Operating Systems Design
7. Process Scheduling

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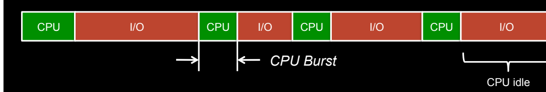
Process Behavior

Most processes exhibit:
- Large # of short CPU bursts between I/O requests
- Small # of long CPU bursts between I/O requests



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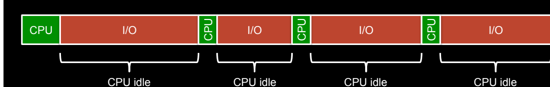
Process Behavior

Interactive process: mostly short CPU bursts



Compute process: mostly long CPU bursts

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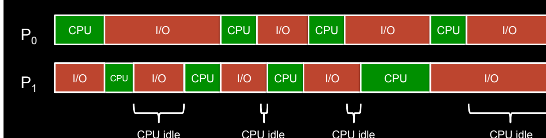
Process Scheduling

Goal:
- Maximize use of CPU & improve throughput
- Let another process run when the current one is waiting on I/O



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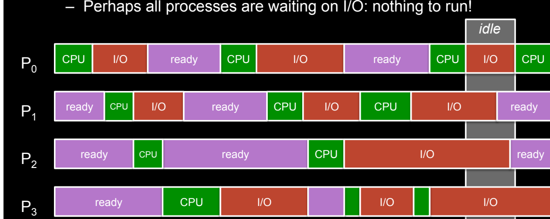
Process Scheduling

Reality:
- Some processes will use long stretches of CPU time
  - Preempt them and let another process run
- More processes may want the CPU: keep them in the *ready* list
- Perhaps all processes are waiting on I/O: nothing to run!



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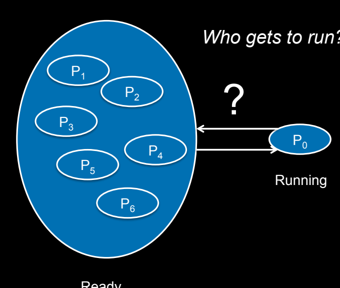
Process Scheduler



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Switching processes

- Scheduling algorithm:
  - Policy: Makes the decision of who gets to run
- Dispatcher:
  - Mechanism to do the context switch

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When does the scheduler make decisions?

Four events affect the decision:

1. Current process goes from *running* to *waiting* state
2. Current process terminates
3. Interrupt causes the scheduler to move a process from *running* to *ready: scheduler decides it's time for someone else to run*
4. Current process goes from *waiting* to *ready*
   I/O (including blocking events, such as semaphores) is complete

- Preemptive scheduler vs.
- Cooperative (non-preemptive) scheduler
  - CPU cannot be taken away
- Run-to-completion scheduler (old batch systems)

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Scheduling algorithm goals

- Be fair (to processes? To users?)
- Be efficient: Keep CPU busy … and don't spend a lot of time deciding!
- Maximize throughput: minimize time users must wait
- Minimize response time
- Be predictable: jobs should take about the same time to run when run multiple times
- Minimize overhead
- Maximize resource use: try to keep devices busy!
- Avoid starvation
- Enforce priorities
- Degrade gracefully

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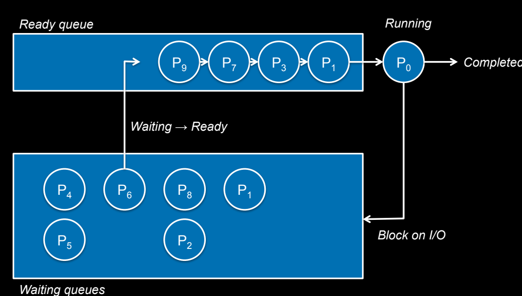
First-Come, First-Served (FCFS)



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First-Come, First-Served (FCFS)

- Non-preemptive
- A process with a long CPU burst will hold up other processes
  - I/O bound jobs may have completed I/O and are ready to run: poor device utilization
  - Poor average response time

