# CS162
# Operating Systems and Systems Programming
# Lecture 12

## Scheduling 2: Classic Policies (Con't), Case Studies, Realtime, Starvation

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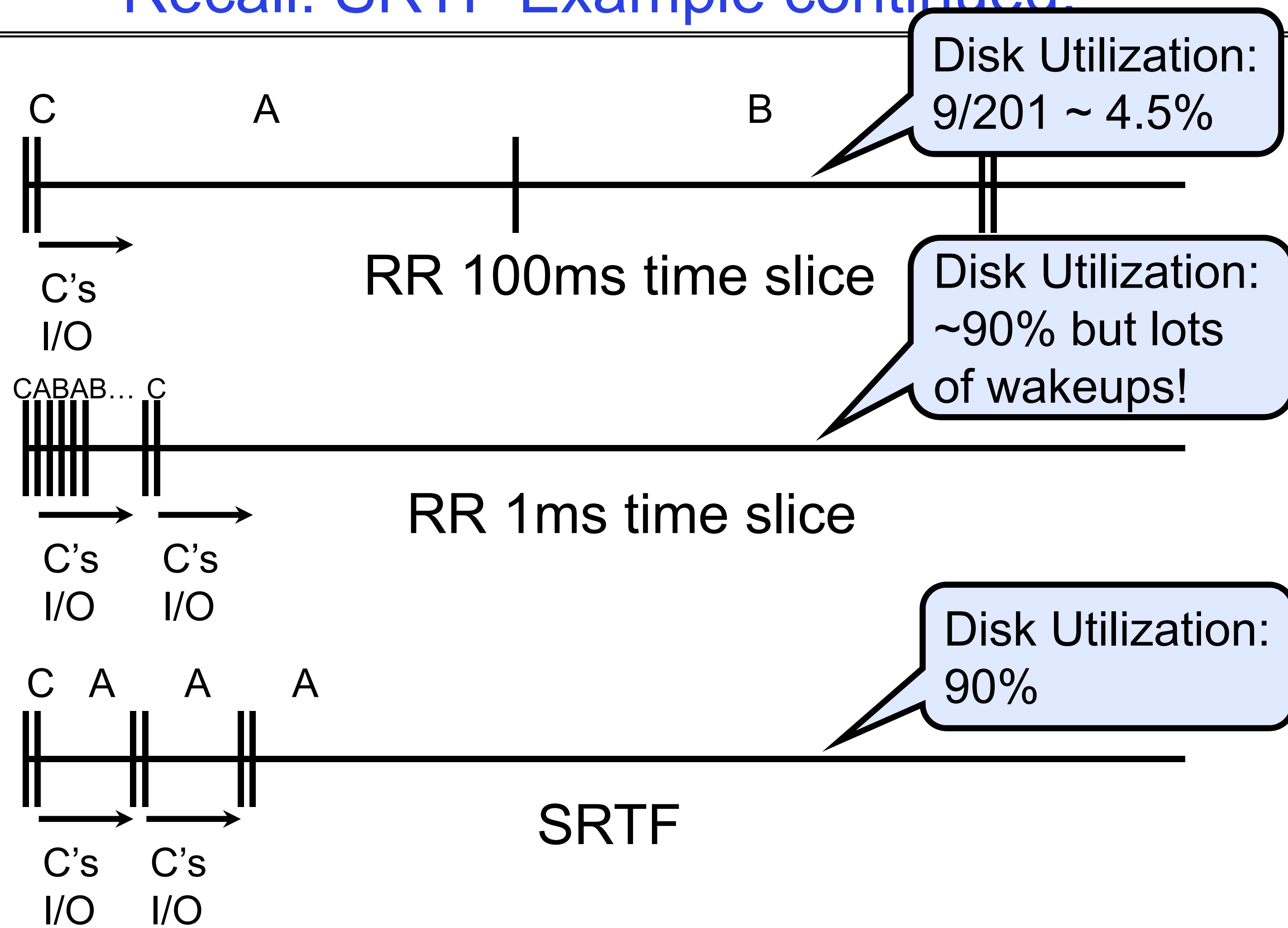
# Recall: SRTF Example continued:



