CS162
Operating Systems and Systems Programming
Lecture 11

Scheduling 2:
Case Studies, Real Time, and Forward Progress

History of Schedulers in Linux

- O(n) scheduler
  - Linux 2.4 to Linux 2.6
- O(1) scheduler
  - Linux 2.6 to 2.6.22
- CFS scheduler
  - Linux 2.6.23 onwards

Case Study: Linux O(n) Scheduler

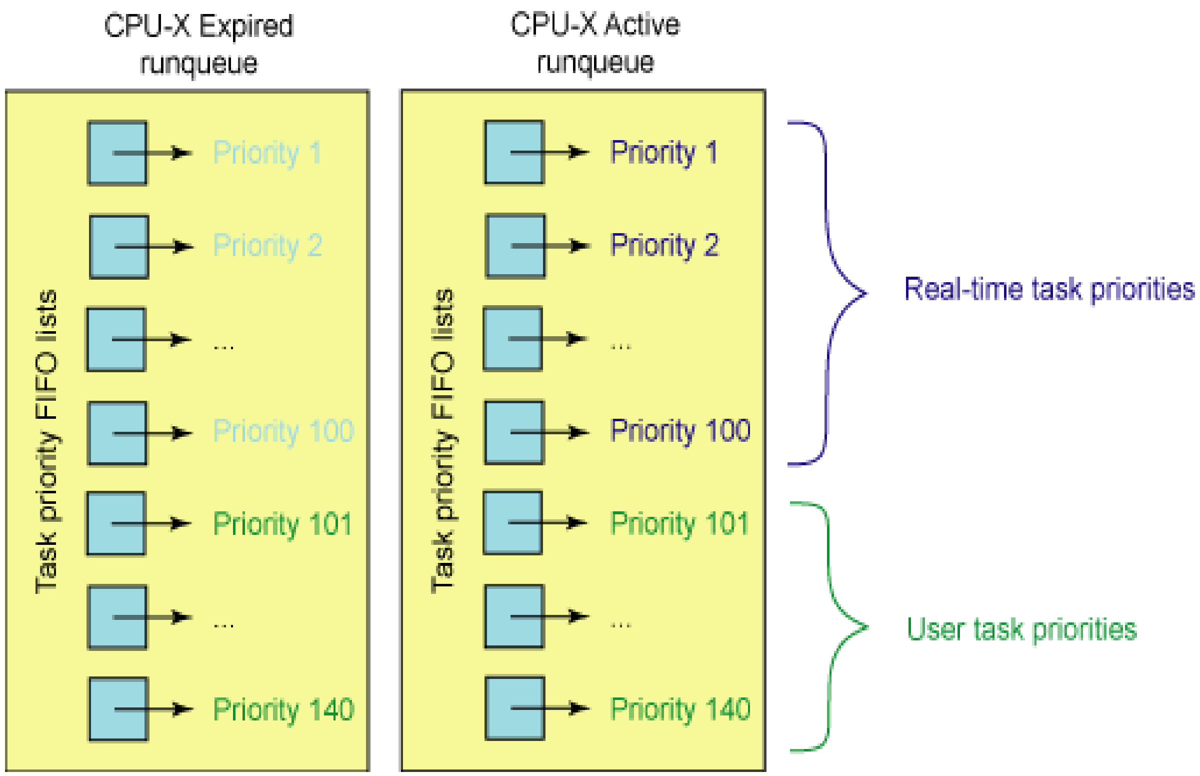
- At every context switch:
  – Scan full list of processes in the ready queue
  – Compute relevant priorities
  – Select the best process to run

- Scalability issues:
  – Context switch cost increases as number of processes increase
  – Single queue even in multicore systems

Case Study: Linux O(1) Scheduler

- Next process to run is chosen in **constant time**
- Priority-based scheduler with 140 different priorities
  – Real-time/kernel tasks assigned priorities 0 to 99 (0 is highest priority)
  – User tasks (interactive/batch) assigned priorities 100 to 139 (100 is highest priority)
    » Can be set using the nice system call.

Case Study: O(1) Scheduler – User tasks



- Per priority-level, each CPU has **two ready queues**
  - An active queue, for processes which have not used up their time quanta
  - An expired queue, for processes who have
- Timeslices/priorities/interactivity credits all computed when jobs finishes timeslice
- Timeslice depends on priority – linearly mapped onto timeslice range
  - Like a multi-level queue (one queue per priority) with different timeslice at each level
  - Execution split into "Timeslice Granularity" chunks – round robin through priority

O(1) Scheduler – User tasks – Priority Adjustment

- User-task priority adjusted ±5 based on heuristics
  - p->sleep_avg = sleep_time – run_time
  - Higher sleep_avg ⇒ more I/O bound the task, more reward (and vice versa)
- Interactive Credit
  - Earned when a task sleeps for a "long" time
  - Spend when a task runs for a "long" time
  - IC is used to provide hysteresis to avoid changing interactivity for temporary changes in behavior
- However, "interactive tasks" get special dispensation
  - To try to maintain interactivity
  - Placed back into active queue, unless some other task has been starved for too long…

Case Study: O(1) Scheduler – Real tasks

- Real-Time Tasks
  - Always preempt non-RT tasks
  - No dynamic adjustment of priorities
  - Scheduling schemes:
    - » SCHED_FIFO: preempts other tasks, no timeslice limit
    - » SCHED_RR: preempts normal tasks, RR scheduling amongst tasks of same priority

Real-Time Scheduling

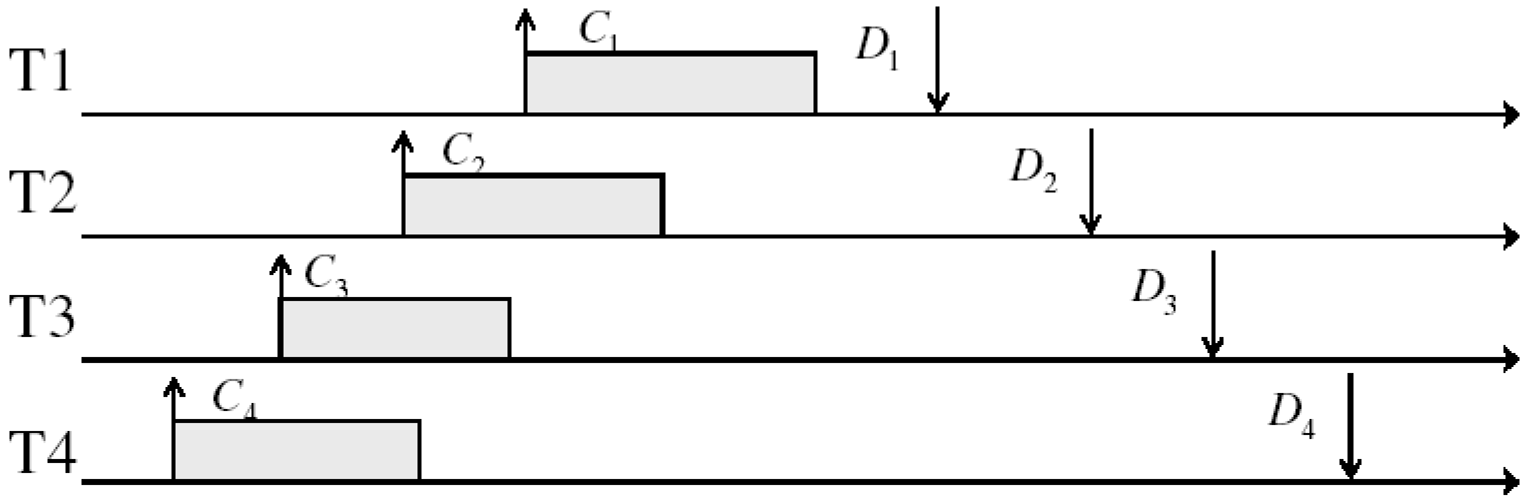
- Goal: Predictability of Performance!
  - We need to predict with confidence worst case response times for systems!
  - In RTS, performance guarantees are:
    - » Task- and/or class centric and often ensured a priori
  - In conventional systems, performance is:
    - » System/throughput oriented with post-processing (… wait and see …)
  - Real-time is about enforcing predictability, and does not equal fast computing!!!

