CS162
Operating Systems and Systems Programming
Lecture 11

Thread Scheduling (con't)
Protection: Address Spaces

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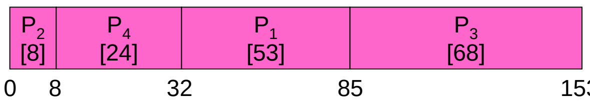
Review: Last Time

- **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: Example with Different Time Quantum

Best FCFS:



	Quantum	P_1	P_2	P_3	P_4	Average
Wait Time	Best FCFS	32	0	85	8	$31\frac{1}{4}$
	Q = 1	84	22	85	57	62
	Q = 5	82	20	85	58	$61\frac{1}{4}$
	Q = 8	80	8	85	56	$57\frac{1}{4}$
	Q = 10	82	10	85	68	$61\frac{1}{4}$
	Q = 20	72	20	85	88	$66\frac{1}{4}$
	Worst FCFS	68	145	0	121	$83\frac{1}{2}$
Completion Time	Best FCFS	85	8	153	32	$69\frac{1}{2}$
	Q = 1	137	30	153	81	$100\frac{1}{2}$
	Q = 5	135	28	153	82	$99\frac{1}{2}$
	Q = 8	133	16	153	80	$95\frac{1}{2}$
	Q = 10	135	18	153	92	$99\frac{1}{2}$
	Q = 20	125	28	153	112	$104\frac{1}{2}$
	Worst FCFS	121	153	68	145	$121\frac{3}{4}$

Review: What if we Knew the Future?

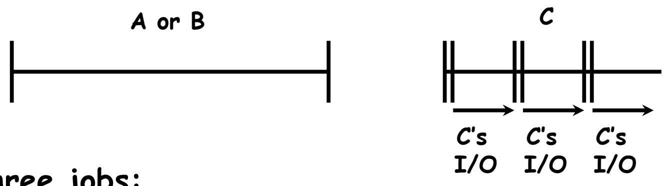
- **Shortest Job First (SJF):**
  - Run whatever job has the least computation to do
- **Shortest Remaining Time First (SRTF):**
  - Preemptive version of SJF: if job arrives and has a shorter time to completion than the remaining time on the current job, immediately preempt CPU
- SJF/SRTF are the best you can do at minimizing average response time
  - Provably optimal (SJF among non-preemptive, SRTF among preemptive)
  - SRTF always at least as good as SJF $\Rightarrow$ focus on SRTF

Goals for Today

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

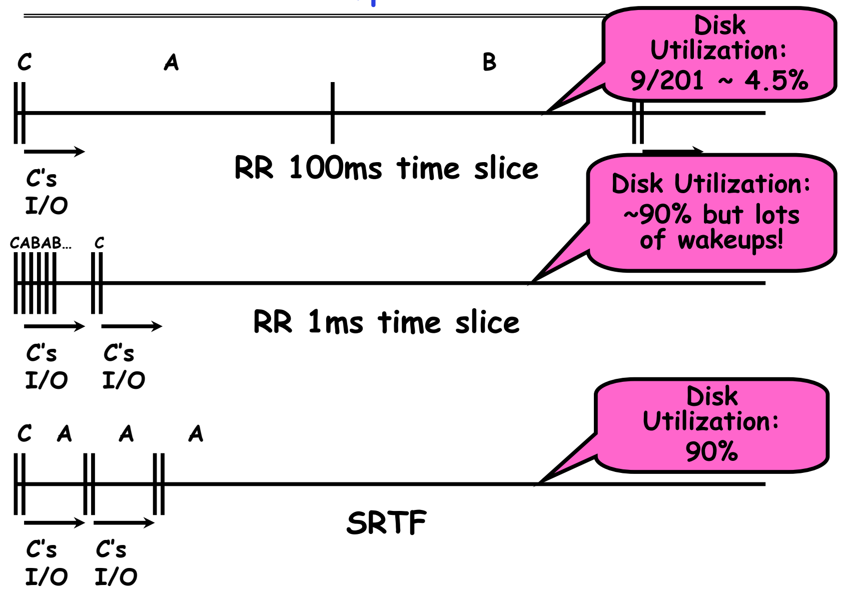
Note: Some slides and/or pictures in the following are adapted from slides ©2005 Silberschatz, Galvin, and Gagne

