Chapter 6: Linux O(1) and CFS Scheduling

CSCI 3753 Operating Systems

Instructor: Chris Womack

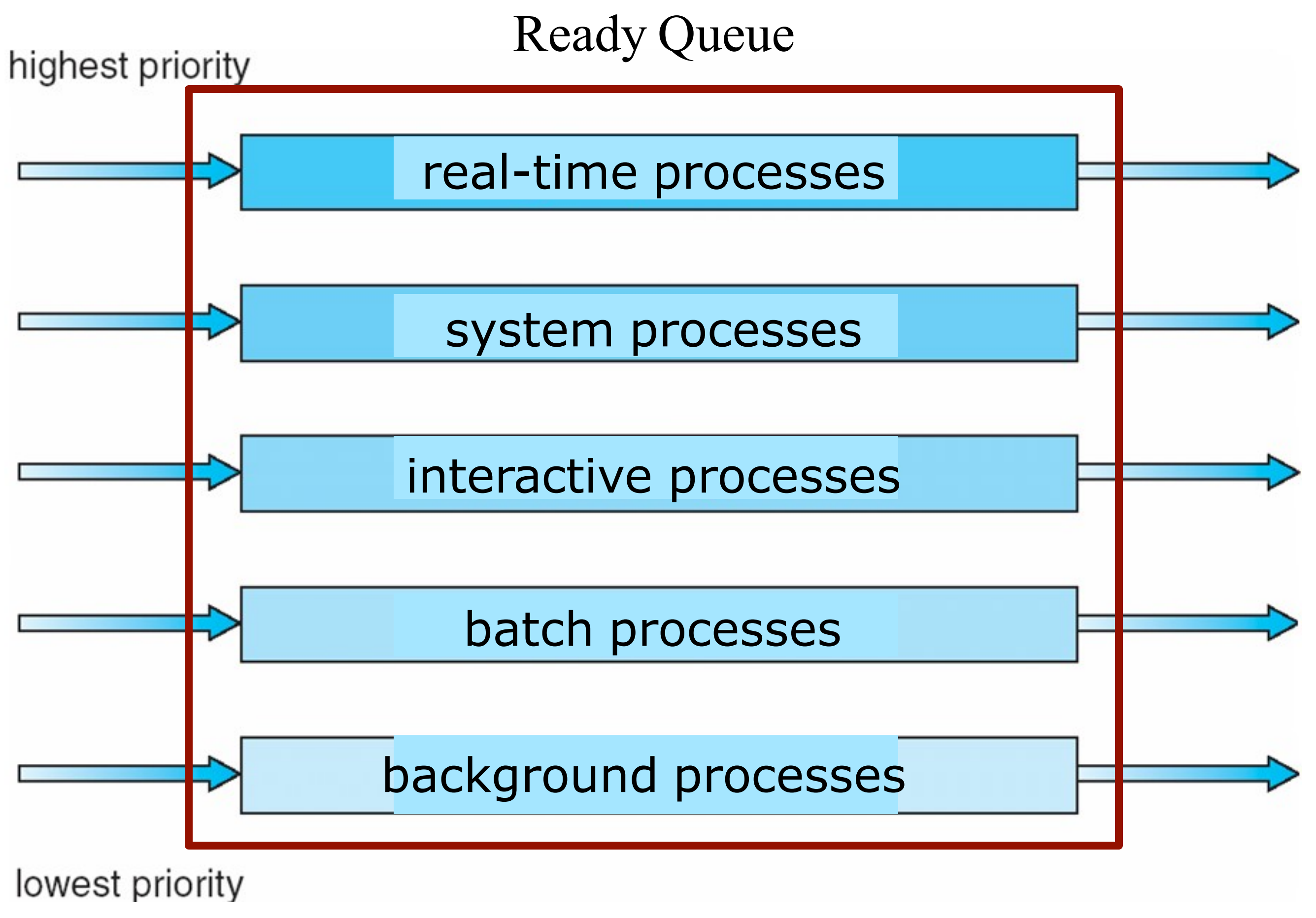
University of Colorado at Boulder

All material by Dr. Rick Han

Recap

- Round Robin Scheduling
  - Fair and Simple to implement
- Deadline-based Scheduling
  - Earliest Deadline First Scheduling
    - Hard Real Time Systems
  - Soft Real Time Systems
- Priority-based Scheduling
  - Multi-level Queues

