Chapter 6: Linux O(1) and CFS Scheduling

CSCI 3753 Operating Systems

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Announcements

- Reading Quiz 6 is due on Thursday.
- Interview grading for PA2 will be a 5 question, in recitation quiz, this Friday. It will be ”Explain…” long answer kinds of questions. These are the same exact questions you would have been asked orally.
- Special accomodation students will still do oral interview grading and will not take the recitation quiz.

Review…

- FCFS – First Come First Served
  - Non-preemptive, long average wait time, each tas runs until finished
- SJF – Shortest Job First
  - Can be preemptive, shortest job runs first, provably optimal for shortest average wait time, can lead to starvation of processes which need a lot of CPU time.

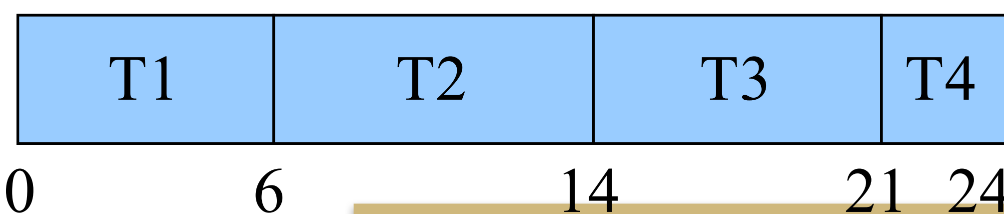
Review…

- Round Robin Scheduling
  - Fair, simple to implement, no starvation, preemptive, can vary the process time-slice based upon priority
- Deadline-based Scheduling
  - Earliest Deadline First Scheduling
    - Hard Real Time Systems
  - Soft Real Time Systems
- Priority-based Scheduling
  - Multi-level Queues

First Come First Serve (FCFS) Scheduling

- Tasks are scheduled according to the order they arrive
  - Simple to implement
  - Can result in high variance

Task	CPU Execution Time
T1	6
T2	8
T3	7
T4	3

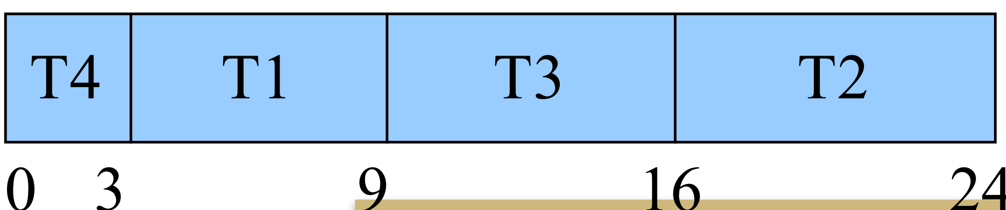


average wait time
= (0+6+14+21)/4
= 10.25 seconds

Shortest Job First Scheduling

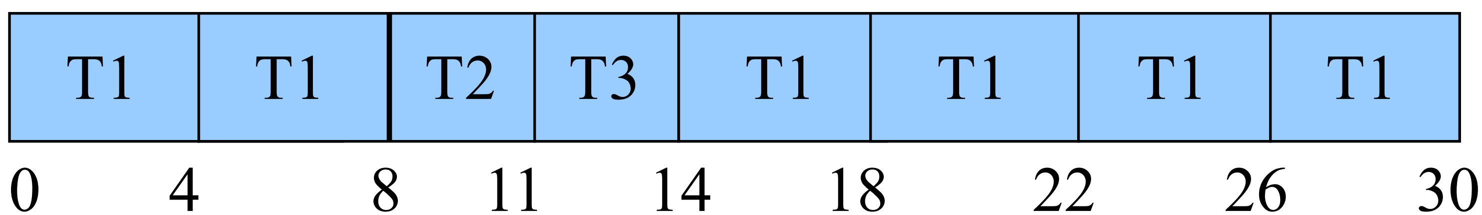
- Schedule tasks with the shortest execution times first
  - Can prove this results in the lowest average wait time