Real-Time Scheduling

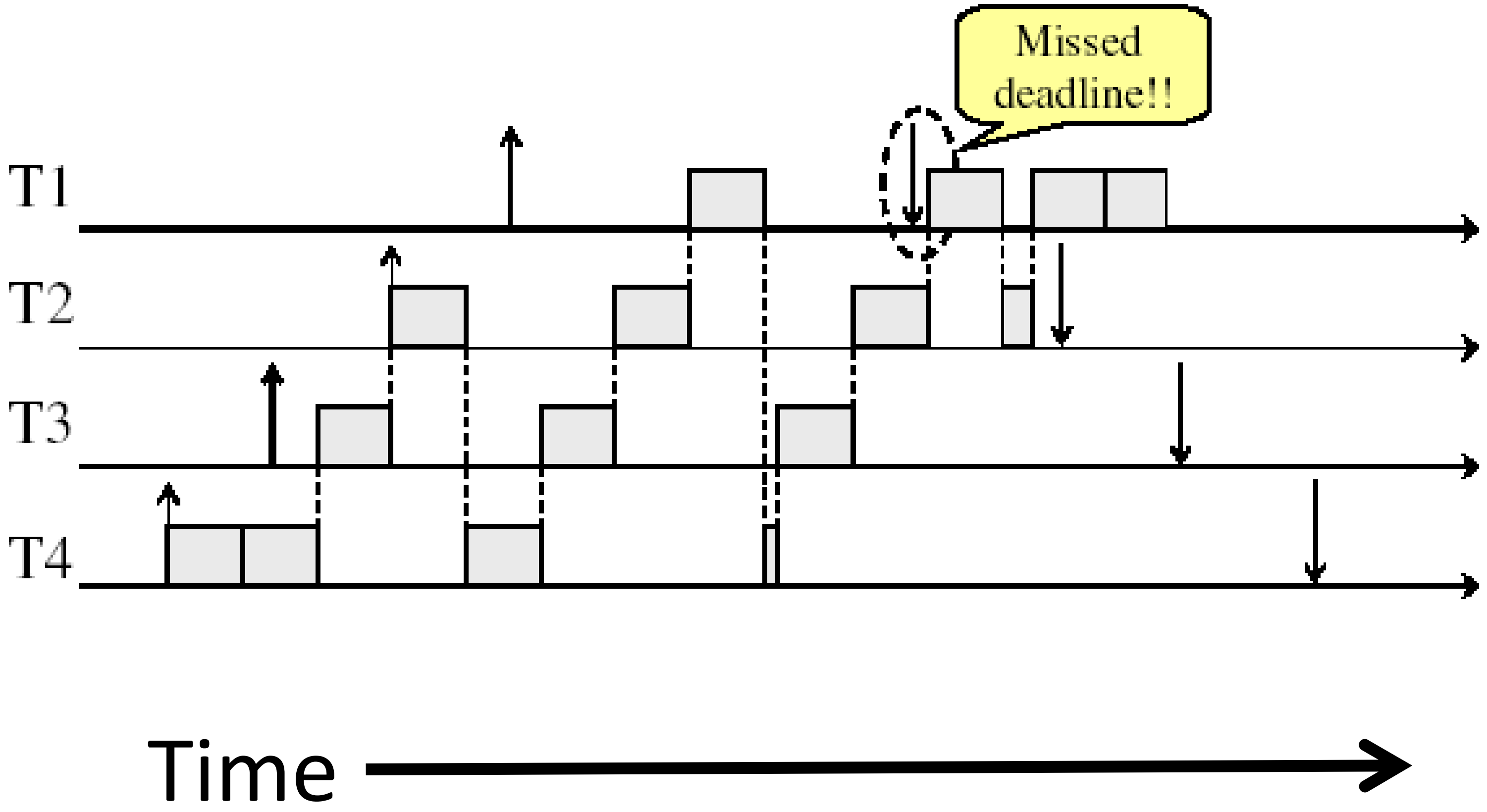
- Hard real-time: for time-critical safety-oriented systems
  - Meet all deadlines (if at all possible)
  - Ideally: determine in advance if this is possible
  - Earliest Deadline First (EDF), Least Laxity First (LLF), Rate-Monitonic Scheduling (RMS), Deadline Monotonic Scheduling (DM)
- Soft real-time: for multimedia
  - Attempt to meet deadlines with high probability
  - Constant Bandwidth Server (CBS)

Example: Workload Characteristics

- Tasks are preemptable, independent with arbitrary arrival (=release) times
- Tasks have deadlines (D) and known computation times (C)
- Example Setup:

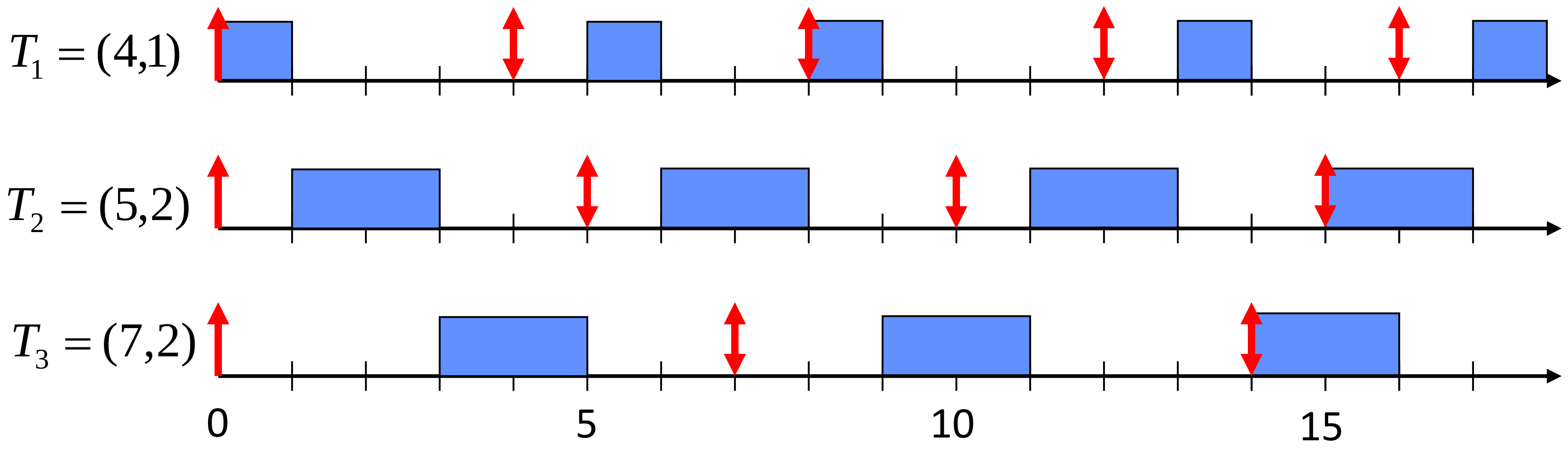


Example: Round-Robin Scheduling Doesn't Work



Earliest Deadline First (EDF)