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

SRTF Example continued:

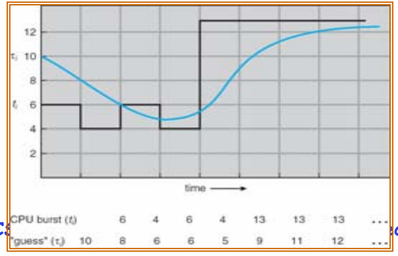


SRTF Further discussion

- 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 (-)

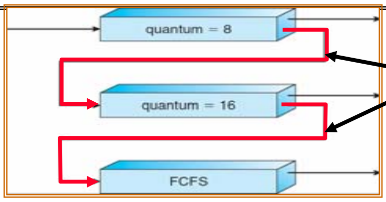
Predicting the Length of the Next CPU Burst

- **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}, etc. be previous CPU burst lengths. Estimate next burst $\tau_n = f(t_{n-1}, t_{n-2}, t_{n-3}, \ldots)$
  - 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 $(0<\alpha\leq 1)$



CPU burst (t_i)		6	4	6	4	13	13	13	…
"guess" (τ_i)	10	8	6	6	5	9	11	12	…

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)

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!

What about 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

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

Lottery Scheduling Example

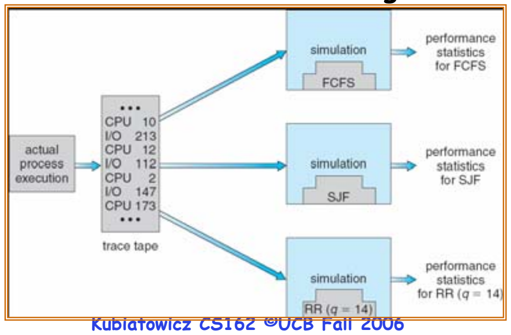
- Lottery Scheduling Example
  - Assume short jobs get 10 tickets, long jobs get 1 ticket

# 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

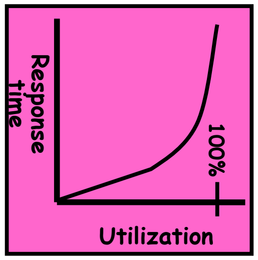
How to Evaluate a Scheduling algorithm?

- 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.



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%

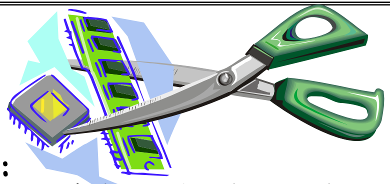


- An interesting implication of this curve:
  - Most scheduling algorithms work fine in the "linear" portion of the load curve, fail otherwise
  - Argues for buying a faster X when hit "knee" of curve

Administrivia

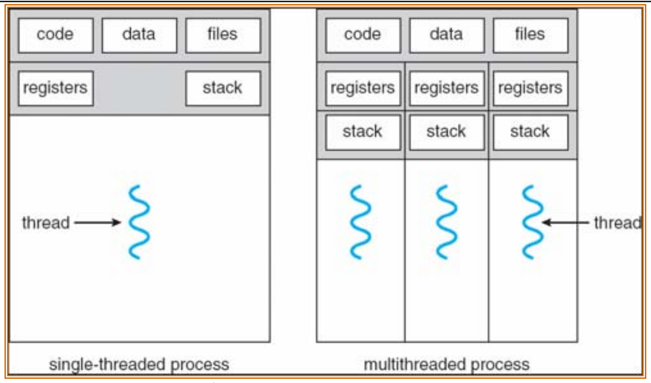
- Midterm I coming up in one week from today!:
  - Wednesday, 10/11, 4:00pm-7:00pm, Here (10 Evans)
  - Should be 2 hour exam with extra time
  - Closed book, one page of hand-written notes (both sides)
- No class on day of Midterm
  - I will post extra office hours for people who have questions about the material (or life, whatever)
- Review Session
  - 7:00pm Sunday 10/8
  - 306 Soda Hall
- Midterm Topics
  - Topics: Everything up to next Monday (10/9)
  - History, Concurrency, Multithreading, Synchronization, Protection/Address Spaces