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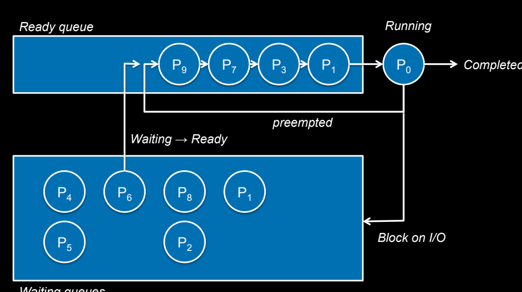
Round-Robin Scheduling

Preemptive: Process can not run for longer than a quantum (time slice)



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Round-Robin Scheduling

- Performance depends on the time slice
  - Long time slice makes this similar to FCFS
  - Short time slice increases overhead % of context switching
- Advantages
  - Every process gets an equal share of the CPU
  - Easy to implement
  - Easy to compute average response time: *f*(# processes on list)
- Disadvantage
  - Giving every process an equal share isn't necessarily good
  - Highly interactive processes will get scheduled the same as CPU-bound processes

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Shortest Remaining Time First Scheduling

- Sort jobs by anticipated CPU burst time
- Schedule shortest ones first
- Optimize average response time

Burst time	2	2	10	3	8	Total time = 25
Process	*E*	*D*	*C*	*B*	*A*	
Total run time	25	23	21	11	8	Mean time = 17.6

last ← *first*

Burst time	10	8	3	2	2	Total time = 25
Process	*C*	*A*	*B*	*D*	*E*	
Total run time	25	15	7	4	2	Mean time = 10.6

Mean completion time for a process falls by almost 40%!

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Shortest Remaining Time First Scheduling

- Biggest problem: *we're optimizing with data we don't have!*
- All we can do is estimate
- Exponential average:

  $e_{n+1} = \alpha t_n + (1 - \alpha)e_n$

  α is a weight factor to balance the weight of the last burst period vs. historic periods ($0 \le \alpha \le 1$)

  If $\alpha = 0$: $e_{n+1} = e_n$ (recent history has no effect)
  If $\alpha = 1$: $e_{n+1} = \alpha t_n$ (use only the last burst time)

- Algorithm can be preemptive or non-preemptive
- Preemptive version is:
  Shortest remaining time first scheduling (vs. SJF)

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Shortest Remaining Time First Scheduling

- Advantage
  - Short-burst jobs run fast
- Disadvantages
  - Long-burst (CPU intensive) jobs get a long mean waiting time
  - Rely on ability to estimate CPU burst length

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Priority Scheduling

Round Robin assumes all processes are equally important

- Not true
  - Interactive jobs need high priority for good response
  - Long non-interactive jobs can worse treatment (get the CPU less frequently): *this goal led us to SRTF*
  - Users may have different status (e.g., administrator)
- Priority scheduling algorithm:
  - Each process has a priority number assigned to it
  - Pick the process with the highest priority
  - Processes with the same priority are scheduled round-robin

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Priority Scheduling

- Priority assignments:
  - Internal: time limits, memory requirements, I/O:CPU ratio, …
  - External: assigned by administrators
- Static & dynamic priorities
  - Static priority: priority never changes
  - Dynamic priority: scheduler changes the priority during execution
    - Increase priority if it's I/O bound for better interactive performance or to increase device utilization
    - Decrease a priority to let lower-priority processes run
    - Example: use priorities to drive SJF/SRTF scheduling

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Priority Scheduling: dealing with starvation

- Starvation
  - Process is blocked indefinitely
  - Steady stream of higher-priority processes keeps it from being scheduled
- Dealing with starvation: Process aging
  - Gradually increase the priority of a process so that eventually its priority will be high enough so it will be scheduled to run
  - Then bring it down again