Task	CPU Execution Time
T1	6
T2	8
T3	7
T4	3



average wait time
= (0+3+9+16)/4
= 7 seconds

Weighted Round Robin



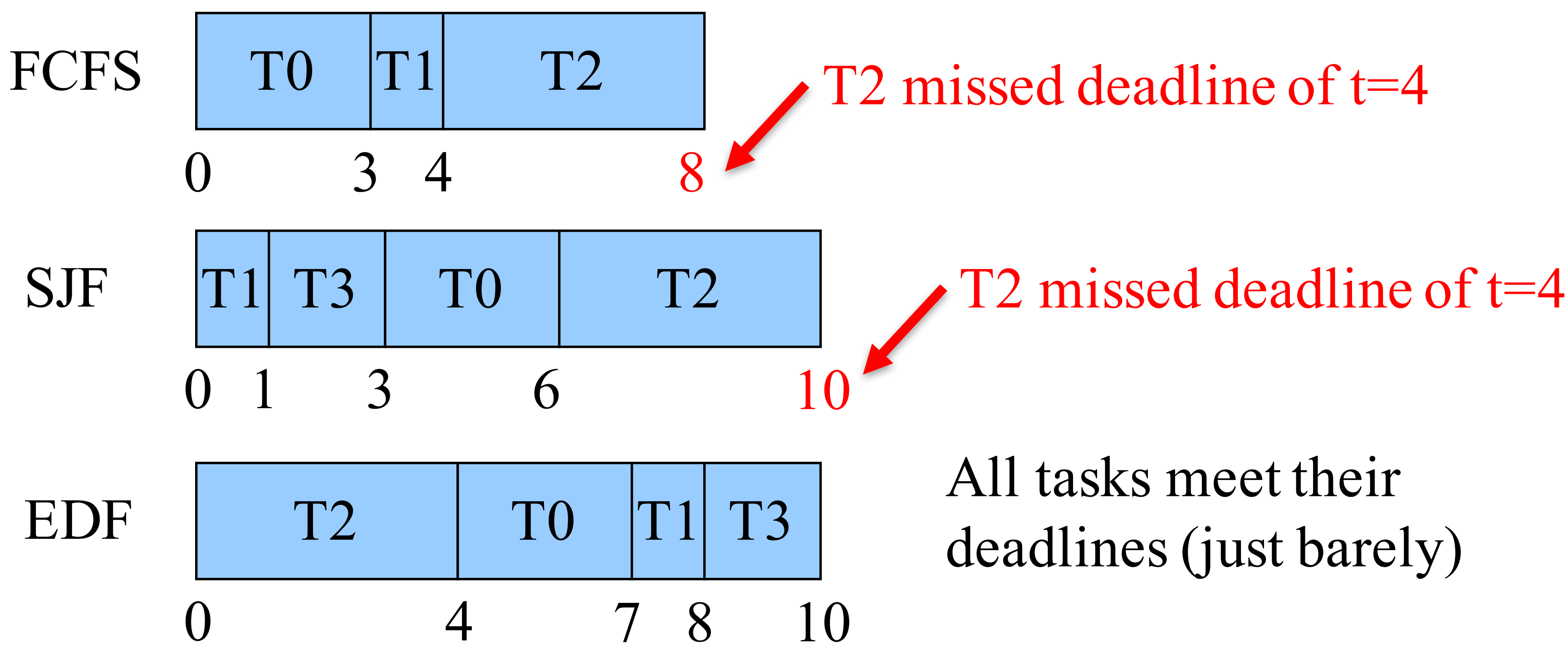
Deadline Scheduling

- Hard real time systems require that certain tasks *must* finish executing by a certain time, or the system fails
  - e.g. robots and self-driving cars need a real time OS (RTOS) whose tasks (actuating an arm/leg or steering wheel) must be scheduled by a certain deadline

Task	CPU Execution Time	Deadline from now
T0	3	7
T1	1	9
T2	4	4
T3	2	10

Earliest Deadline First (EDF) Scheduling

- Choose the task with the earliest deadline
  - This task most urgently needs to be completed



Deadline Scheduling

- Even EDF may not be able to meet all deadlines:
  - In previous example, if T3's deadline was t=9, then EDF cannot meet T3's deadline
- When EDF fails, the results of further failures, i.e. missed deadlines, are unpredictable
  - Which tasks miss their deadlines depends on when the failure occurred and the system state at that time
    - Could be a cascade of failures
  - This is one disadvantage of EDF

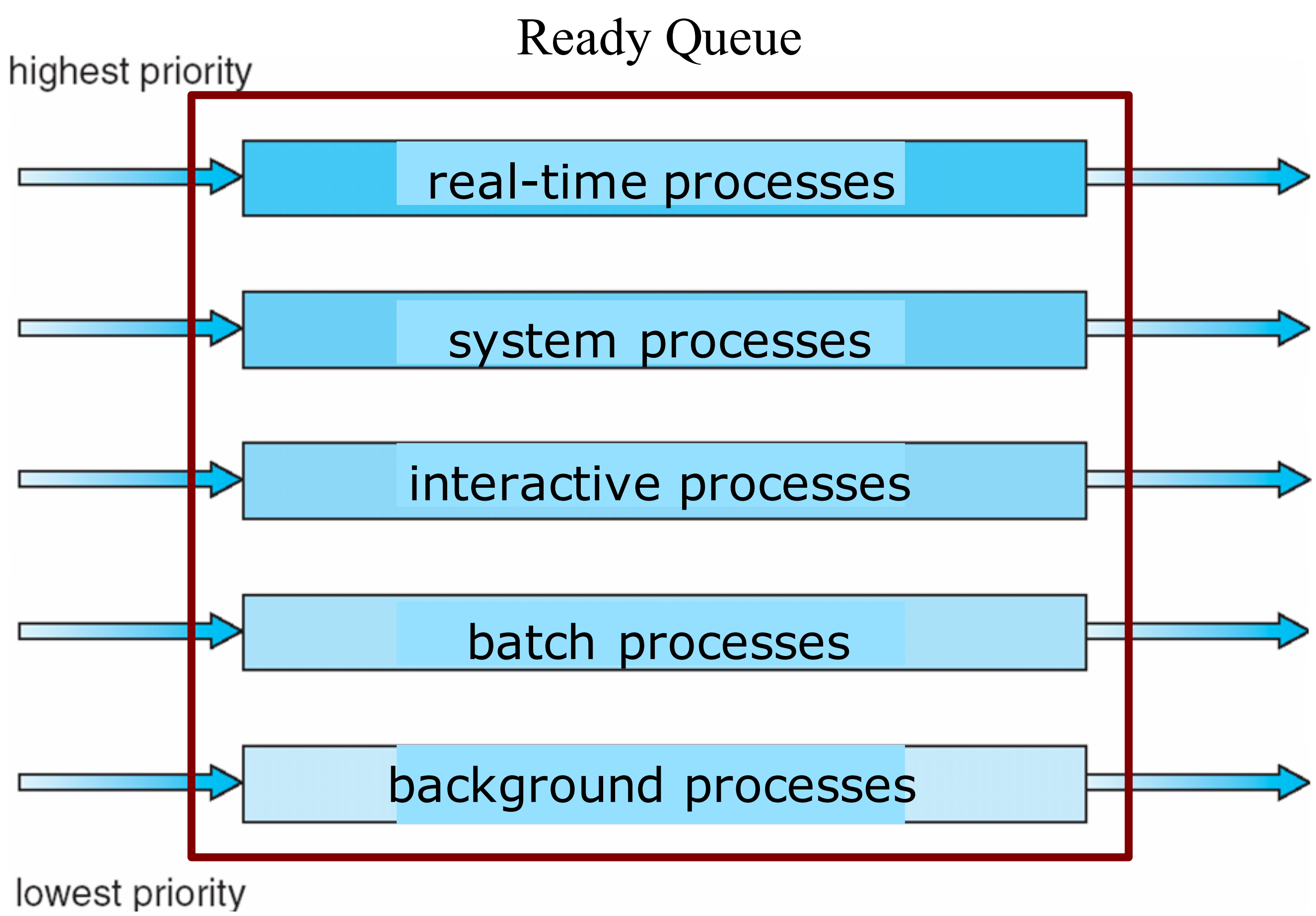
Deadline Scheduling

- Admission control policy
  - Check on entry to system whether a task's deadline can be met,
    - Examine the current set of tasks already in the ready queue and their deadlines
    - If all deadlines can be met with the new task, then admit it. The *schedulability* of the set of real-time tasks has been verified.
    - Else, deny admission to this task if its deadline can't be met.
  - Note FCFS, SJF and priority had no notion of refusing admission