# SRTF Further discussion

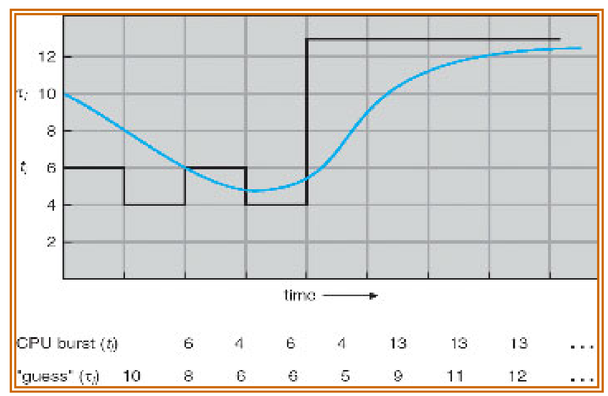
- Starvation
  – SRTF can lead to starvation if many small jobs!
  – Large jobs never get to run
- Somehow need to predict future
  – How can we do this?
  – Some systems ask the user
    » When you submit a job, have to say how long it will take
    » To stop cheating, system kills job if takes too long
  – But: hard to predict job's runtime even for non-malicious users
- 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

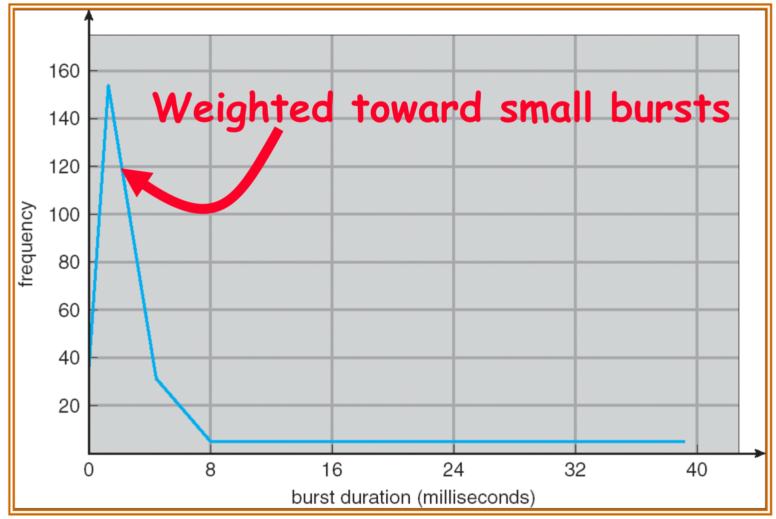
    $\tau_n = \alpha t_{n-1} + (1-\alpha)\tau_{n-1}$

    with $(0<\alpha\leq1)$

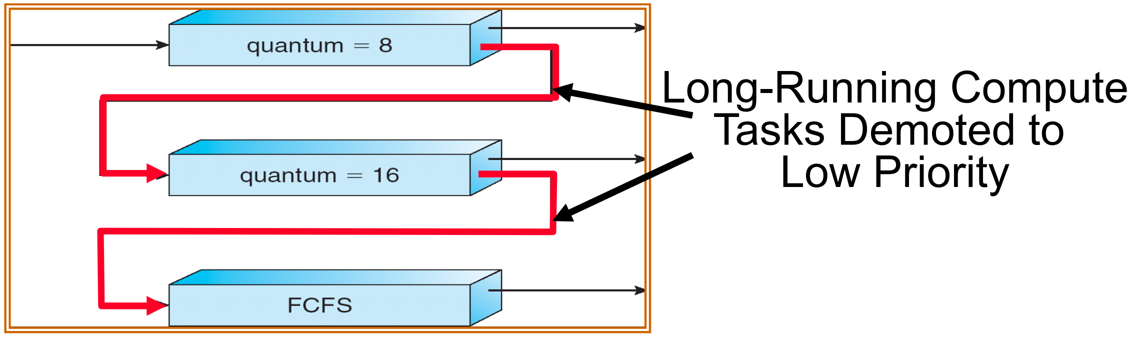


# How to Handle Simultaneous Mix of Diff Types of Apps?

- Consider mix of interactive and high throughput apps:
  – How to best schedule them?
  – How to recognize one from the other?
    » Do you trust app to say that it is "interactive"?
  – Should you schedule the set of apps identically on servers, workstations, pads, and cellphones?
- For instance, is Burst Time (observed) useful to decide which application gets CPU time?
  – Short Bursts ⇒ Interactivity ⇒ High Priority?
- Assumptions encoded into many schedulers:
  – Apps that sleep a lot and have short bursts must be interactive apps – they should get high priority
  – Apps that compute a lot should get low(er?) priority, since they won't notice intermittent bursts from interactive apps
- Hard to characterize apps:
  – What about apps that sleep for a long time, but then compute for a long time?
  – Or, what about apps that must run under all circumstances (say periodically)