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)

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

Binding of Instructions and Data to Memory

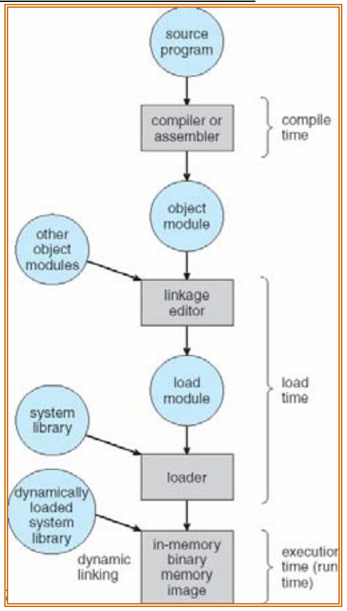
- Binding of instructions and data to addresses:
  - Choose addresses for instructions and data from the standpoint of the processor

```
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?

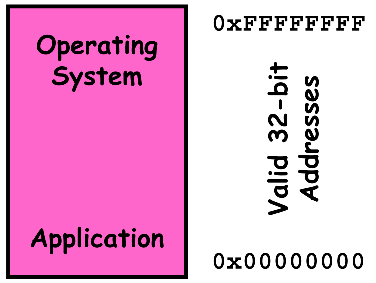
Multi-step Processing of a Program for Execution

- 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



Recall: Uniprogramming

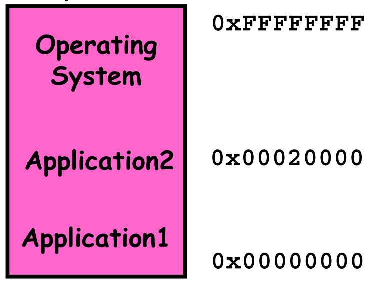
- Uniprogramming (no Translation or Protection)
  - Application always runs at same place in physical memory since only one application at a time
  - Application can access any physical address



  - Application given illusion of dedicated machine by giving it reality of a dedicated machine
- Of course, this doesn't help us with multithreading

Multiprogramming (First Version)

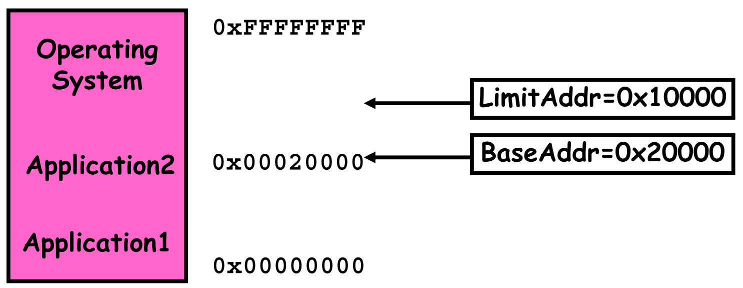
- Multiprogramming without Translation or Protection
  - Must somehow prevent address overlap between threads



  - 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

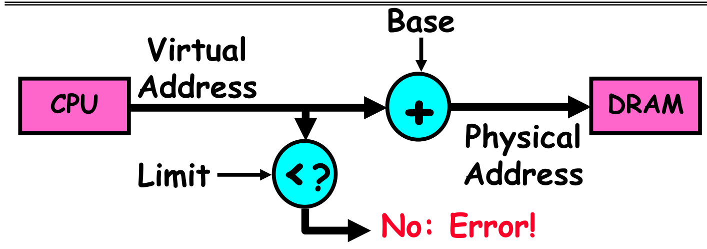
Multiprogramming (Version with Protection)

- Can we protect programs from each other without translation?



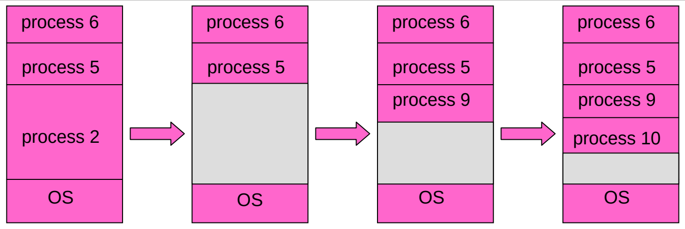
  - Yes: use two special registers *BaseAddr* and *LimitAddr* to prevent user from straying outside designated area
    - » If user tries to access an illegal address, cause an error
  - During switch, kernel loads new base/limit from TCB
    - » User not allowed to change base/limit registers

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