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Multilevel Queues

- Priority classes
  - Examples: System processes, interactive processes, slow interactive processes, background non-interactive processes
  - Each priority class gets its own queue
  - Processes are permanently assigned to a specific queue
- Goals
  - Priority scheduler with queues per priority level
  - Each queue may have a different scheduling algorithm
  - Quantum is increased at each lower priority level
    - Lower-priority processes tend to be compute bound

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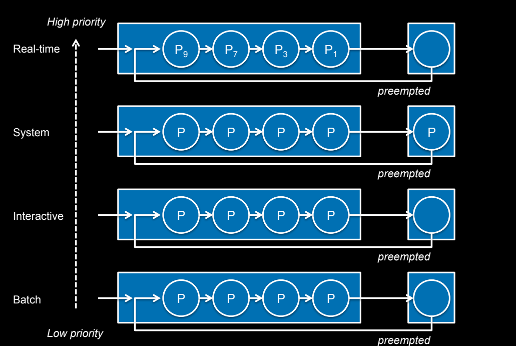
Multilevel Queues



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Multilevel Feedback Queues

Goals

- *Allow processes to move between queues*
- Separate processes based on CPU burst behavior
  - I/O-bound processes will end up on higher-priority queues
  - If a process does not finish its quantum then it will stay at the same level, otherwise it moves to a lower level
- Quantum is increased at each lower priority level
  - Lower-priority processes tend to be compute bound
- Processes that wait too long may be moved to a higher-priority queue (aging)
- Each queue may have a different scheduling algorithm

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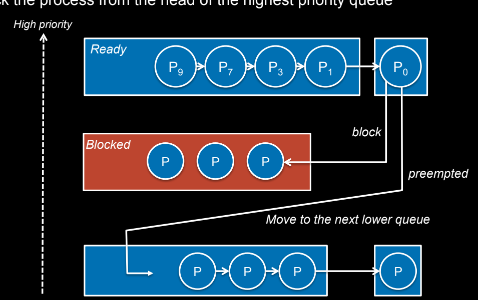
Multilevel Feedback Queues

Pick the process from the head of the highest priority queue



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Multilevel Feedback Queues

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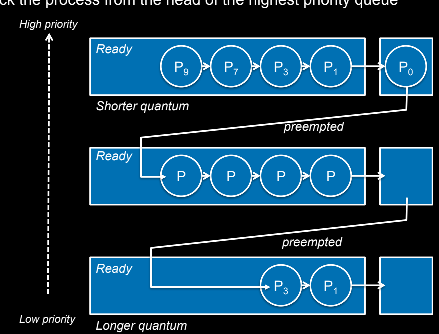

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Multilevel Feedback Queues

- Advantage
  - Good for separating processes based on CPU burst needs
  - Let I/O bound processes run often
  - Give CPU-bound processes longer chunks of CPU
  - No need to estimate interactivity! (Estimates were often flawed)
- Disadvantages
  - Priorities get controlled by the system.
    A process is considered important because it uses a lot of I/O
  - Processes whose behavior changes may be poorly scheduled
  - System can be gamed by scheduling bogus I/O

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Symmetric multiprocessor scheduling

- Processor affinity
  - Try to reschedule a process onto the same CPU
  - Cached memory may be present on the CPU's cache
- Types of affinity
  - Hard : force a process to stay on the same CPU
  - Soft affinity: best effort, but the process may be rescheduled on a different CPU
    - Load balancing: ensure that CPUs are busy
    - It's better to run a job on another CPU than wait
    - If the run queue for a CPU is empty, get a job from another CPU's run queue: *pull migration*
    - Check load periodically: if not balanced, move jobs. *Push migration*

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Hierarchy of symmetric multiprocessors

- Multiple processors
- Multiple cores
  - Shared caches among cores (e.g., Intel i7 cores share L3 cache)
- Hyperthreading
  - Presented as two cores to the operating system
  - Memory stall: CPU has to wait (e.g., to get data on a cache miss)
  - When the issuing logic can no longer schedule instructions from one thread and there are idle functional units in the CPU core, it will try to schedule a suitable instruction from the other thread.
- Good schedulers will know the difference