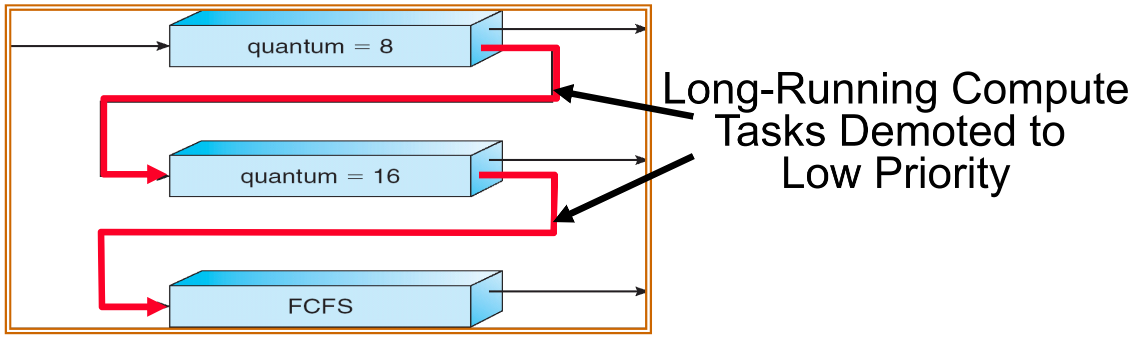


# Multi-Level Feedback Scheduling



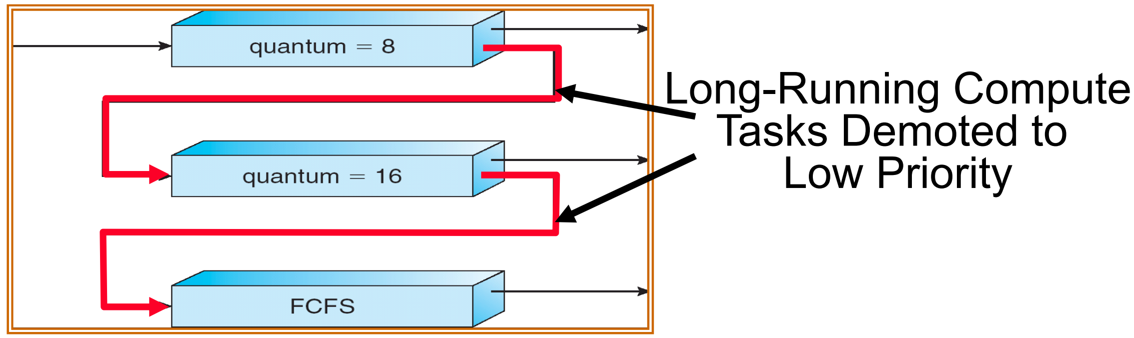

- Another method for exploiting past behavior (first use in CTSS)
  – Multiple queues, each with different priority
    » Higher priority queues often considered "foreground" tasks
  – Each queue has its own scheduling algorithm
    » e.g. foreground – RR, background – FCFS
    » Sometimes multiple RR 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