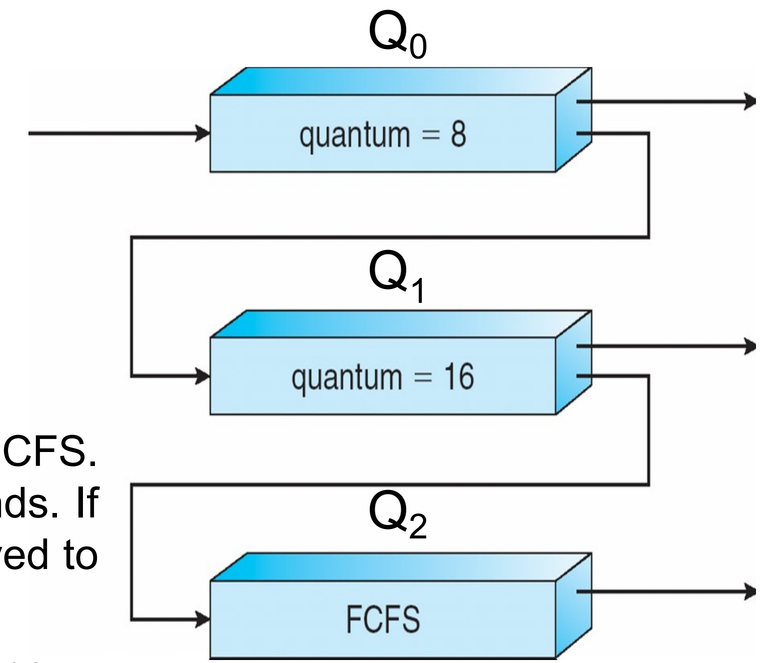
Multilevel Queue Scheduling



(modified)

Example of Multilevel Feedback Queue

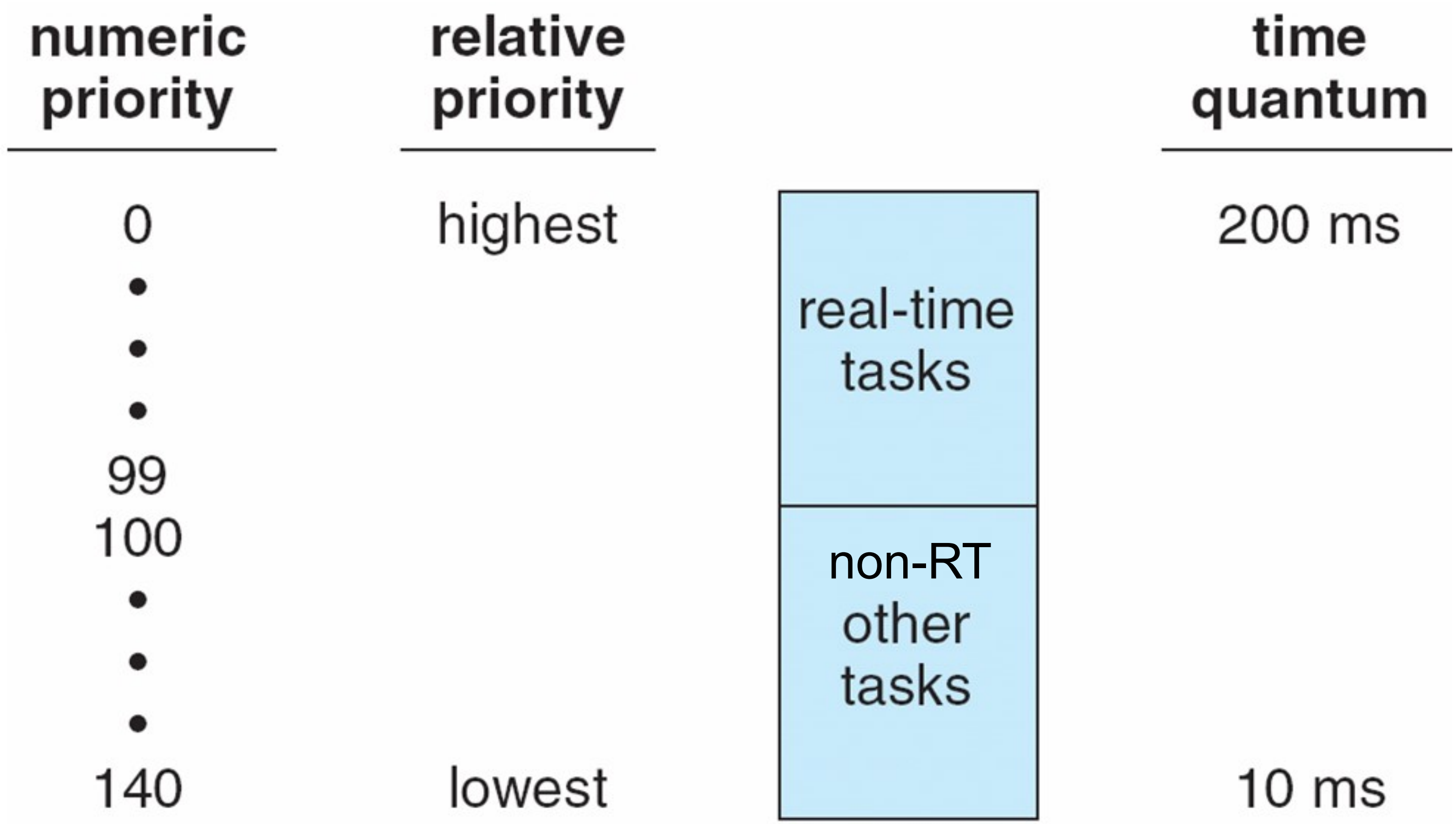
- Three queues:
  - Q_0 – RR with time quantum 8 milliseconds
  - Q_1 – RR time quantum 16 milliseconds
  - Q_2 – FCFS
- Scheduling
  - A new job enters queue Q_0 which is served FCFS. When it gains CPU, job receives 8 milliseconds. If it does not finish in 8 milliseconds, job is moved to queue Q_1.
  - At Q_1 job is again served FCFS and receives 16 additional milliseconds. If it still does not complete, it is preempted and moved to queue Q_2.
  - Interactive processes are more likely to finish early, processing a small amount of data, while compute-bound processes will exhaust their time slice. So interactive processes will gravitate towards higher priority queues.