- Tasks periodic with period P and computation C in each period: (P_i, C_i) for each task i
- Preemptive priority-based dynamic scheduling:
  - Each task is assigned a (current) priority based on how close the absolute deadline is (i.e. $D_i^{t+1} = D_i^t + P_i$ for each task!)
  - The scheduler always schedules the active task with the closest absolute deadline



EDF Feasibility Testing

- For n tasks with computation time C and deadline D, a feasible schedule exists if:

$$\sum_{i=1}^{n}\left(\frac{C_i}{D_i}\right) \leq 1$$

Case 1:

T1: (2,1) T2: (2,1)

½ + ½ = 1

Case 1:

T1: (2,2) T2: (2,1)

1 + ½ = 1.5

Ensuring Progress

- Starvation: thread fails to make progress for an indefinite period of time

- Starvation (this lecture) ≠ Deadlock (next lecture) because starvation *could* resolve under right circumstances
  - Deadlocks are unresolvable, cyclic requests for resources

- Causes of starvation:
  - Scheduling policy never runs a particular thread on the CPU
  - Threads wait for each other or are spinning in a way that will never be resolved

- Let's explore what sorts of problems we might encounter and how to avoid them…

Strawman: Non-Work-Conserving Scheduler

- A *work-conserving* scheduler is one that does not leave the CPU idle when there is work to do

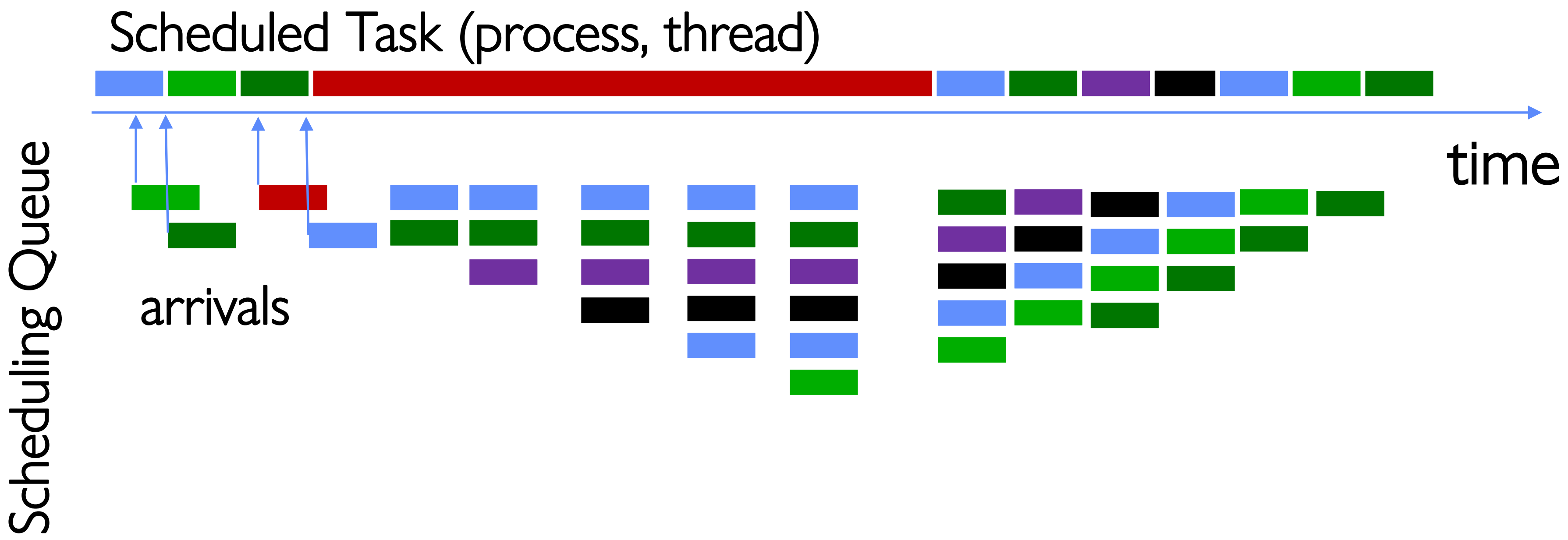
- A non-work-conserving scheduler could trivially lead to starvation

- In this class, we'll assume that the scheduler is work-conserving (unless stated otherwise)

Strawman: Last-Come, First-Served (LCFS)

- Stack (LIFO) as a scheduling data structure
  - Late arrivals get fast service
  - Early ones wait – extremely unfair
  - In the worst case – *starvation*
- When would this occur?
  - When arrival rate (offered load) exceeds service rate (delivered load)
  - Queue builds up faster than it drains
- Queue can build in FIFO too, but "serviced in the order received"…

Is FCFS Prone to Starvation?



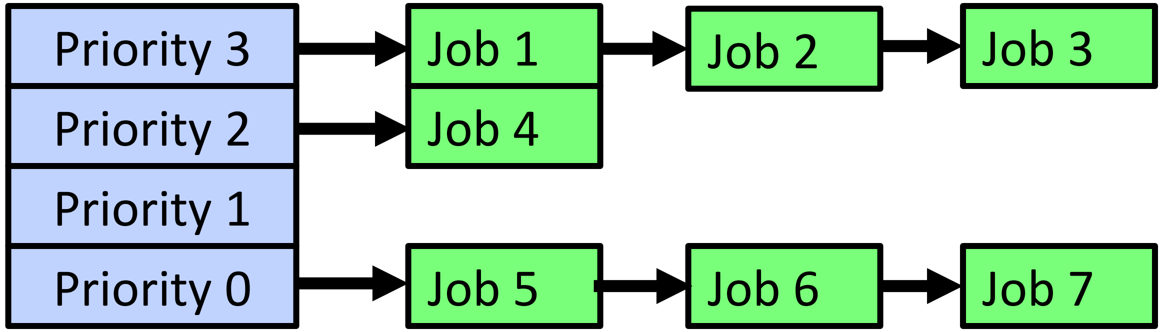
- If a task never yields (e.g., goes into an infinite loop), then other tasks don't get to run
- Problem with all non-preemptive schedulers…
  - And early personal OSes such as original MacOS, Windows 3.1, etc

Is Round Robin (RR) Prone to Starvation?