Soft Real Time Systems

- *Soft* real time systems seek to meet most deadlines, but allow some to be missed
  - Unlike hard real time systems, where every deadline must be met or else the system fails
  - Soft real time scheduler may seek to provide probabilistic guarantees
    - e.g. if 60% of deadlines are met, that may be sufficient for some systems
  - Linux supports a soft real-time scheduler based on priorities – we'll see this next

Multilevel Queue Scheduling



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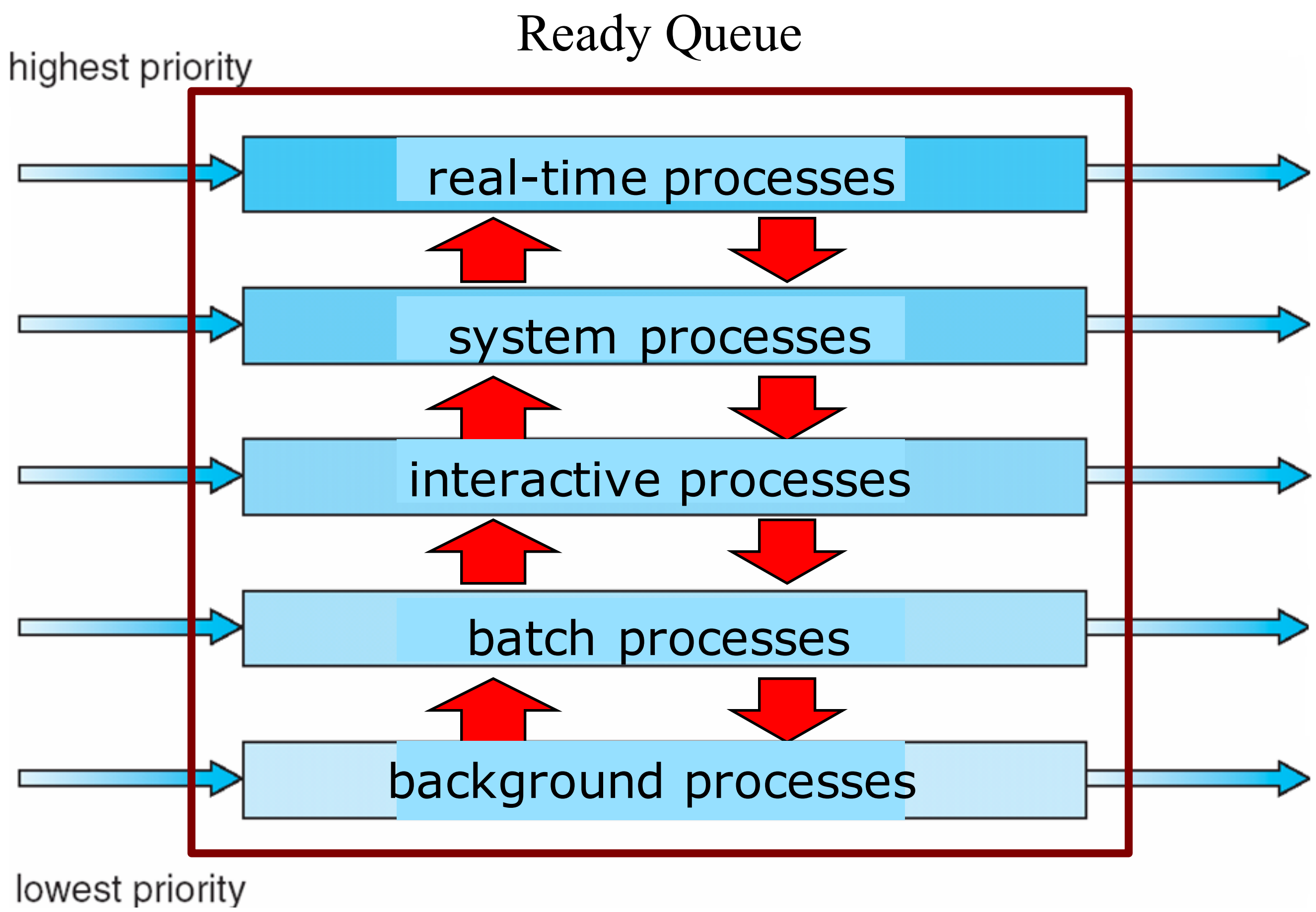
Multilevel Feedback Queue Scheduling



(modified)

Multilevel Feedback Queue

- Multilevel-feedback-queue scheduler defined by the following parameters:
  - number of queues
  - scheduling algorithms for each queue
  - method used to determine when to upgrade a process
  - method used to determine when to demote a process
  - method used to determine which queue a process will enter when that process needs service

Multi-level Feedback Queues

- Criteria for process movement among priority queues could depend upon age of a process:
  - old processes move to higher priority queues, or conversely, high priority processes are eventually demoted
  - sample aging policy: if priorities range from 1-128, can decrease (increment) the priority by 1 every T seconds
  - eventually, the low priority process will get scheduled on the CPU