# Scheduling Details

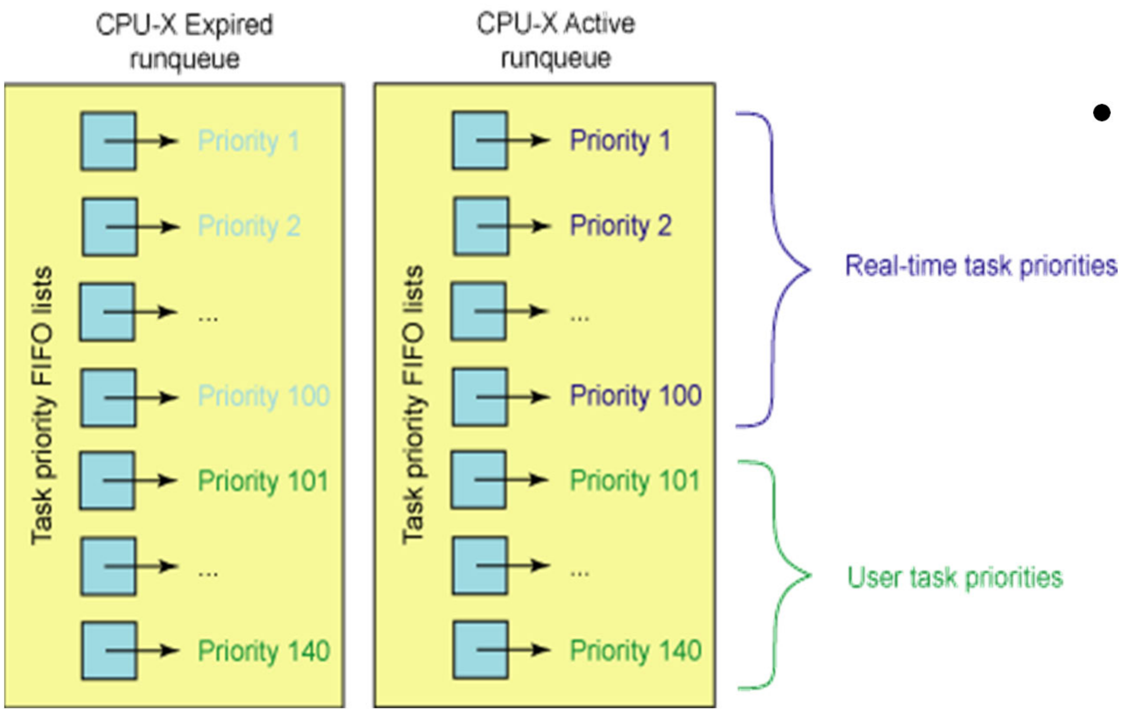



- Countermeasure: user action that can foil intent of the OS designers
  - For multilevel feedback, put in a bunch of meaningless I/O to keep job's priority high
  - Of course, if everyone did this, wouldn't work!
- Example of Othello program:
  - Playing against competitor, so key was to do computing at higher priority the competitors.
    - » Put in printf's, ran much faster!

# Case Study: Linux O(1) Scheduler


- Priority-based scheduler: 140 priorities
  - 40 for "user tasks" (set by "nice"), 100 for "Realtime/Kernel"
  - Lower priority value ⇒ higher priority (for realtime values)
  - Highest priority value ⇒ Lower priority (for nice values)
  - All algorithms O(1)
    - » Timeslices/priorities/interactivity credits all computed when job finishes time slice
    - » 140-bit bit mask indicates presence or absence of job at given priority level
- Two separate priority queues: "active" and "expired"
  - All tasks in the active queue use up their timeslices and get placed on the expired queue, after which queues swapped
- 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

# Linux O(1) Scheduler




- Lots of ad-hoc heuristics
  - Try to boost priority of I/O-bound tasks
  - Try to boost priority of starved tasks

# O(1) Scheduler Continued

- Heuristics
  - 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…
- 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

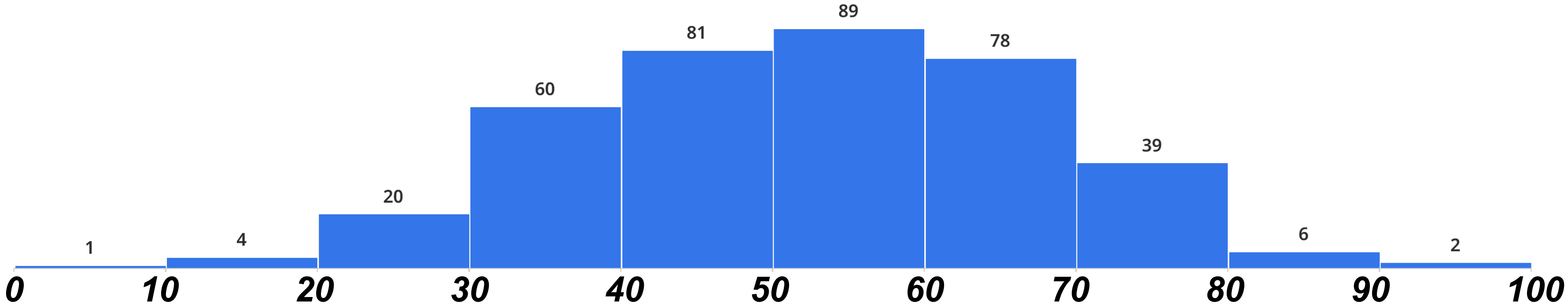
# So, Does the OS Schedule Processes or Threads?