Multi-level Feedback Queues

- Most modern OSs use or have used multi-level feedback queues for priority-based preemptive scheduling
  - e.g. Windows NT/XP, Mac OS X, FreeBSD/NetBSD and Linux pre-2.6
  - Linux 1.2 used a simple round robin scheduler
  - Linux 2.2 introduced scheduling classes (priorities) for real-time and non-real-time processes and SMP (symmetric multi-processing) support

Linux Priorities and Time-slice length



More Linux Scheduler History

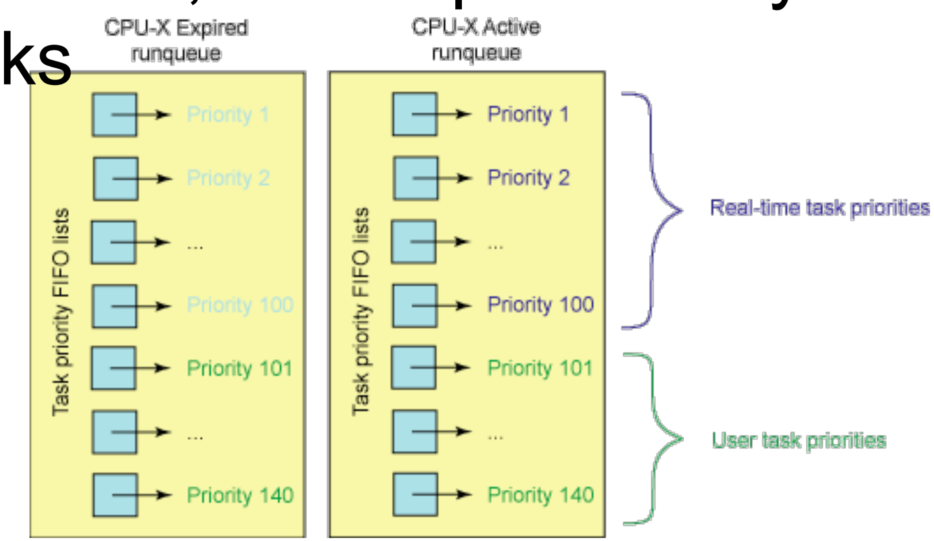
- Linux 2.4 introduced an O(N) scheduler – help interactive processes
  - If an interactive process yields its time slice before it's done, then its "goodness" is rewarded with a higher priority next time it executes
  - Keep a list of goodness of all tasks.
  - But this was unordered. So had to search over entire list of N tasks to find the "best" next task to schedule – hence O(N)
    - doesn't scale well

More Linux Scheduler History

- Linux 2.6-2.6.23 uses an O(1) scheduler
  - Iterate over fixed # of 140 priorities to find the highest priority task
  - The amount of search time is bounded by the # priorities, not the # of tasks.
  - Hence O(1) is often called “constant time”
  - scales well because larger # tasks doesn’t affect time to find best next task to schedule