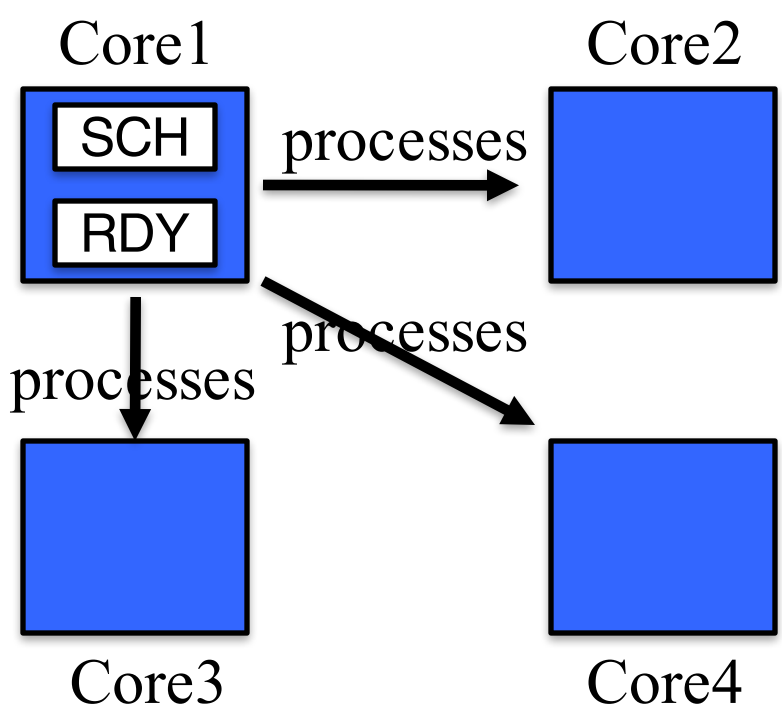
Multi-level Feedback Queues

- Criteria for process movement among priority queues could depend upon behavior of a process:
  - could be CPU-bound processes move down the hierarchy of queues, allowing interactive and I/O-bound processes to move up
  - give a time slice to each queue, with smaller time slices higher up
  - if a process doesn’t finish by its time slice, it is moved down to the next lowest queue
  - over time, a process gravitates towards the time slice that typically describes its average local CPU burst

New Material

Multi-core Scheduling

- Scheduling over multiple processors or cores is a new challenge.
  - A single CPU/processor may support multiple cores

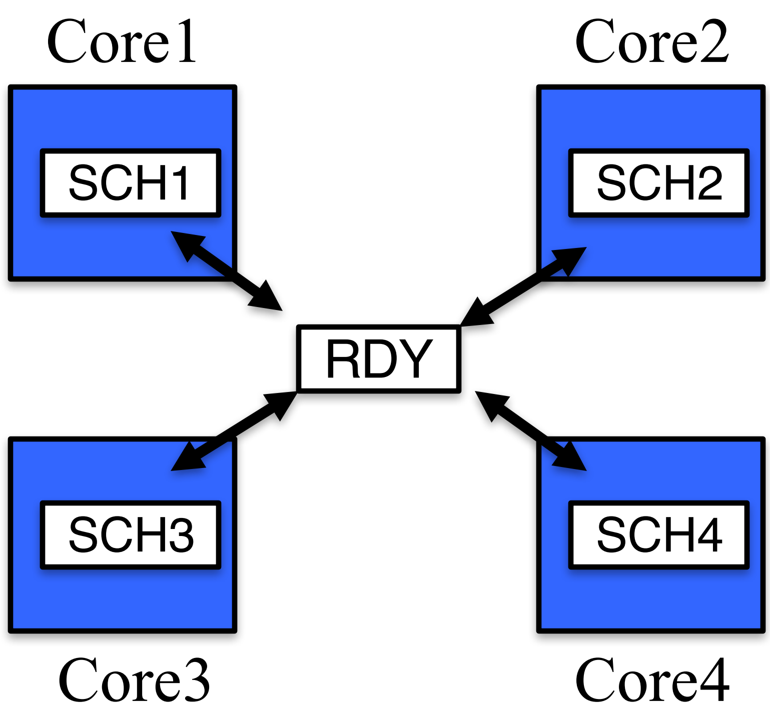


SCH = Scheduler, RDY = Ready Queue

- Variety of multi-core schedulers being tried. We'll just mention some design themes.
- In *asymmetric multiprocessing* (left) – 1 CPU handles all scheduling, decides which processes run on which cores

Multi-core Scheduling

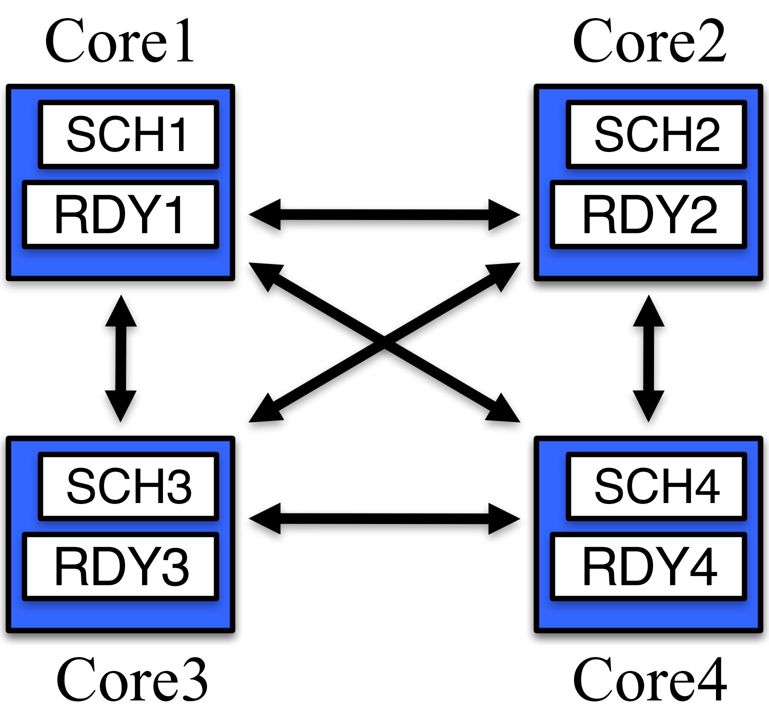
- In symmetric multi-processing (SMP), each core is self-scheduling. All modern OSs support some form of SMP. Two types:
  1. All cores share a single global ready queue.