- Each of *N* processes gets ~1/*N* of CPU (in window)
  - With quantum length *Q* ms, process waits at most *(N-1)*Q* ms to run again
  - So a process can't be kept waiting indefinitely

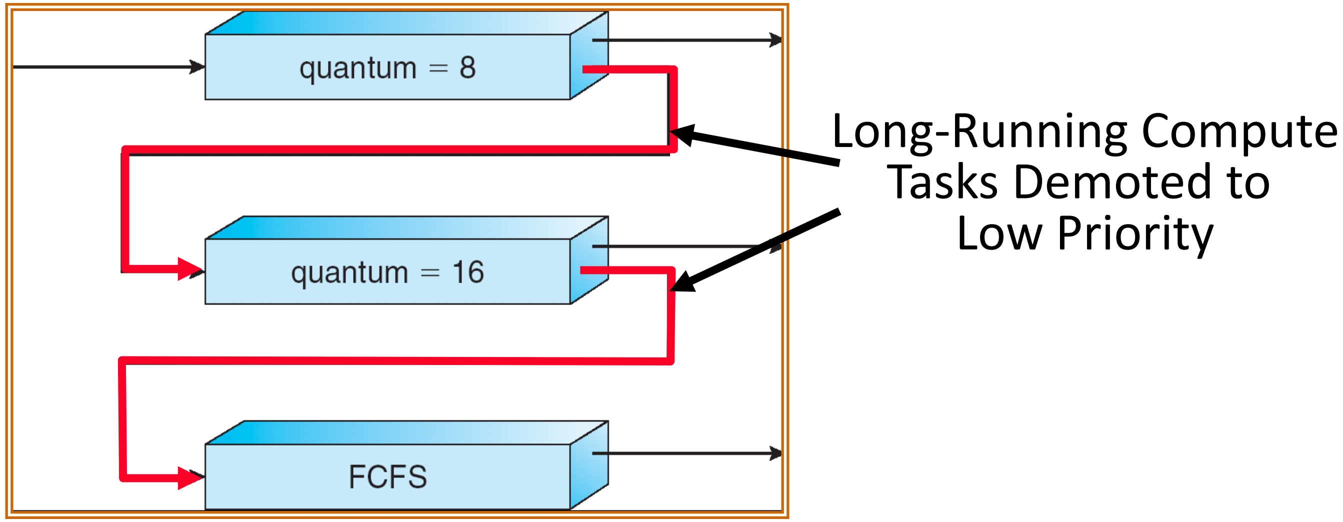
- So RR is fair in terms of *waiting time*
  - Not necessarily in terms of throughput…

Is Priority Scheduling Prone to Starvation?



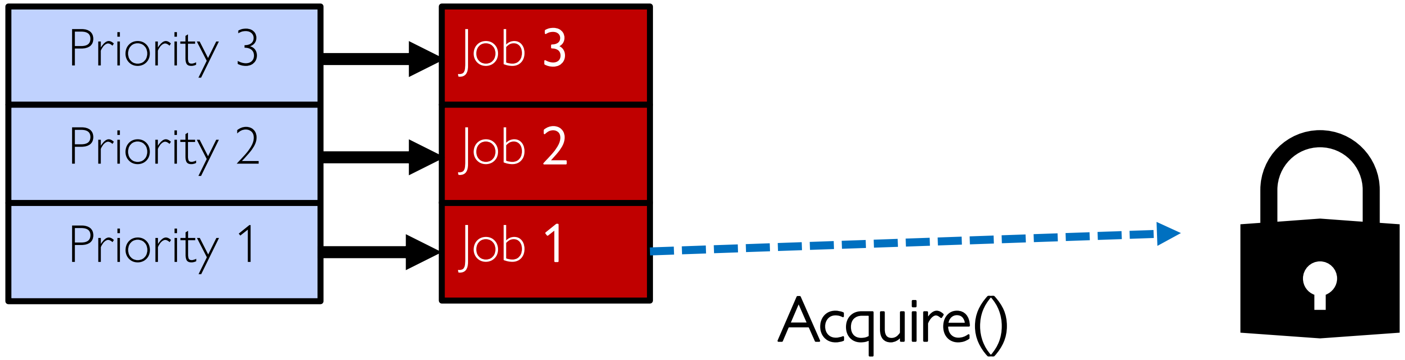
- Recall: Priority Scheduler always runs the thread with highest priority
  – Low priority thread might never run!
  – Starvation…
- But there are more serious problems as well…
  – Priority inversion: even high priority threads might become starved

Are SRTF and MLFQ Prone to Starvation?



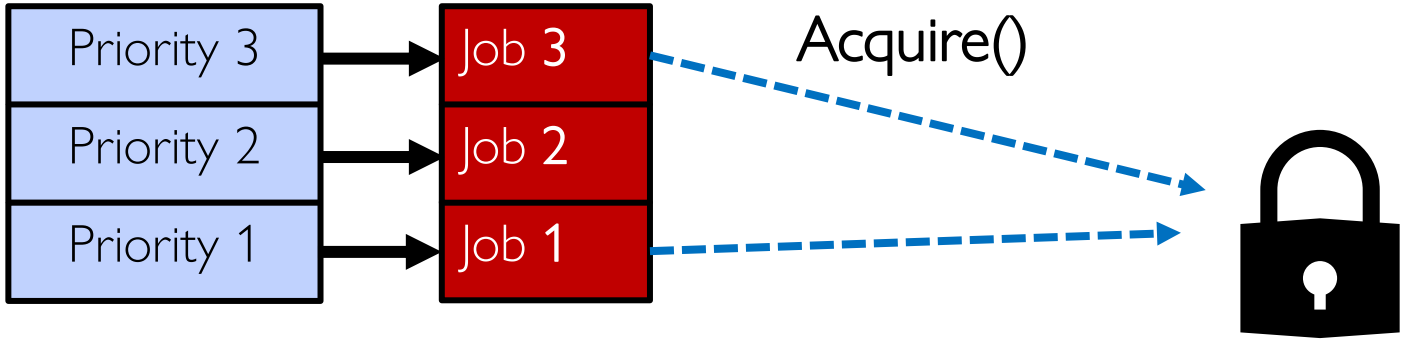
- In SRTF, long jobs are starved in favor of short ones
  – Same fundamental problem as priority scheduling
- MLFQ is an approximation of SRTF, so it suffers from the same problem

Priority Inversion



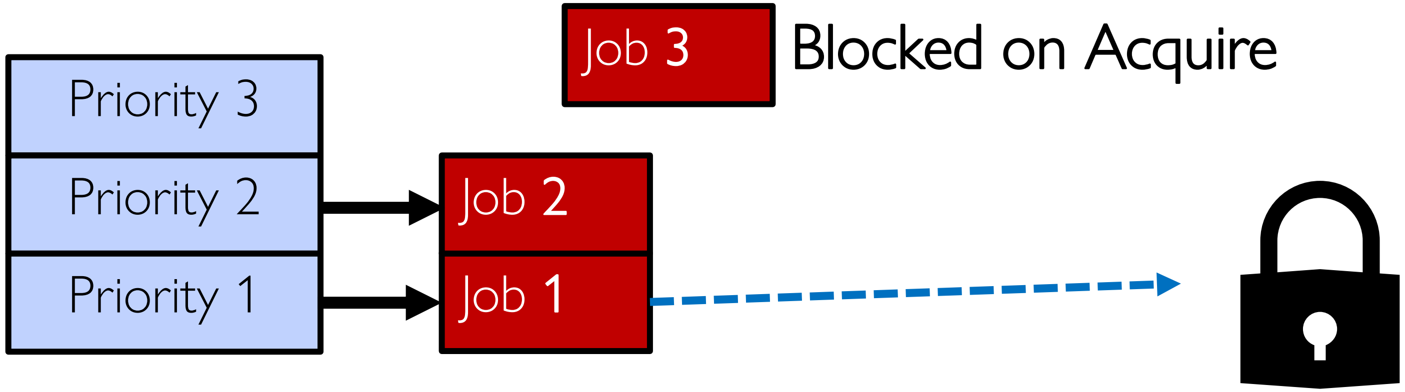
- **At this point, which job does the scheduler choose?**
- Job 3 (Highest priority)

Priority Inversion



- Job 3 attempts to acquire lock held by Job 1

Priority Inversion



- At this point, which job does the scheduler choose?
- Job 2 (Medium Priority)
- Priority Inversion

Priority Inversion

- Where high priority task is blocked waiting on low priority task
- Low priority one ***must*** run for high priority to make progress
- Medium priority task can starve a high priority one

- When else might priority lead to starvation or "live lock"?