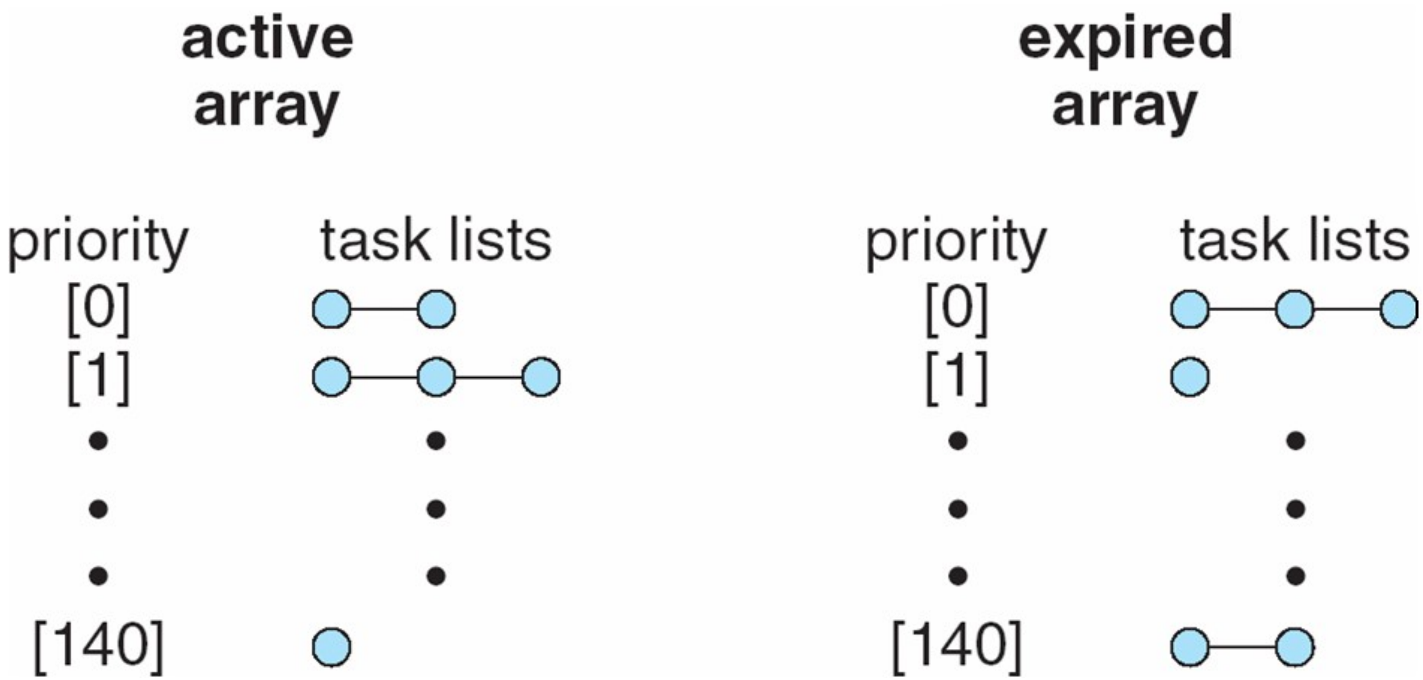
O(1) Scheduler in Linux

- Linux maintains two queues:
  - an active array or run queue and an expired array/ queue, each indexed by 140 priorities
- Active array contains all tasks with time remaining in their time slices, and expired array contains all expired tasks
- Once a task has exhausted its time slice, it is moved to the expired queue



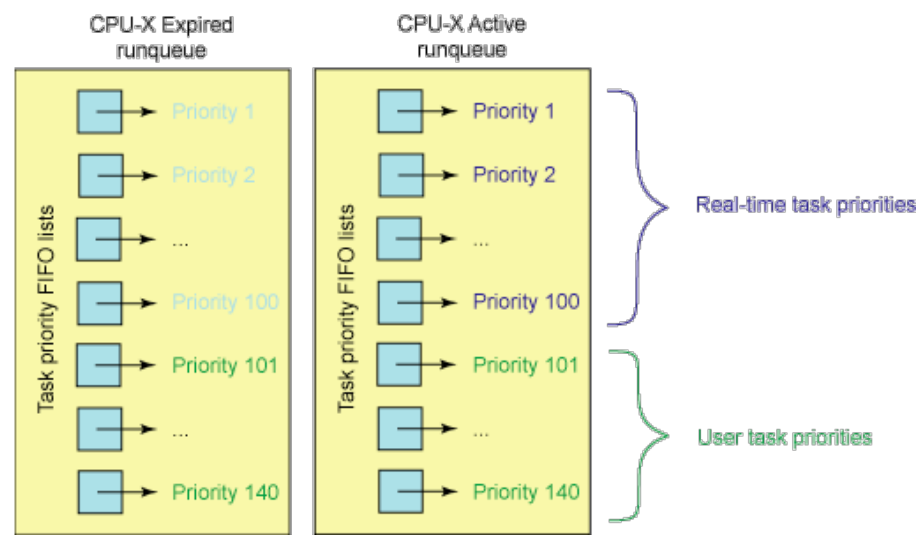
From http://www.ibm.com/developerworks/linux/library/l-scheduler/