- Here, each core has its own scheduler. When idle, each scheduler requests another process from the shared ready queue. Puts it back when time slice done.
  - Synchronization needed to write/read shared ready queue

Multi-core Scheduling

2. Another self-scheduling SMP approach is when each core has its own ready queue
   - Most modern OSs support this paradigm



- a typical OS scheduler plus a ready queue designed for a single CPU can run on each core…
- Except that processes now can migrate to other cores/processors
  - There has to be some additional coordination of migration

Multi-core Scheduling

- Caching is important to consider
  - Each CPU has its own cache to improve performance
  - If a process migrates too much between CPUs, then have to rebuild L1 and L2 caches each time a process starts on a new core/processor
  - L3 caches that span multiple cores can help alleviate this, but there is a performance hit, because L3 is slower than L1 and L2.
  - In any case, L1 and L2 caches still have to be rebuilt.

Multi-core Scheduling

- To maximally exploit caching, processes tend to stick to a given core/processor = processor affinity
  - In hard affinity, a process specifies via a system call that it insists on staying on a given CPU core
  - In soft affinity, there is still a bias to stick to a CPU core, but processes can on occasion migrate.
  - Linux supports both

Multi-core Scheduling

- Load balancing
  - Goal: Keep workload evenly distributed across cores
  - Otherwise, some cores will be under-utilized.
  - When there is a single shared ready queue, there is automatic load balancing
    - cores just pull in processes from the ready queue whenever they're idle.

Multi-core Scheduling

- Load balancing when there are separate ready Q's,
  - push migration – a dedicated task periodically checks the load on each core, and if imbalance, pushes processes from more-loaded to less-loaded cores
  - Pull migration – whenever a core is idle, it tries to pull a process from a neighboring core
  - Linux and FreeBSD use a combination of pull and push

Multi-core Scheduling

- Load balancing can conflict with caching
  - Push/pull migration causes caches to be rebuilt
- Load balancing can conflict with power management
  - Mobile devices typically want to save power
  - One approach is to power down unused cores
  - Load balancing would keep as many cores active as possible, thereby consuming power
- In systems, often conflicting design goals