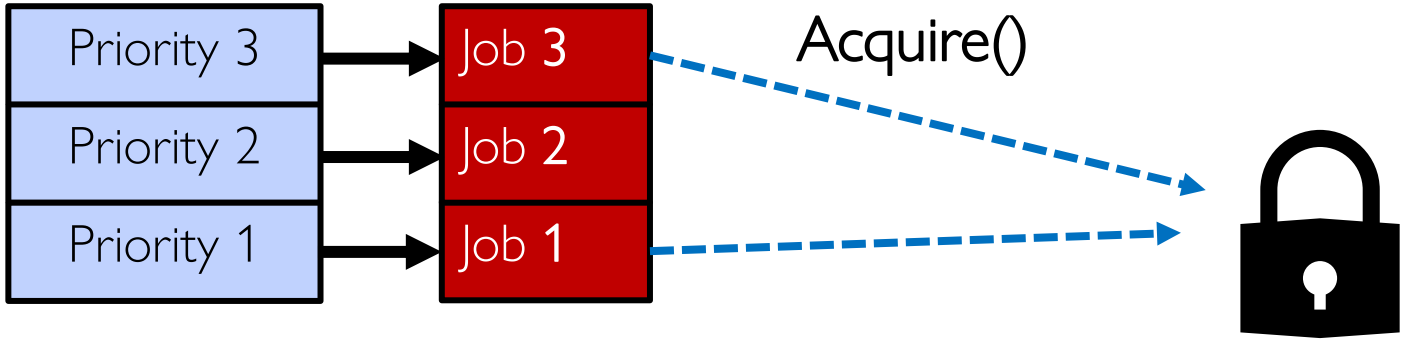
High Priority

```
while (try_lock) {
…
}
```

Low Priority

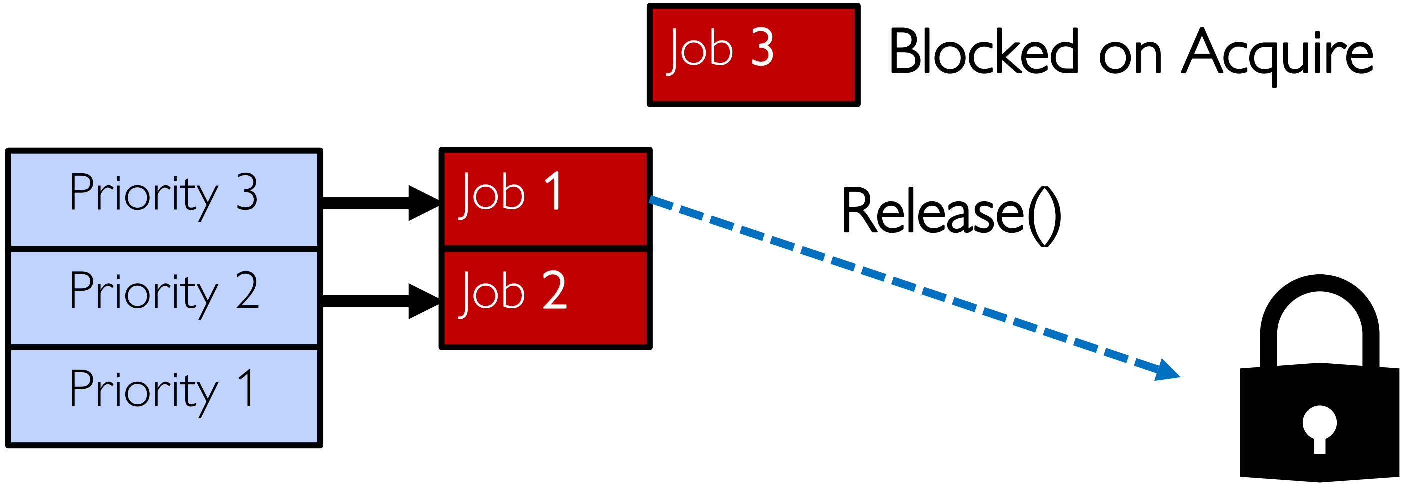
```
lock.acquire(…)
…
lock.release(…)
```

One Solution: Priority Donation/Inheritance



- Job 3 temporarily grants Job 1 its "high priority" to run on its behalf

One Solution: Priority Donation/Inheritance



- Job 3 temporarily grants Job 1 its “high priority” to run on its behalf

Case Study: Martian Pathfinder Rover

- July 4, 1997 – Pathfinder lands on Mars
  - First US Mars landing since Vikings in 1976; first rover
- And then…a few days into mission…:
  - Multiple system resets occur to realtime OS (VxWorks)
  - System would reboot randomly, losing valuable time and progress
- Problem? Priority Inversion!
  - Low priority task grabs mutex trying to communicate with high priority task:

Priority 2	Data Distribution Task: needs lock
Priority 1	Lots of random medium stuff
Priority 0	ASI/MET collector: grab lock

  - Realtime watchdog detected lack of forward progress and invoked reset to safe state
    - » High-priority data distribution task was supposed to complete with regular deadline
- Original developers turned off priority donation !