O(1) Scheduler in Linux



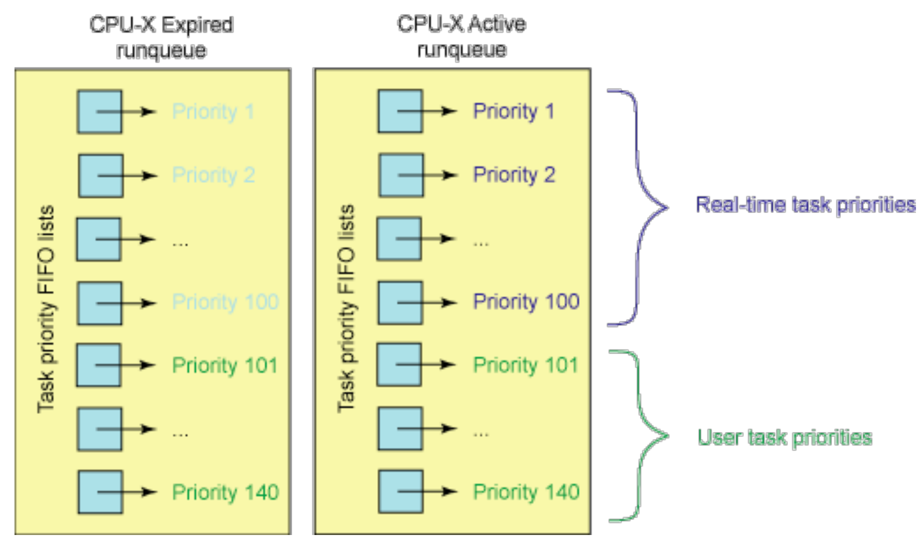
O(1) Scheduler in Linux

- An expired task is not eligible for execution again until all other tasks have exhausted their time slice
- Scheduler chooses task with highest priority from active array
  - Just search linearly through the active array from priority 1 until you find the first priority whose queue contains at least one unexpired task



O(1) Scheduler in Linux

- # of steps to find the highest priority task is in the worst case 140
  - This search is bounded and depends only on the # priorities, not # of tasks, unlike the O(N) scheduler
  - hence this is O(1) in complexity
- When all tasks have exhausted their time slices, the two priority arrays are exchanged
  - the expired array becomes the active array

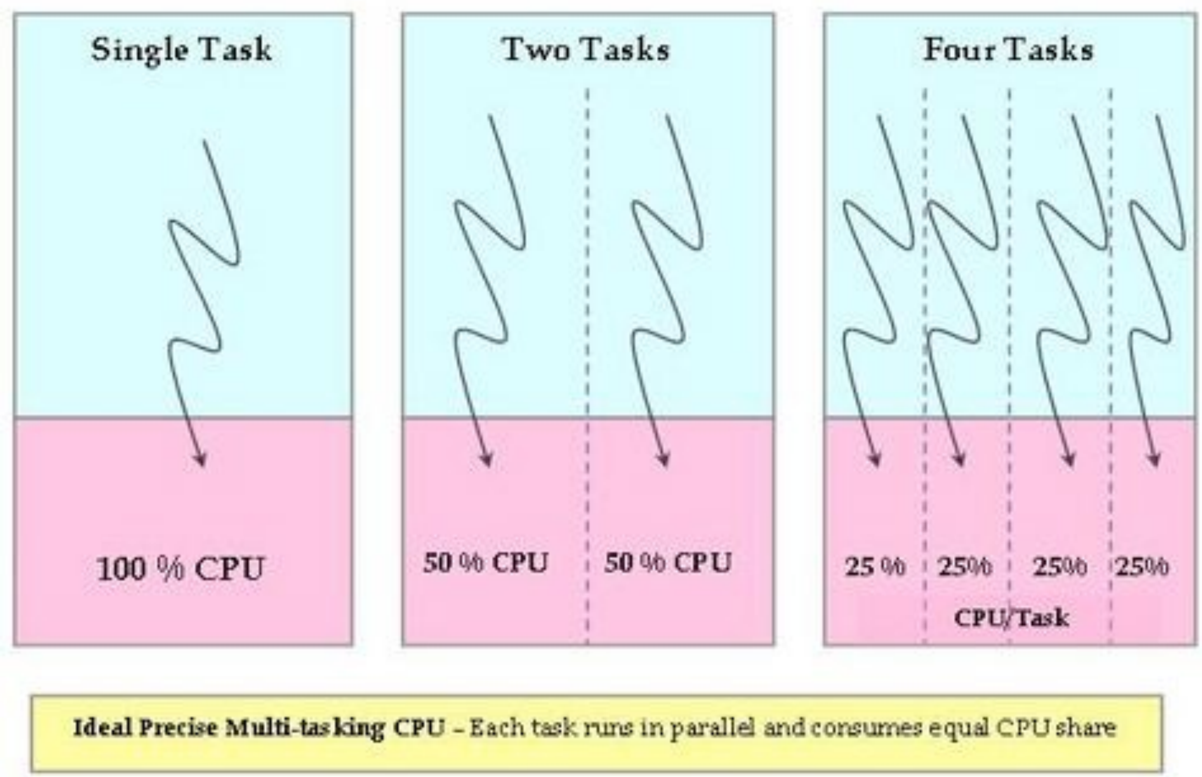


O(1) Scheduler in Linux

- When a task is moved from run to expired, Linux recalculates its priority according to a heuristic
  - New priority = nice value +/- f(interactivity)
    - f() can change the priority by at most +/-5, and is closer to -5 if a task has been sleeping while waiting for I/O
    - interactive tasks tend to wait longer times for I/O, and thus their priority is boosted -5, and closer to +5 for compute-bound tasks
  - This dynamic reassignment of priorities affects only the lowest 40 priorities for non-RT/user tasks (corresponds to the nice range of +/- 20)
  - The heuristics became difficult to implement/maintain