Linux Scheduler History

1. O(N) Scheduler
2. O(1) Scheduler
3. CFS Scheduler for non real-time processes, various queues for real-time processes

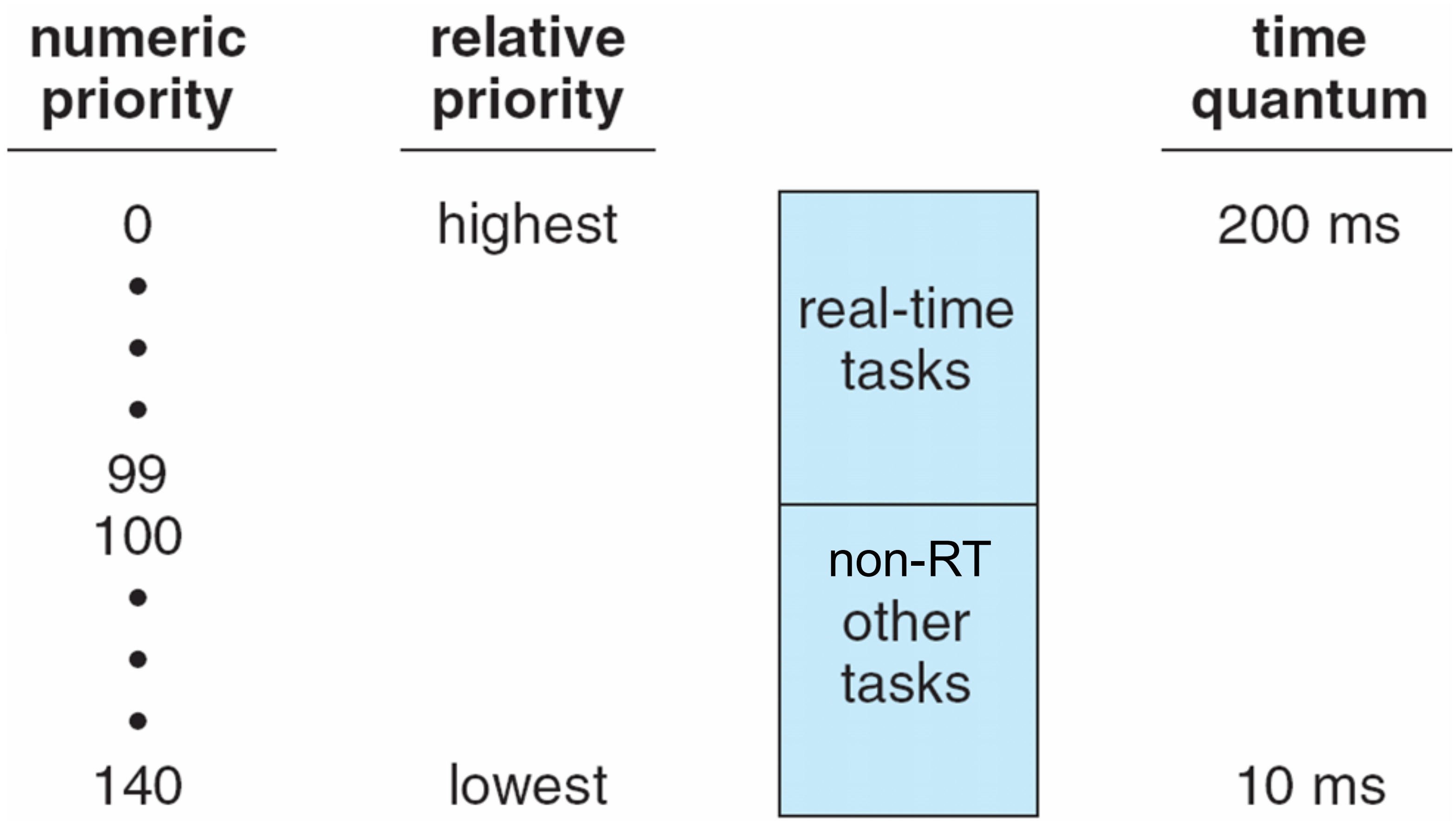
Linux Scheduler History

- 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

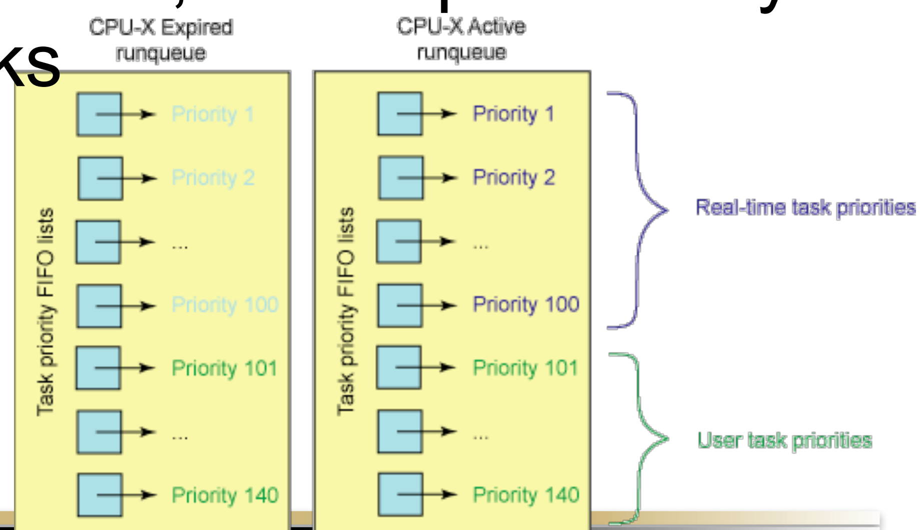
- Linux 2.6-2.6.23 uses an O(1) scheduler
  - Iterate over fixed # of 140 priorities to find the highest priority task
  - The amount of search time is bounded by the # priorities, not the # of tasks.
  - Hence O(1) is often called "constant time"
  - scales well because larger # tasks doesn't affect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