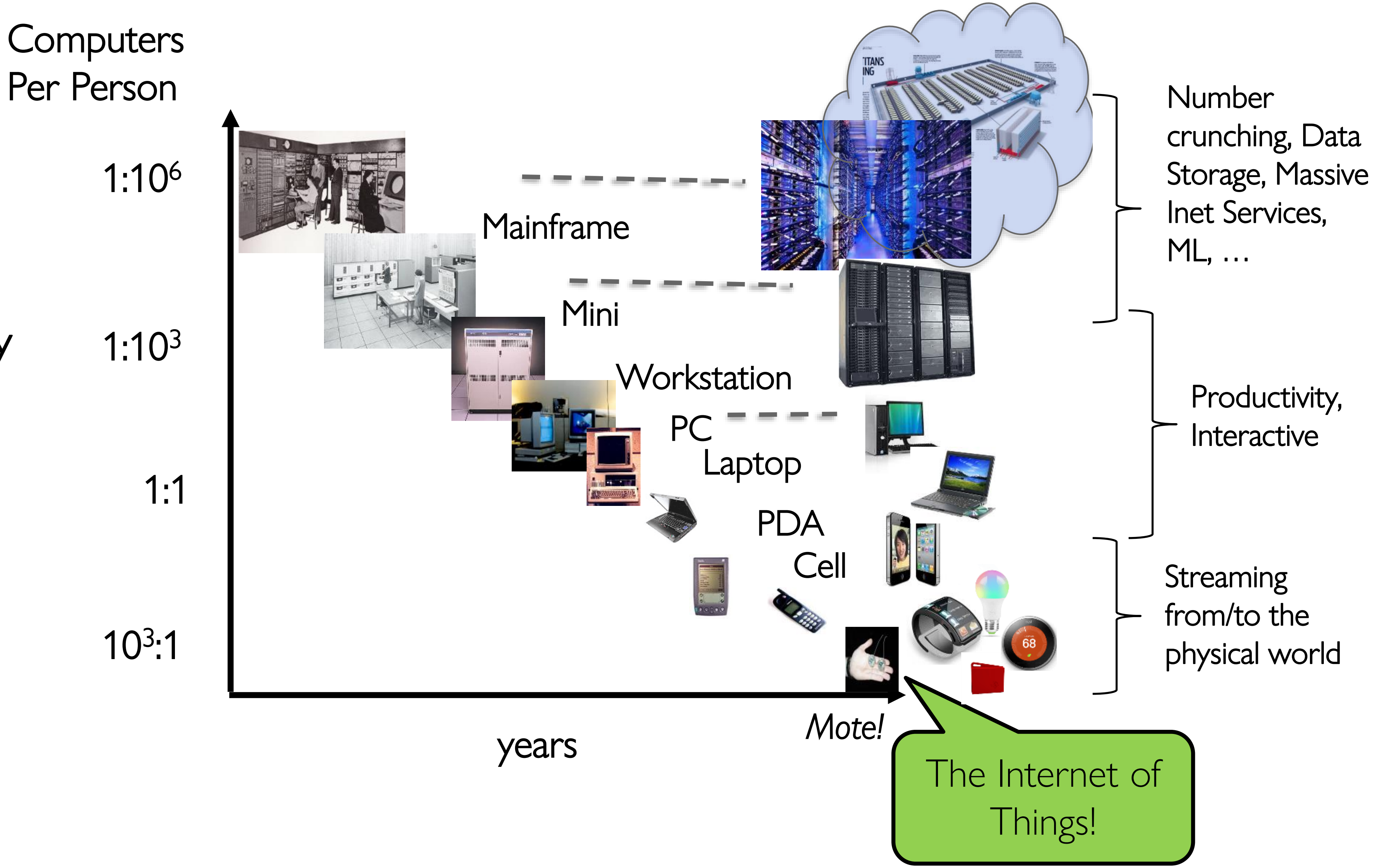
Cause for Starvation: Priorities?

- The policies we've studied so far:
  - Always prefer to give the CPU to a prioritized job
  - Non-prioritized jobs may never get to run

- But priorities were a means, not an end
- Our end goal was to serve a mix of CPU-bound, I/O bound, and Interactive jobs effectively on common hardware
  - Give the I/O bound ones enough CPU to issue their next file operation and wait (on those slow discs)
  - Give the interactive ones enough CPU to respond to an input and wait (on those slow humans)
  - Let the CPU bound ones grind away without too much disturbance

Recall: Changing Landscape…

Bell's Law: New computer class every 10 years



Changing Landscape of Scheduling

- Priority-based scheduling rooted in "time-sharing"
  - Allocating precious, limited resources across a diverse workload
    - » CPU bound, vs interactive, vs I/O bound
- 80's brought about personal computers, workstations, and servers on networks
  - Different machines of different types for different purposes
  - Shift to fairness and avoiding extremes (starvation)
- 90's emergence of the web, rise of internet-based services, the data-center-is-the-computer
  - Server consolidation, massive clustered services, huge flashcrowds
  - It's about predictability, 95th percentile performance guarantees

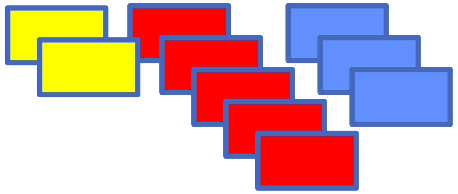
DOES PRIORITIZING SOME JOBS *NECESSARILY* STARVE THOSE THAT AREN'T PRIORITIZED?

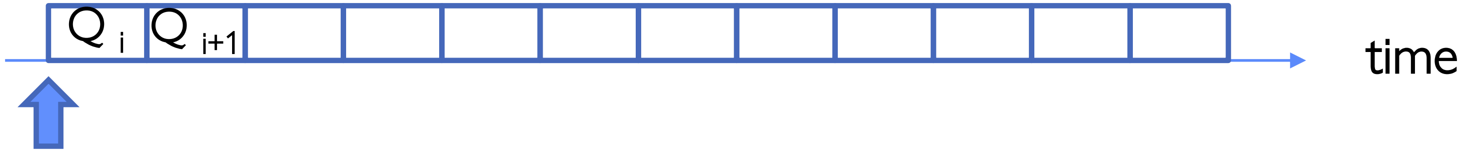
Key Idea: Proportional-Share Scheduling

- The policies we've studied so far:
  - Always prefer to give the CPU to a prioritized job
  - Non-prioritized jobs may never get to run

- Instead, we can share the CPU *proportionally*
  - Give each job a share of the CPU according to its priority
  - Low-priority jobs get to run less often
  - But all jobs can at least make progress (no starvation)

Recall: Lottery Scheduling





- Given a set of jobs (the mix), provide each with a share of a resource
  - e.g., 50% of the CPU for Job A, 30% for Job B, and 20% for Job C
- Idea: Give out tickets according to the proportion each should receive,
- Every quantum (tick): draw one at random, schedule that job (thread) to run

Unfairness

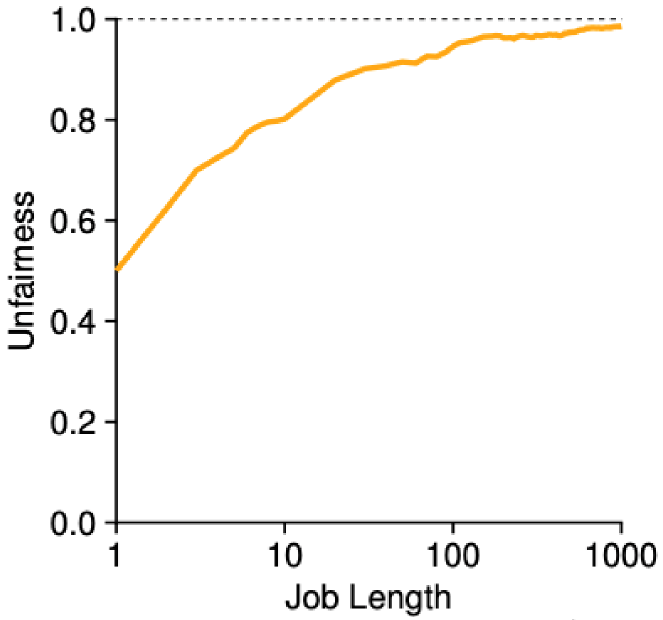


Figure 9.2: **Lottery Fairness Study**

- E.g., Given two jobs A and B of same run time (# Qs) that are each supposed to receive 50%,