Completely Fair Scheduler (CFS) in Linux

- Linux 2.6.23+/3.* has a "completely fair" scheduler
- Based on concept of an "ideal" multitasking CPU
- If there are N tasks, an ideal CPU gives each task 1/N of CPU *at every instant of time*



CFS Intuition

- On an ideal CPU, N tasks would run truly in parallel, each getting 1/N of CPU and each executing at every instant of time
  - Example: for a 4 GHz processor, if there are 4 tasks, each gets a 1 GHz processor for each instant of time
  - Each such task makes progress at every instant of time
  - This is “fair” sharing of the CPU among each of the tasks

CFS Intuition

- In practice, we know a real (1-core) CPU cannot run N tasks truly in parallel
  - Only 1 task can run at a time
  - Time slice in/out the N tasks, so that in steady state each task gets ~ 1/N of CPU
  - This gives the illusion of parallelism
  - Thus, what we have is concurrency, i.e. the N tasks run concurrently, but not truly in parallel

CFS Intuition

- Ingo Molnar (designer of CFS):
  - "CFS basically models an 'ideal, precise multitasking CPU' on real hardware."
- So CFS's goal is to approximate an ideally shared CPU
- Approach: when a task is given T seconds to execute, keep a running balance of the amount of time owed to other tasks as if they all ran on an ideal CPU

CFS Intuition

- Example:
  - Task T1 is given a T second time slice on the CPU
  - Suppose there are 3 other tasks T2, T3, and T4
  - On an ideal CPU, in any interval of time T, then T1, T2, T3 and T4 would each have had the equivalent of time T/4 on the CPU
  - Instead, on a real CPU
    - T1 is given T instead of T/4, so T1 has been overallocated 3T/4
    - T2, T3 and T4 are owed time T/4 on the CPU, i.e. they have each been forced to *wait* the equivalent of T/4

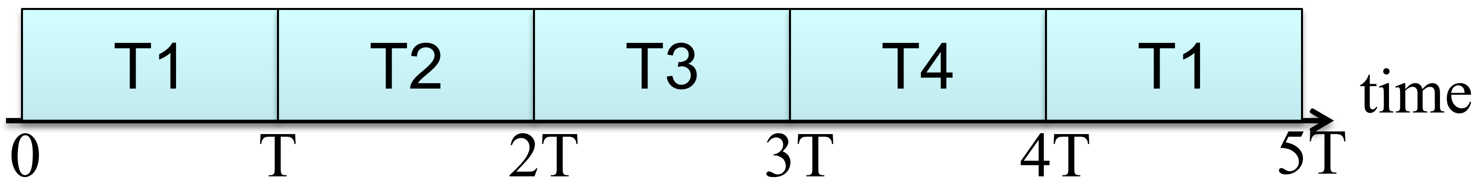
CFS Intuition

- Example:
  - The current accounting balance is summarized in the table below

	Time owed to task, i.e. wait time W_i:			
Giving time T to task:	T1	T2	T3	T4
T1	-3T/4	T/4	T/4	T/4

  - In general, at any given time t in the system, each task T_i has an amount of time owed to it on an ideal CPU, i.e. the amount of time it was forced to wait, its *wait time $W_i(t)$,*

CFS Intuition



- Example: let's have round robin over 4 tasks

	Time owed to task, i.e. wait time W_i:			
Giving time T to task:	T1	T2	T3	T4
T1	-3T/4	T/4	T/4	T/4
then T2	-T/2	-T/2	T/2	T/2
then T3	-T/4	-T/4	-T/4	3T/4
then T4	0	0	0	0

- After 1 round robin, the balances owed all = 0, so every task receives its fair share of CPU over time 4T

CFS Intuition

- Suppose a 5th task T5 is added to the round robin
  - Now the amount owed/wait time is calculated as T/5 for each task not chosen for a time slice, and as -4T/5 for the chosen task for a time slice
  - In general, if there are N runnable tasks, then
    - (N-1)T/N is subtracted from the balance owed/wait time of the chosen task
    - T/N is added to the balanced owed/wait time of all other ready-to-run tasks
  - T5 is initially owed no CPU time, so $W_5 = 0$
    - Example: If T5 had arrived just after T2's time slice, then T5's wait time =0 would place it above T1 and T2 but below T3 and T4 in terms of amount of time owed on the CPU