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Scheduler Examples

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Solaris Scheduler

- Priority-based scheduler: 170 priorities (0-169)
  - High priority → short quantum
- Six scheduling classes
  - Each class has priorities and scheduling algorithms

1. Time sharing (0-59)
   Default class. Dynamic priorities via a multilevel feedback queue *DEFAULT*
2. Interactive (0-59)
   Like TS but higher priority for in-focus windows in GUI
3. Real-time (100-159)
   Fixed priority, fixed time quantum; high priority values
4. System (60-99)
   Used to schedule kernel threads: run until they block or complete
5. Fair share (0-59)
   Processes scheduled on % of CPU
6. Fixed priority (0-59)
   Fixed priority

Highest priority (160-169): interrupt-handling threads

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Solaris Scheduler

- Default class: time sharing
  - Multilevel feedback queue
  - Small time slice for high priority queue
  - Long time slice for low priority queue
- Interactive class: similar but gives windowing apps higher priority
- Highest priority: threads in the real-time class
- System class: runs kernel threads (scheduler & paging)
  - Not preempted
- Fair share: set of processes get a "CPU share"
- Fixed priority: like time-sharing but never adjusted

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Windows Scheduler

- Two classes:
  - Variable class: priorities 1-15
  - Real-time class: priorities 16-31
- Each priority level has a queue
  - Pick the highest priority thread that is ready to run
- Relative priority
  - Threads have relative levels within their class
  - When a quantum expires, the thread's priority is lowered but never below the base
  - When a thread wakes from wait, the priority is increased
    - Higher increase if waiting for keyboard input
  - Priority is increased for foreground window processes

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Linux Schedulers

- Linux 1.2: Round Robin scheduler (fast & simple)
- Linux 2.2: Scheduling classes
  - Classes: Real-time, non-real-time, non-preemptible
  - Support for symmetric multiprocessing
- Linux 2.4: O(N) scheduler
  - Iterates over every task at each scheduling event
  - If a time slice was not fully used, ½ of the remaining slice was added to the new time slice for the process.
  - "goodness" metric decided who goes next
  - One queue (in a mutex): no processor affinity

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Linux 2.6 O(1) scheduler goals

Addressed three problems

- Scalability: O(1) instead of O(n) to not suffer under load
- Support processor affinity
- Support preemption

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Linux 2.6 O(1) scheduler

- One runqueue per CPU: 140 priority lists serviced round robin
  - Two priority ranges: 0-99 for real-time; 100-140 for others
  - *High priority processes get a longer quantum!*
  - If a process uses its time slice, it will not get executed until all other processes exhaust their quanta
- runqueue data structure:
  - Two arrays sorted by priority value:
    - **Active**: all tasks with time remaining in their slices
    - **Expired**: all tasks that used up their time slice
  - Scheduler chooses the highest priority task from the active queue
  - When the active queue is empty, the expired queue becomes active

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Linux 2.6 O(1) scheduler

- Real-time tasks: static priorities
- Non real-time tasks: dynamic priorities
  - I/O-bound processes get priority increased by up to 5 levels
  - CPU-bound processes get priority decreased up to 5 levels
  - Interactivity determined by %sleep : %compute time ratio
- SMP load balancing
  - Every 200ms, check if CPU loads are unbalanced
  - If so, move tasks from a loaded CPU to a less-loaded one
  - If a CPU's runqueue is empty, move from the other runqueue
- Downside of O(1) scheduler
  - A lot of code with complex heuristics

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Linux Completely Fair Scheduler

- Latest scheduler (introduced in 2.6.23)
- Goal: give a "fair" amount of CPU time to tasks
- Keep track of time given to a task ("virtual runtime")
  - Also use "sleeper fairness": tasks get a "fair" share of the CPU even if they sleep from time to time
- Priorities
  - Used as a decay factor for the time a task is permitted to execute
  - Allowable time decreases for low priority tasks