Linux Priorities and Time-slice length



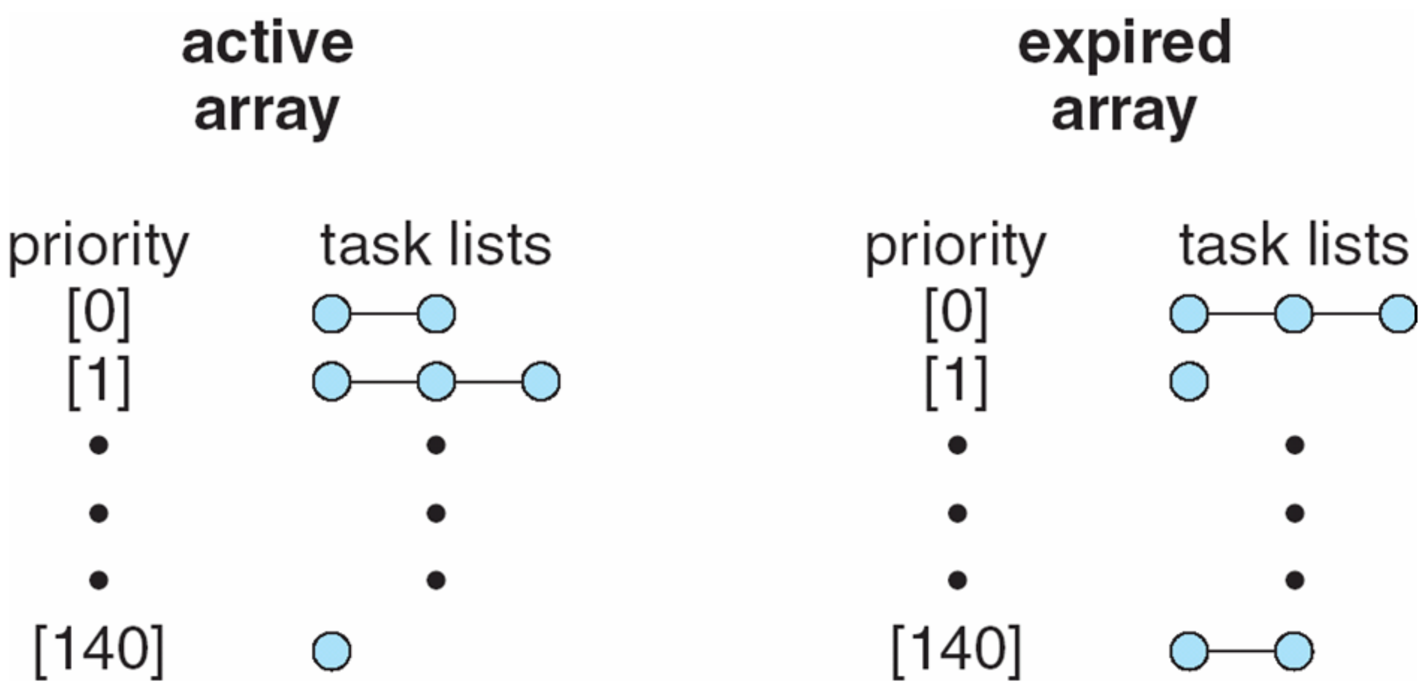
O(1) Scheduler in Linux

- 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



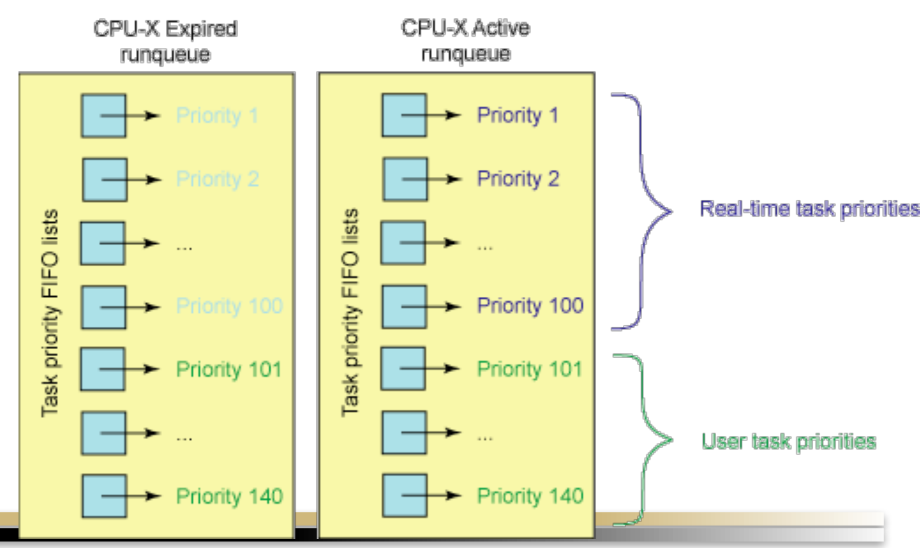
From http://www.ibm.com/developerworks/linux/library/l-scheduler/