  U = finish time of first / finish time of last

- As a function of run time

Stride Scheduling

- Deterministic proportional fair sharing

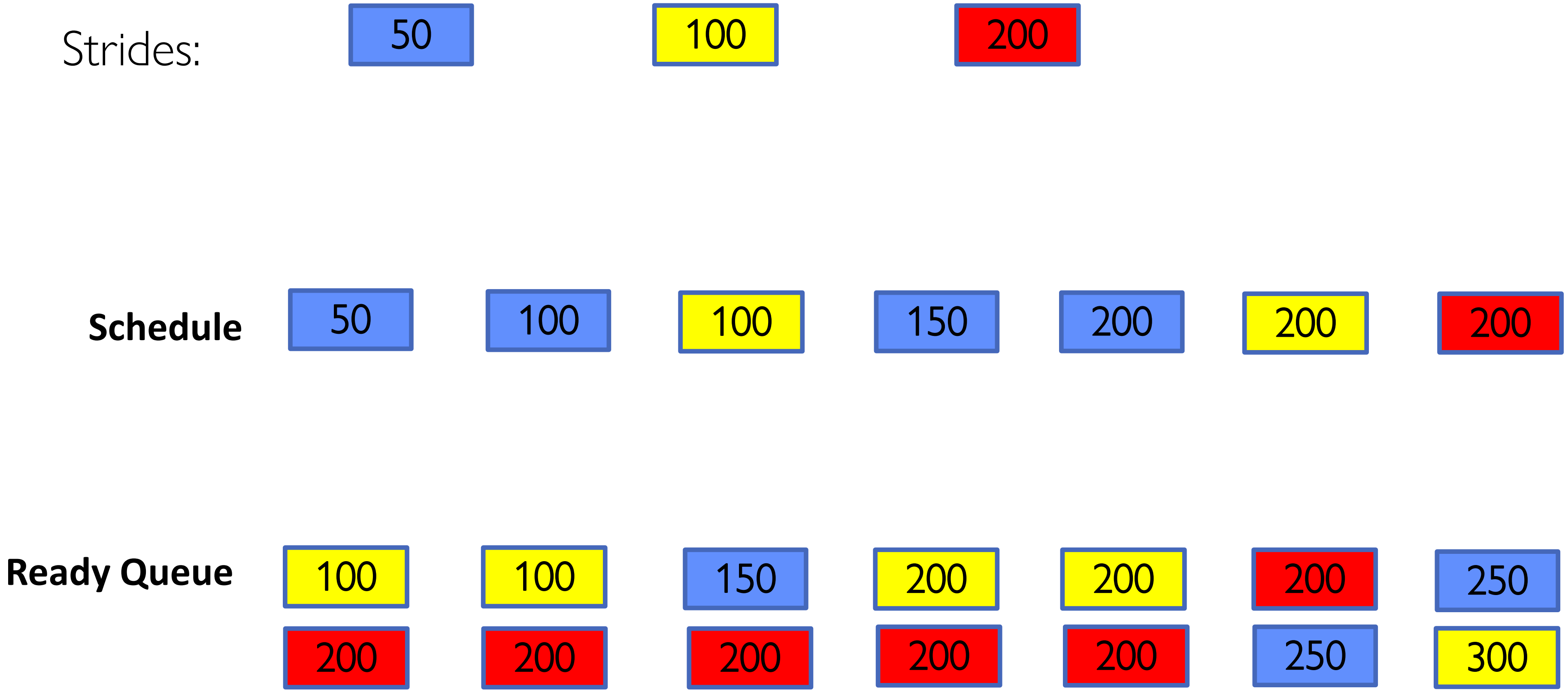
- "Stride" of each job is $\frac{big\#W}{N_i}$
  - The larger your share of tickets, the smaller your stride
  - Ex: W = 10,000, A=100 tickets, B=50, C=250
  - A stride: 100, B: 200, C: 40

- Each job as a "pass" counter . Scheduler: pick job with lowest *pass*, runs it, add its *stride* to its *pass*

- Low-stride jobs (lots of tickets) run more often
  - Job with twice the tickets gets to run twice as often

Stride Scheduling

W = 10,000, A=200 tickets, B=100 tickets, C=50 tickets

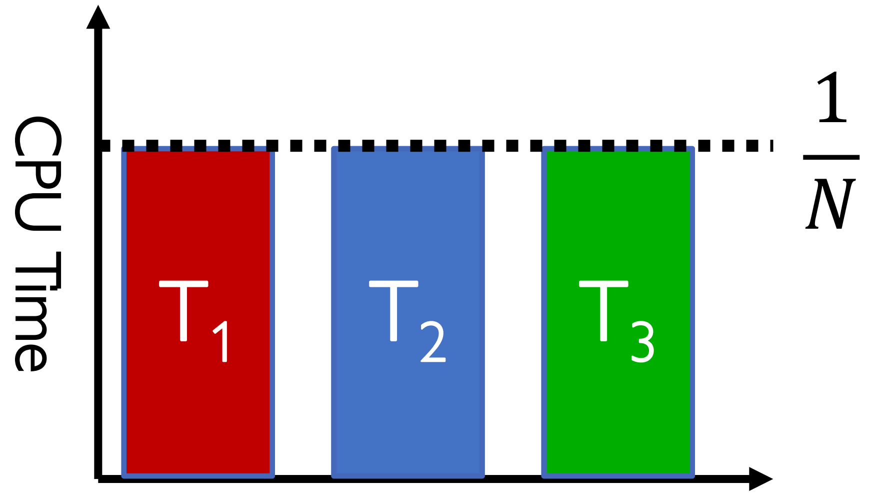


Linux Completely Fair Scheduler (CFS)

- Goal: Each process gets an equal share of CPU
  - *N* threads "simultaneously" execute on $\frac{1}{N}$ of CPU
  - The *model* is somewhat like simultaneous multithreading – each thread gets $\frac{1}{N}$ of the cycles

- In general, can't do this with real hardware
  - OS needs to give out full CPU in time slices
  - Thus, we must use something to keep the threads roughly in sync with one another

Model: "Perfectly" subdivided CPU:

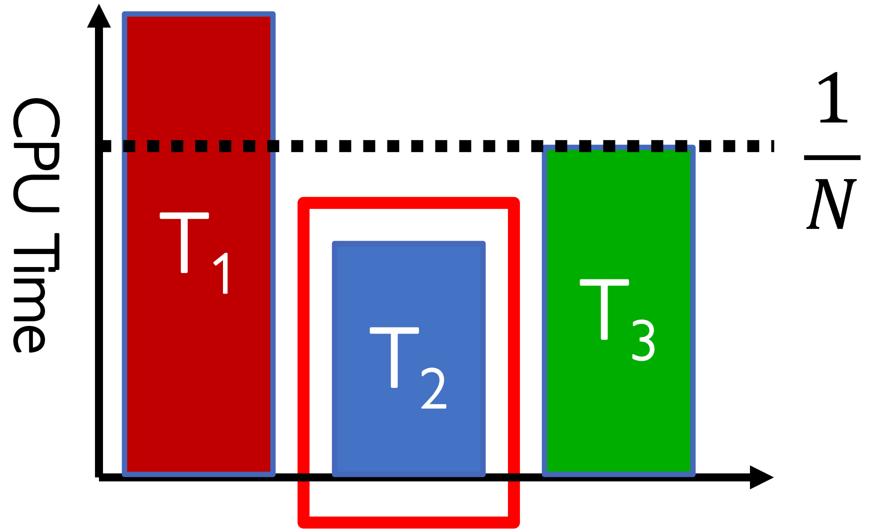


Linux Completely Fair Scheduler (CFS)

- Basic Idea: track CPU time per thread

- Scheduling Decision:
  - "Repair" illusion of complete fairness
  - Choose thread with minimum CPU time
  - Closely related to Fair Queueing

CFS: Average rate of execution = $\frac{1}{N}$:



- Use red-black tree for this…
  - O(log N) to add/remove threads, where N is number of threads

- Sleeping threads don't advance their CPU time, so they get a boost when they wake up again…
  - Get interactivity automatically!