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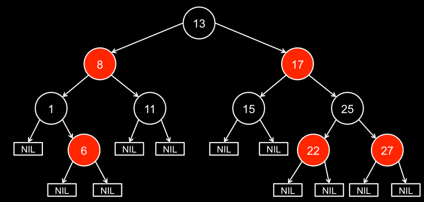
Linux Completely Fair Scheduler

- No run queues
- Time-sorted read-black tree instead of a run queue
  - Self-balancing binary tree: search, insert, & delete in O(log n)



Most deserving: Used least amount of time

Least deserving: Used most time

From: http://en.wikipedia.org/wiki/File:Red-black_tree_example.svg

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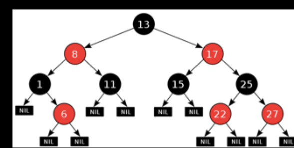
Linux Completely Fair Scheduler

- Goal: give a "fair" amount of CPU time to tasks
- Keep track of time given to a task ("virtual runtime")
  - Also "sleeper fairness": tasks that are waiting receive a fair share of the CPU when they are ready
- Time-sorted read-black tree instead of a run queue



Red-black tree: self-balancing binary tree O(log n)

Most deserving: Used least amount of time

Least deserving: Used most time

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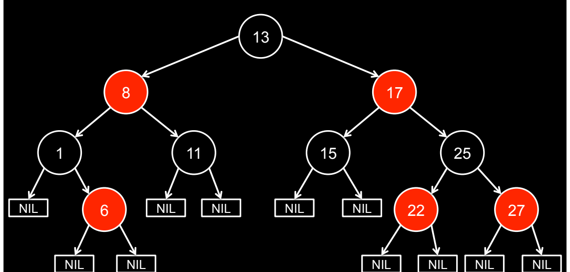

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CFS: picking a process

- Scheduling decision:
  - Pick the leftmost task
- When a process is done:
  - Add execution time to the per-task run time count
  - Insert the task back in the queue
- Heuristic: *decay factors*
  - Determine how long a task can execute
  - Higher priority tasks have lower factors of decay.
  - Avoids having run queues per priority level

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Group Scheduling

- Default operation: be fair to each task
- Assign one virtual runtime to a group of processes
  - Per user scheduling
  - cgroup pseudo file system interface for configuring groups
  - E.g., a user with 5 processes can get the same % of CPU as a user with 50 processes
- Default task group: init_task_group
- Improve interactive performance
  - A task calls *__proc_set_tty* to move to a tty task group
- /proc/sys/kernel/sched_granularity_ns
  - Tunable parameter to tune the scheduler between desktop (highly interactive) and server loads

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More on the Linux scheduler

- Modular scheduler core: Scheduling classes
  - Scheduling class defines common set of functions that define the behavior of that scheduler
    - Add a task, remove a task, choose the next task
  - Each task belongs to a scheduling class
  - sched_fair.c
    - implements the CFS scheduler
  - sched_rt.c
    - implements a priority-based round-robin real-time scheduler
- Scheduling domains
  - Group one or more processors hierarchically
  - One or more processors can share scheduling policies

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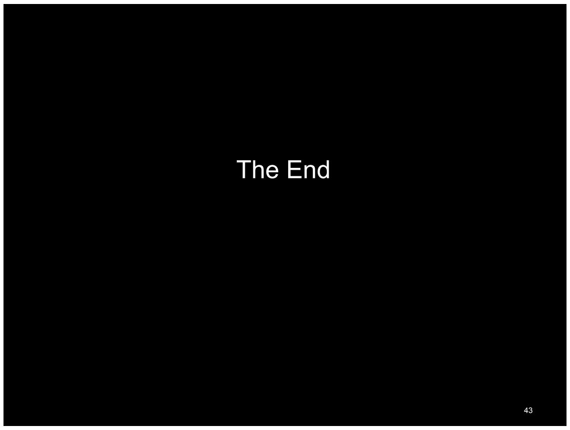
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