Issues with simple segmentation method

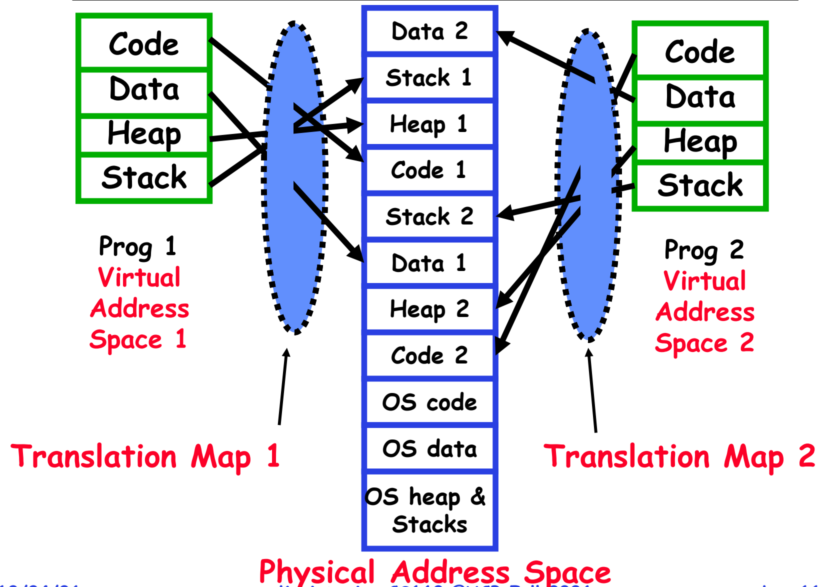


- Fragmentation problem
  - Not every process is the same size
  - Over time, memory space becomes fragmented
- Hard to do inter-process sharing
  - Want to share code segments when possible
  - Want to share memory between processes
  - Helped by by providing multiple segments per process
- Need enough physical memory for every process

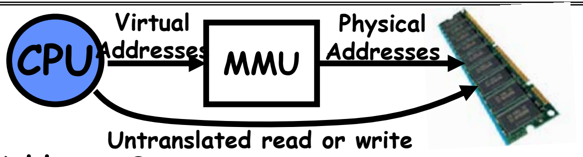
Multiprogramming (Translation and Protection version 2)

- 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

Example of General Address Translation



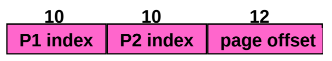
Two Views of Memory

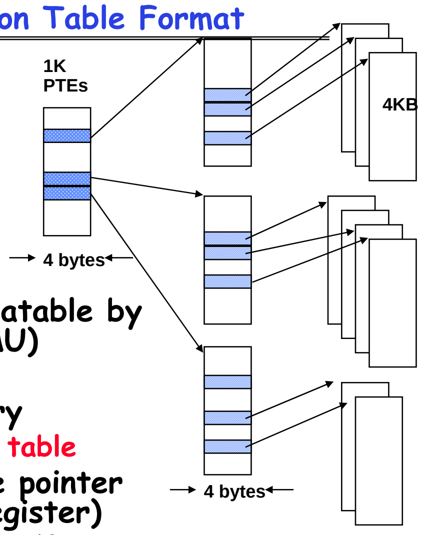


- Recall: Address Space:
  - All the addresses and state a process can touch
  - Each process and kernel has different address space
- Consequently: two views of memory:
  - View from the CPU (what program sees, virtual memory)
  - View fom memory (physical memory)
  - Translation box converts between 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

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

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 (Priviledge Level) from 0 – 3
    - » PL0 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 PL0 ("user") and PL3 ("kernel")

For Protection, Lock User-Programs in Asylum

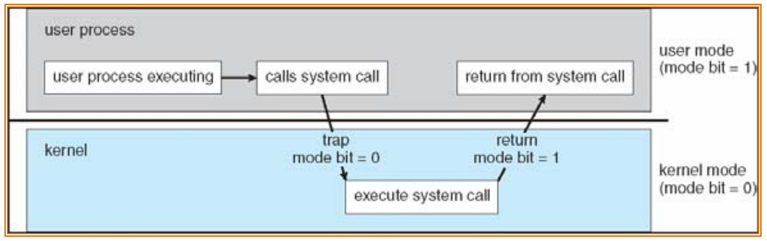
- Idea: Lock user programs in padded cell with no exit or sharp objects
  - Cannot change mode to kernel mode
  - User cannot modify page table mapping
  - Limited access to memory: cannot adversely effect other processes
    - » Side-effect: Limited access to memory-mapped I/O operations (I/O that occurs 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