O(1) Scheduler in Linux



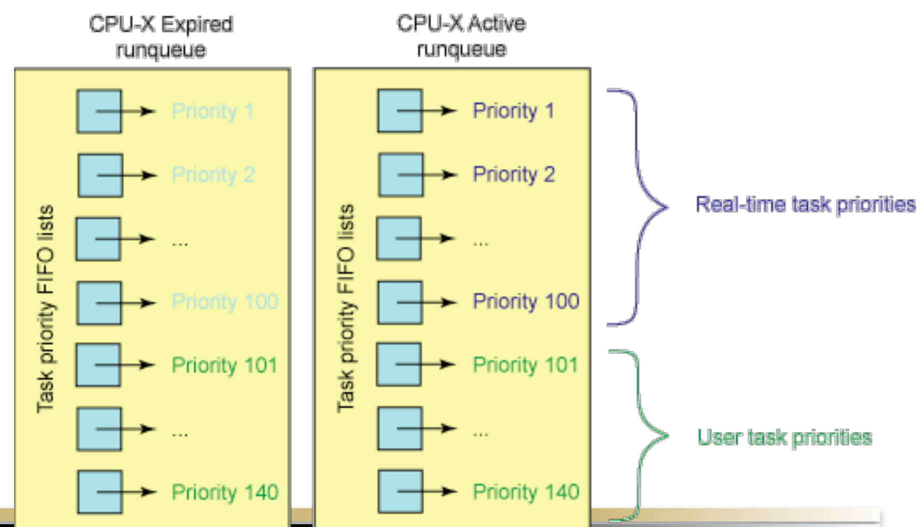
O(1) Scheduler in Linux

- 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

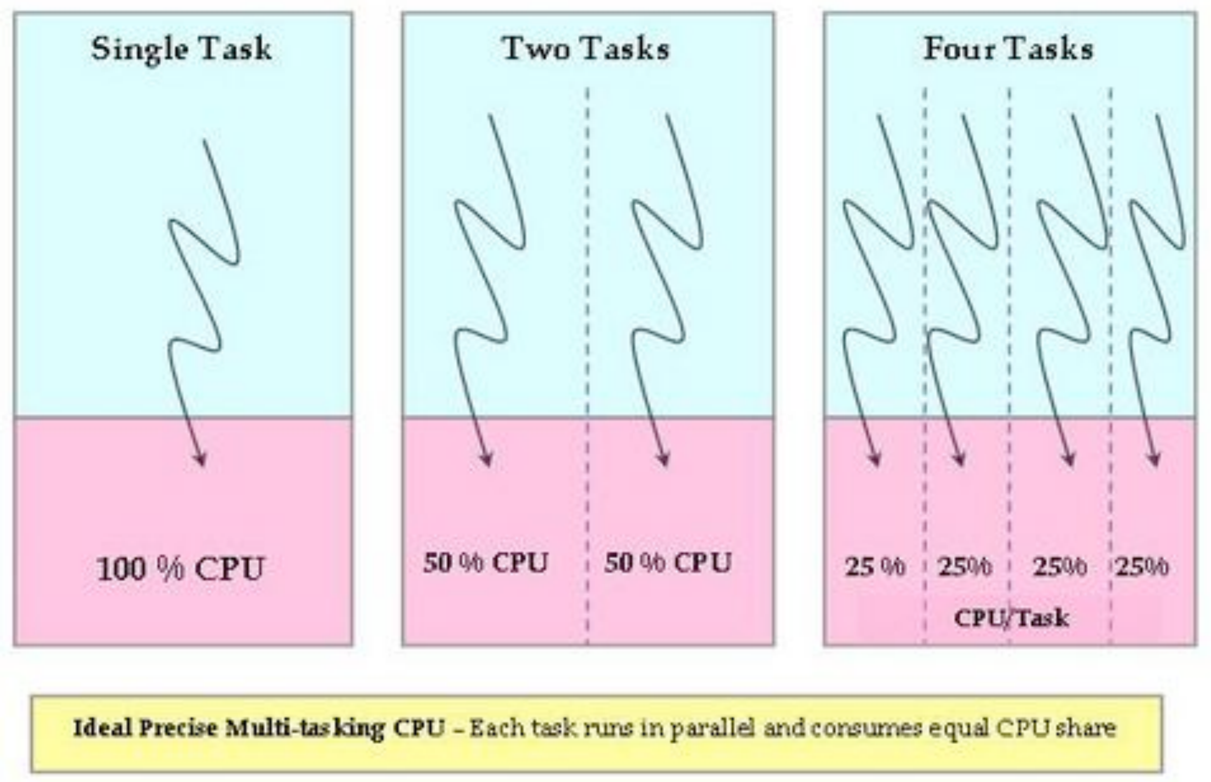


O(1) Scheduler in Linux

- 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

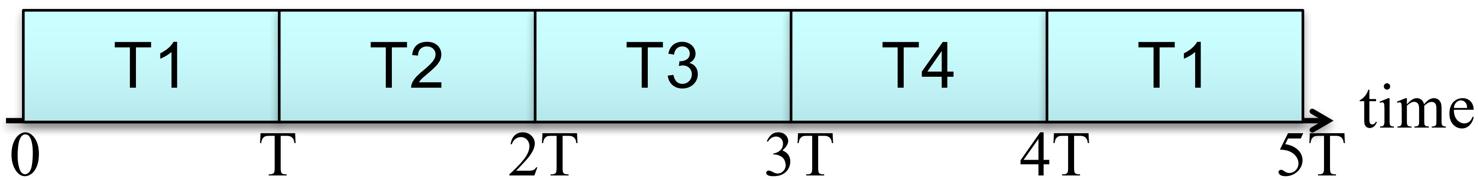
CFS Intuition

- 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:	<u>T1</u>	<u>T2</u>	<u>T3</u>	<u>T4</u>
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 $W_i(k) = T(k)/N(k) - R_i(k)$

CFS Scheduler and Priorities

- All non-RT tasks of differing priorities are combined into one RB tree
  - Don't need 40 separate run queues, one for each priority - elegant!

1. Higher priority tasks get larger run time slices
   - Each task has a weight that is a function of the task's niceness priority
   - The *run time allocated to a task = (a default target latency of 20 ms for desktop systems) * (task's weight) / (sum of weights of all runnable tasks)*
   - Lower niceness => higher the priority => more run time is given on the CPU

CFS Scheduler and Priorities

- The weight is roughly equivalent to 1024 / (1.25 ^ nice_value).
  - So the relative ratio between different niceness priorities is geometric
- Recall niceness ranges from -20 to +19
  - -20 corresponds to Linux priority 100
  - +19 corresponds to Linux priority 139
- Example: tasks 1 & 2 have niceness 0 & 5
  - Ratio of weights of task 1/task 2 = 1024/335 = 3X
  - Every 20 ms, Task 1 gets run time = 20 ms*1024/(1024+335) = 15 ms
  - Every 20 ms, Task 2 gets run time = 5 ms

Wait Time Calculation

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

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

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

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

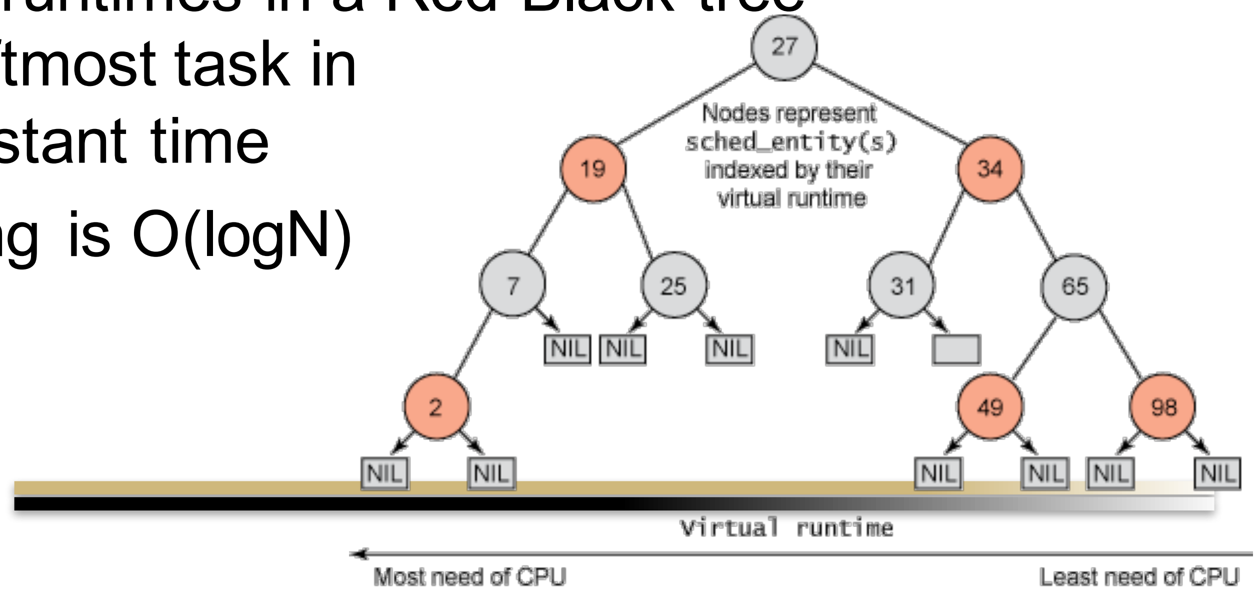
Total run time given task i. Let's define it as $Rtotal_i(k)$

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

- Selects the task with the maximum wait time
- This is equivalent to selecting the task with the minimum virtual run time
  - See derivation from last lecture
  - To quickly find the task with the minimum vruntime, order the vruntimes in a Red-Black tree
  - Choose leftmost task in tree in constant time
  - Rebalancing is O(logN)



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 (least run time)
  - 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

Real Time Scheduling in Linux

- Linux also includes three real-time scheduling classes:
  - Real time FIFO – soft real time (SCHED_FIFO)
  - Real time Round Robin – soft real time (SCHED_RR)
  - Real time Earliest Deadline First – hard real time as of Linux 3.14 (SCHED_DEADLINE)
- Only processes with the priorities 0-99 have access to these RT schedulers

Real Time Scheduling in Linux

- "When a Real time FIFO task starts running, it continues to run until it voluntarily yields the processor, blocks or is preempted by a higher-priority real-time task.
  - It has no timeslices.
  - All other tasks of lower priority will not be scheduled until it relinquishes the CPU.
  - Two equal-priority Real time FIFO tasks do not preempt each other."

Real Time Scheduling in Linux

- "SCHED_RR is similar to SCHED_FIFO, except that such tasks are allotted timeslices based on their priority and run until they exhaust their timeslice"
- Non-real time tasks continue to use CFS algorithm