CFS Scheduler in Linux

- Goal of CFS Scheduler: *select the task with the longest wait time*
  - i.e. choose $\max\limits_{i} W_i$
  - This is the task that is owed the most time on the CPU and so should be run next to achieve fairness most quickly

Wait Time Calculation

- Each scheduling decision at time k incurs a wait time $W_i(k)$, either positive or negative, to each task i
- Total accumulated wait time for each task i at time k is:

$$Wtotal_i(k) = \sum_{j=1}^{k} W_i(j)$$

Wait Time Calculation

- Each wait time $W_i(k)$ =
  - Either a penalty of T/N added to $Wtotal_i$ if task i is not chosen to be scheduled, or
  - (N-1)T/N is *subtracted* from the sum (=T-T/N) if task i is chosen to be scheduled
- So $W_i(k)$= either T/N or –T+T/N
  - note how T/N is added regardless of the case!
- Hence $W_i(k)$ = T/N - execution/run time given to task i at time k, which may be zero
  - Define run time $R_i(k)$ as the execution/run time given to task i at time k, which may be zero
  - So $W_i(k) = T/N - R_i(k)$

Wait Time Calculation

- In general, each scheduling decision at time k may choose:
  - An arbitrary amount of time T(k) to schedule the chosen task, i.e. it doesn't have to be a fixed time slot T
  - The number of runnable tasks N(k) may change at each decision time k
- So $W_i(k) = T(k)/N(k) - R_i(k)$

Wait Time Calculation

- Total accumulated wait time for each task i at time k is:

$$Wtotal_i(k) = \sum_{j=1}^{k} W_i(j) = \sum_{j=1}^{k} [T(j)/N(j) + R_i(j)]$$

$$= \underbrace{\sum_{j=1}^{k} T(j)/N(j)}_{\text{Global fair clock measuring how system time advances in an ideal CPU with N varying tasks, also called rq->fair\_clock in CFS' 1st implementation}} + \underbrace{\sum_{j=1}^{k} R_i(j)}_{\text{Total run time given task i. Let's define it as } Rtotal_i(k)}$$

Global fair clock measuring how system time advances in an ideal CPU with N varying tasks, also called rq->fair_clock in CFS' 1st implementation

Total run time given task i. Let's define it as $Rtotal_i(k)$

CFS Scheduler in Linux

- Recall: CFS scheduler chooses task with max $Wtotal_i(k)$ at each scheduling decision k
- Maximizing $Wtotal_i(k)$ equivalent to minimizing the quantity [Global fair clock - $Wtotal_i(k)$]
- 1st CFS scheduler:
  – Had to track global fair clock and $Wtotal_i(k)$ for each task i
  – Then would compute the values [Global fair clock - $Wtotal_i(k)$]
  – Then ordered these values in a Red-Black tree
  – Then selected leftmost node in tree (has minimum value) and scheduled the task corresponding to this node

CFS Scheduler in Linux

- Revised CFS scheduler:
  - We note that [Global fair clock - $Wtotal_i(k)$] = run time $Rtotal_i(k)$!
  - Minimizing over the quantities [Global fair clock - $Wtotal_i(k)$] is equivalent to minimizing over the accumulated run times $Rtotal_i(k)$
  - 1st CFS scheduler had to track complex values like the global fair clock, and accumulated wait times
    - These both needed the # runnable tasks N(k) at each scheduling decision time k, which keeps changing
  - New approach just sums run times given each task
  - this simple approach still achieves fairness according to our derivation

Virtual Run Time

- Revised CFS scheduler simply sums the run times given each task and chooses the one to schedule with the minimum sum
  - This is equivalent to choosing the task owed the most time on an ideal fair CPU according to our derivation, and thus achieves fairness
  - Caveat: when a new task is added to the run queue, it may have been blocked a long time, so its run time may be very low compared to other tasks in the run queue
    - Such a task would consume a long time before its accumulated run time rises to a level close to the other executing tasks' total run times, which would effectively block other tasks from running in a timely manner

Virtual Run Time

- Revised CFS scheduler accommodates new tasks as follows:
  - Define a virtual run time *vruntime*
    - As before, each normally running task i simply adds its given run times to its own accumulated sum $vruntime_i$
  - When a new task is added to the run queue (or an existing task becomes unblocked from I/O), assign it a new virtual run time = minimum of current vruntimes in the run queue
    - This quantity is defined as *min_vruntime*
  - This approach re-normalizes the newly active task's run time to about the level of the virtual run times of the currently runnable tasks

