cell on own
  - Would defeat purpose of protection!
  - So, how does the user program get back into kernel?



- **System call:** Voluntary procedure call into kernel
  - Hardware for controlled User→Kernel transition
  - Can any kernel routine be called?
    - » No! Only specific ones.
  - System call ID encoded into system call instruction
    - » Index forces well-defined interface with kernel

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## System Call Continued

- What are some system calls?
  - I/O: open, close, read, write, lseek
  - Files: delete, mkdir, rmdir, truncate, chown, chgrp, ..
  - Process: fork, exit, wait (like join)
  - Network: socket create, set options
- Are system calls constant across operating systems?
  - Not entirely, but there are lots of commonalities
  - Also some standardization attempts (POSIX)
- What happens at beginning of system call?
  - » On entry to kernel, sets system to kernel mode
  - » Handler address fetched from table/Handler started
- System Call argument passing:
  - In registers (not very much can be passed)
  - Write into user memory, kernel copies into kernel mem
    - » User addresses must be translated!w
    - » Kernel has different view of memory than user
  - Every Argument must be explicitly checked!

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## User→Kernel (Exceptions: Traps and Interrupts)

- A system call instruction causes a synchronous exception (or "trap")
  - In fact, often called a software "trap" instruction
- Other sources of **Synchronous Exceptions:**
  - Divide by zero, Illegal instruction, Bus error (bad address, e.g. unaligned access)
  - Segmentation Fault (address out of range)
  - Page Fault (for illusion of infinite-sized memory)
- Interrupts are **Asynchronous Exceptions**
  - Examples: timer, disk ready, network, etc....
  - **Interrupts can be disabled, traps cannot!**
- On system call, exception, or interrupt:
  - Hardware enters kernel mode with interrupts disabled
  - Saves PC, then jumps to appropriate handler in kernel
  - For some processors (x86), processor also saves registers, changes stack, etc.
- Actual handler typically saves registers, other CPU state, and switches to kernel stack

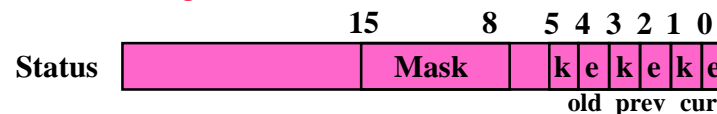
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## Additions to MIPS ISA to support Exceptions?

- Exception state is kept in "Coprocessor 0"
  - Use mfc0 read contents of these registers:
    - » **BadVAddr (register 8):** contains memory address at which memory reference error occurred
    - » **Status (register 12):** interrupt mask and enable bits
    - » **Cause (register 13):** the cause of the exception
    - » **EPC (register 14):** address of the affected instruction



- Status Register fields:
  - Mask: Interrupt enable
    - » 1 bit for each of 5 hardware and 3 software interrupts
  - k = kernel/user: 0⇒kernel mode
  - e = interrupt enable: 0⇒interrupts disabled
  - **Exception⇒6 LSB shifted left 2 bits, setting 2 LSB to 0:**
    - » run in kernel mode with interrupts disabled

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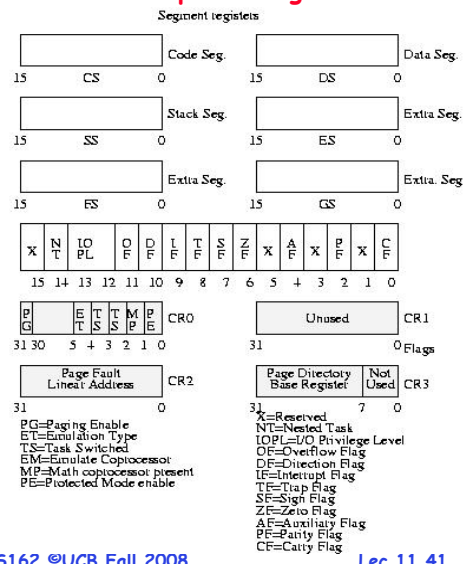
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## Intel x86 Special Registers

## Communication

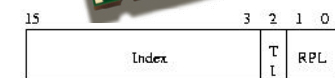


### 80386 Special Registers



- Now that we have isolated processes, how can they communicate?

- Shared memory: common mapping to physical page
  - » As long as place objects in shared memory address range, threads from each process can communicate
  - » Note that processes A and B can talk to shared memory through different addresses
  - » In some sense, this violates the whole notion of protection that we have been developing
- If address spaces don't share memory, all inter-address space communication must go through kernel (via system calls)
  - » Byte stream producer/consumer (put/get): Example, communicate through pipes connecting stdin/stdout
  - » Message passing (send/receive): Will explain later how you can use this to build remote procedure call (RPC) abstraction so that you can have one program make procedure calls to another
  - » File System (read/write): File system is shared state!



RPL = Requestor Privilege Level  
TL = Table Indicator  
(0 = GDT, 1 = LDT)  
Index = Index into table

Typical Segment Register  
Current Priority is RPL  
Of Code Segment (CS)

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## Closing thought: Protection without Hardware

- Does protection require hardware support for translation and dual-mode behavior?
  - No: Normally use hardware, but anything you can do in hardware can also do in software (possibly expensive)
- Protection via Strong Typing
  - Restrict programming language so that you can't express program that would trash another program
  - Loader needs to make sure that program produced by valid compiler or all bets are off
  - Example languages: LISP, Ada, Modula-3 and Java
- Protection via software fault isolation:
  - Language independent approach: have compiler generate object code that provably can't step out of bounds
    - » Compiler puts in checks for every "dangerous" operation (loads, stores, etc). Again, need special loader.
    - » Alternative, compiler generates "proof" that code cannot do certain things (Proof Carrying Code)
  - Or: use virtual machine to guarantee safe behavior (loads and stores recompiled on fly to check bounds)

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## Summary

- Shortest Job First (SJF)/Shortest Remaining Time First (SRTF):
  - Run whatever job has the least amount of computation to do/least remaining amount of computation to do
  - Pros: Optimal (average response time)
  - Cons: Hard to predict future, Unfair
- Multi-Level Feedback Scheduling:
  - Multiple queues of different priorities
  - Automatic promotion/demotion of process priority in order to approximate SJF/SRTF
- Lottery Scheduling:
  - Give each thread a priority-dependent number of tokens (short tasks  $\Rightarrow$  more tokens)
  - Reserve a minimum number of tokens for every thread to ensure forward progress/fairness
- Evaluation of mechanisms:
  - Analytical, Queuing Theory, Simulation

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## Summary (2)

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- **Memory is a resource that must be shared**
  - **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
- **Full translation of addresses through Memory Management Unit (MMU)**
  - Every Access translated through page table
  - Changing of page tables only available to user
- **Dual-Mode**
  - Kernel/User distinction: User restricted
  - User→Kernel: System calls, Traps, or Interrupts
  - Inter-process communication: shared memory, or through kernel (system calls)