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)

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

System Call Continued

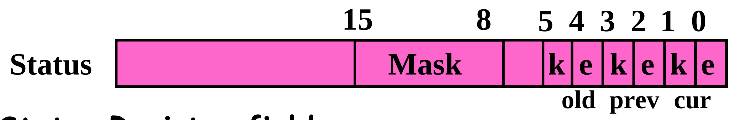
- What are some system calls?
  - I/O: open, close, read, write, lseek
  - Files: delete, mkdir, rmdir, truncate, chown, chgrp, ..
  - Process: fork, exit, wait (like join)
  - Network: socket create, set options
- Are system calls constant across operating systems?
  - Not entirely, but there are lots 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!

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

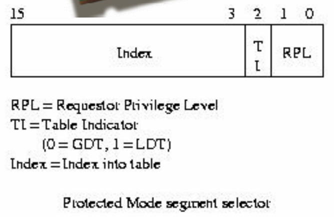
Additions to MIPS ISA to support Exceptions?

- 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



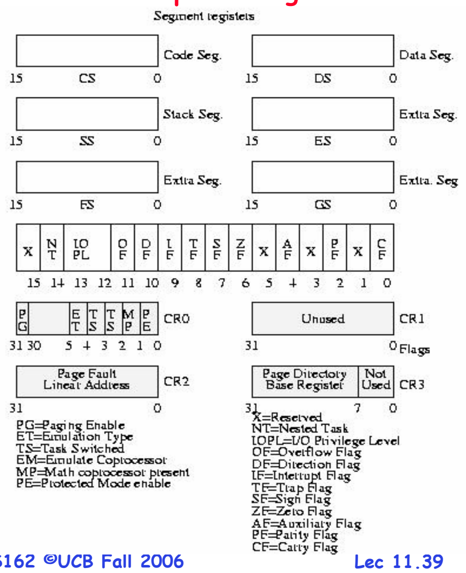
- Status Register fields:
  - Mask: Interrupt enable
    - » 1 bit for each of 5 hardware and 3 software interrupts
  - k = kernel/user: 0⇒kernel mode
  - e = interrupt enable: 0⇒interrupts disabled
  - Exception⇒6 LSB shifted left 2 bits, setting 2 LSB to 0:
    - » run in kernel mode with interrupts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

Intel x86 Special Registers



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

80386 Special Registers



Communication

- 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!

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)

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⇒more tokens)
  - Reserve a minimum number of tokens for every thread to ensure forward progress/fairness
- Evaluation of mechanisms:
  - Analytical, Queuing Theory, Simulation

Summary (2)

- 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)