Virtual Run Time

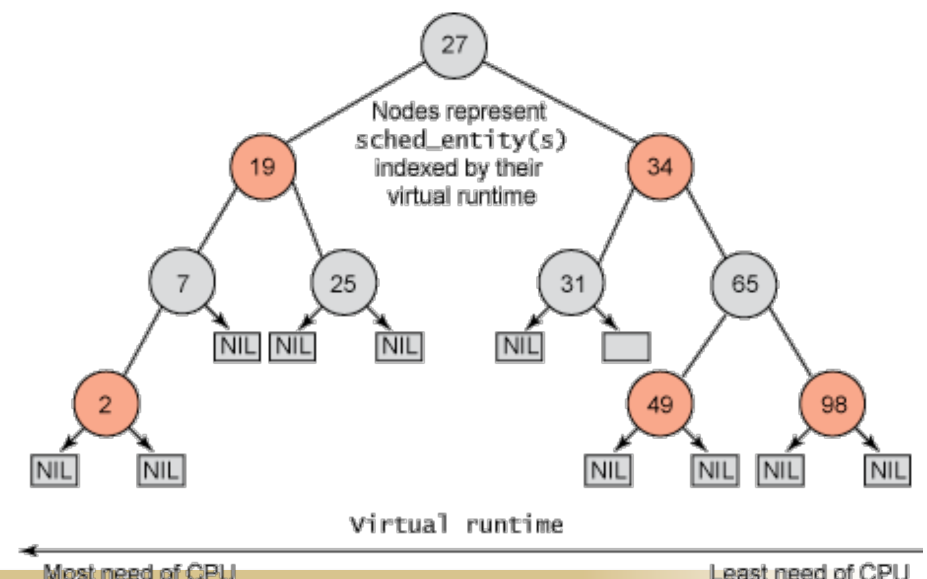
- Since each newly active task's is given a re-normalized run time, then the run time calculated is not the actual execution time given a task
  - Hence we need to define a new term $vruntime_i(k)$, rather than use the absolute accumulated run time $Rtotal_i(k)$
- *Intuitively, CFS choosing the task with the minimum virtual run time prioritizes the task that been given the least time on the CPU*
  - *This is the task that should get service first to ensure fairness*

CFS Scheduler in Linux

- *So revised CFS scheduler chooses the task with the minimum $vruntime_i(k)$ at each scheduling decision time k*
- This approach is responsive to interactive tasks!
  - They get instant service after they unblock from their I/O
  - This is because they are given a re-normalized $vruntime_i(k) = min\_vruntime$,
  - Since CFS chooses the next task to schedule as the one with the minimum vruntime, then the interactive task will be chosen first and get service immediately

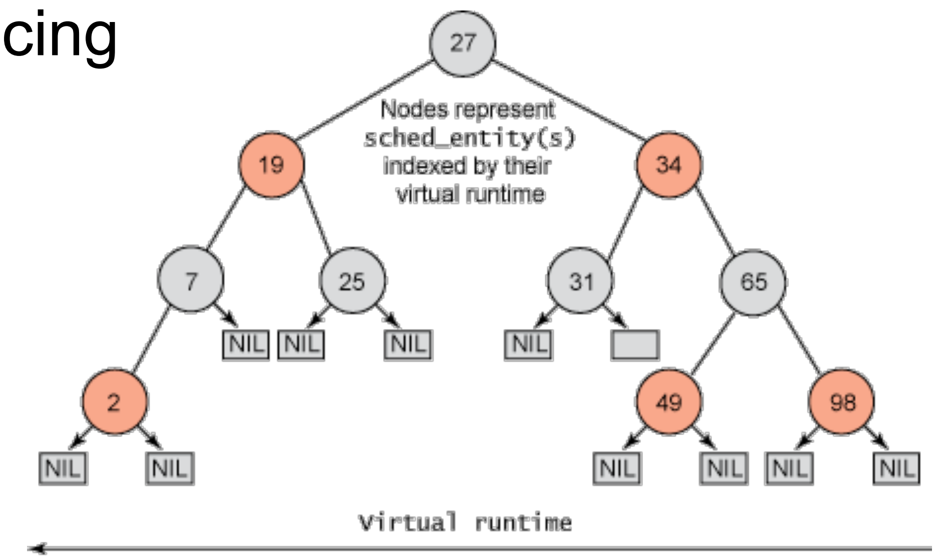
CFS' Red Black Tree

- To quickly find the task with the minimum vruntime, order the vruntimes in a Red-Black tree
  - This is a balanced tree, ordered from left (minimum vruntime) to right (maximum vruntime)
- Finding the minimum is fast, simple and constant time!
  - Choose leftmost task in tree with lowest virtual run time to schedule next



CFS' Red Black Tree

- As tasks run more, their virtual run time increases
  - so they migrate to other positions further to the right in the tree
  - Must re-insert nodes to tree, and rearrange tree, but the RB tree is self-balancing
- Inserting nodes is an O(logN) operation due to RB tree
  - This is viewed as acceptable overhead



CFS' Red Black Tree

- Tasks that haven't had CPU execution in a while will migrate left and eventually get service
  - Intuitively, this eventual migration leftwards makes CFS fair
- Newly active tasks, e.g. interactive ones, will be added to the left of the tree and get service quickly