Linux CFS: Responsiveness/Starvation Freedom

- In addition to fairness, we want **low response time** and starvation freedom
  – Make sure that everyone gets to run at least a bit!

- Constraint 1: *Target Latency*
  – Period of time over which every process gets service
  – Quanta = Target_Latency / n

- Target Latency: 20 ms, 4 Processes
  – Each process gets 5ms time slice

- Target Latency: 20 ms, 200 Processes
  – Each process gets 0.1ms time slice (!!!)
  – Recall Round-Robin: large context switching overhead if slice gets to small

Linux CFS: Throughput

- Goal: Throughput
  - Avoid excessive overhead
- Constraint 2: Minimum Granularity
  - Minimum length of any time slice

- Target Latency 20 ms, Minimum Granularity 1 ms, 200 processes
  - Each process gets 1 ms time slice

Aside: Priority in Unix – Being Nice

- The industrial operating systems of the 60s and 70's provided priority to enforced desired usage policies.
  - When it was being developed at Berkeley, instead it provided ways to "be nice".
- `nice` values range from -20 to 19
  - Negative values are "not nice"
  - If you wanted to let your friends get more time, you would nice up your job
- Scheduler puts higher nice-value tasks (lower priority) to sleep more …
  - In O(1) scheduler, this translated fairly directly to priority (and time slice)
- How does this idea translate to CFS?
  - Change the rate of CPU cycles given to threads to change relative priority

Linux CFS: Proportional Shares

- How to we achieve proportional fair sharing?
  - Allow different threads to have different *rates* of execution (cycles/time)

- Use weights! Key Idea: Assign a weight w_i to each process *I* to compute the switching quanta Q_i
  - Basic equal share: $Q_i = \textbf{Target Latency} \cdot \frac{1}{N}$
  - Weighted Share: $Q_i = \left({}^{w_i}/_{\sum_p w_p}\right) \cdot \textbf{Target Latency}$

- Reuse **`nice`** value to reflect share, rather than priority,
  - Remember that lower nice value ⇒ higher priority
  - CFS uses nice values to scale weights exponentially: Weight=1024/(1.25)$^{\text{nice}}$

- So, we use "Virtual Runtime" instead of CPU time

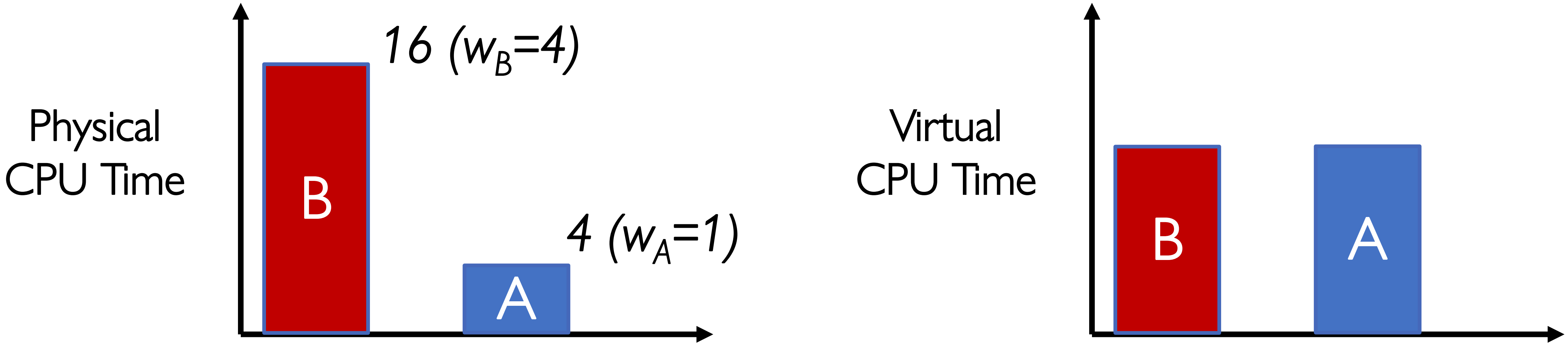
Example: Linux CFS: Proportional Shares

- Target Latency = 20ms
- Minimum Granularity = 1ms

- Example: Two CPU-Bound Threads
  - Thread A has weight 1
  - Thread B has weight 4

- Time slice for A? 4 ms
- Time slice for B? 16 ms

Linux CFS: Proportional Shares



- Track a thread's *virtual* runtime rather than its true physical runtime
  – Higher weight: Virtual runtime increases more slowly
  – Lower weight: Virtual runtime increases more quickly

Linux CFS: Proportional Shares

- Scheduler's Decisions are based on Virtual CPU Time

- Use of Red-Black tree to hold all runnable processes as sorted on vruntime variable
  - O(1) time to find next thread to run (top of heap!)
  - O(log N) time to perform insertions/deletions
    - » Cash the item at far left (item with earliest vruntime)
  - When ready to schedule, grab version with smallest vruntime (which will be item at the far left).

Choosing the Right Scheduler

I Care About:	Then Choose:
CPU Throughput	FCFS
Avg. Response Time	SRTF Approximation
I/O Throughput	SRTF Approximation
Fairness (CPU Time)	Linux CFS
Fairness – Wait Time to Get CPU	Round Robin
Meeting Deadlines	EDF
Favoring Important Tasks	Priority

Summary (1 of 2)

- Scheduling Goals:
  - Minimize Response Time (e.g. for human interaction)
  - Maximize Throughput (e.g. for large computations)
  - Fairness (e.g. Proper Sharing of Resources)
  - Predictability (e.g. Hard/Soft Realtime)
- 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
- 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
- Multi-Level Feedback Scheduling:
  - Multiple queues of different priorities and scheduling algorithms
  - Automatic promotion/demotion of process priority in order to approximate SJF/SRTF

Summary (2 of 2)

- Realtime Schedulers such as EDF
  - Guaranteed behavior by meeting deadlines
  - Realtime tasks defined by tuple of compute time and period
  - Schedulability test: is it possible to meet deadlines with proposed set of processes?
- Lottery Scheduling:
  - Give each thread a priority-dependent number of tokens (short tasks⇒more tokens)
- Stride Scheduling
  - Always fair, unlike lotter scheduling:
- Linux O(1) scheduler
  - Scales as number of processes grows
  - Became overly complex because of heuristics
- Linux CFS Scheduler: Fair fraction of CPU
  - Approximates an "ideal" multitasking processor
  - Practical example of "Fair Queueing"