- Many textbooks use the “old model”—one thread per process
- Usually it's really: **threads** (e.g., in Linux) but can be **task groups** (also Linux)

- Note: switching threads vs. switching processes incurs different costs:
  - Switch threads: Save/restore registers
  - Switch processes: Change active address space too!
    - Expensive
    - Disrupts caching

- Recall, However: Simultaneous Multithreading (or “Hyperthreading”)
  - Different threads interleaved on a cycle-by-cycle basis and can be in different processes (have different address spaces)

# Administrivia




- Midterm 1 results: Mean: 52.4, StdDev: 15.0, Min: 9.6, Max: 93.2!
- Project 1 due tomorrow (Wednesday, 2/28)
  – Code and final report
- Also due Tomorrow: Peer evaluations
  – These are a required mechanism for evaluating group dynamics
  – Project scores are a zero-sum game
    » In the normal/best case, all partners get the same grade
    » In groups with issues, we may take points from non-participating group members and give them to participating group members!
- Homework 3:
  – Due Tuesday 3/5
  – Can be done in Rust (if you want!)

# Multi-Core Scheduling

- Algorithmically, not a huge difference from single-core scheduling

- Implementation-wise, helpful to have *per-core* scheduling data structures
  - Cache coherence

- *Affinity scheduling*: once a thread is scheduled on a CPU, OS tries to reschedule it on the same CPU
  - Cache reuse, branch prediction
  - Example for O(1) scheduler: 1 set of queues/core with background rebalancing

# Recall: *Spinlocks for multiprocessing*

- Spinlock implementation:

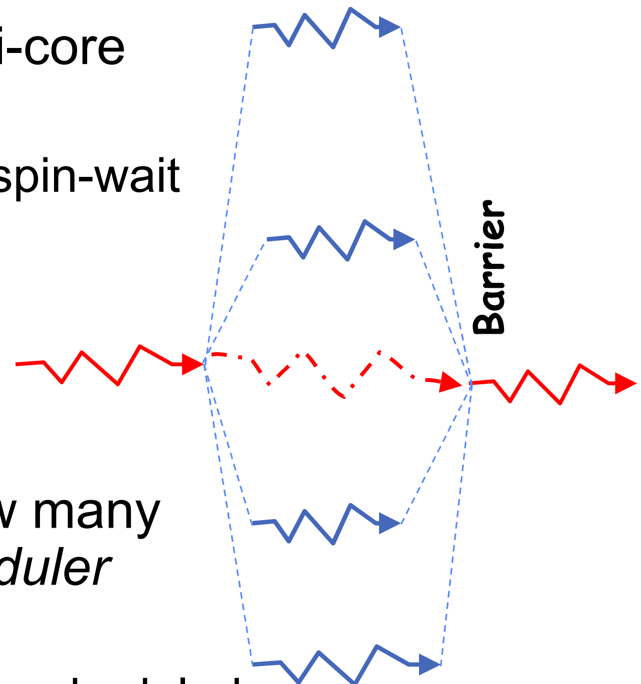
```
int value = 0; // Free
Acquire() {
   while (test&set(&value)) {}; // spin while busy
}
Release() {
   value = 0;                   // atomic store
}
```

- Spinlock doesn't put the calling thread to sleep—it just busy waits
  - When might this be preferable?
    - » Waiting for limited number of threads at a barrier in a multiprocessing (multicore) program
    - » Wait time at barrier would be greatly increased if threads must be woken inside kernel
- Every `test&set()` is a write, which makes value ping-pong around between core-local caches (using lots of memory!)
  - So – really want to use `test&test&set()` !
- As we discussed in Lecture 8, the extra read eliminates the ping-ponging issues:

```
// Implementation of test&test&set():
Acquire() {
   do {
      while(value);            // wait until might be free
   } while (test&set(&value)); // exit if acquire lock
}
```

# Gang Scheduling and Parallel Applications

- When multiple threads work together on a multi-core system, try to schedule them together
  - Makes spin-waiting more efficient (inefficient to spin-wait for a thread that's suspended)
  - Multiple phases of parallel and serial execution



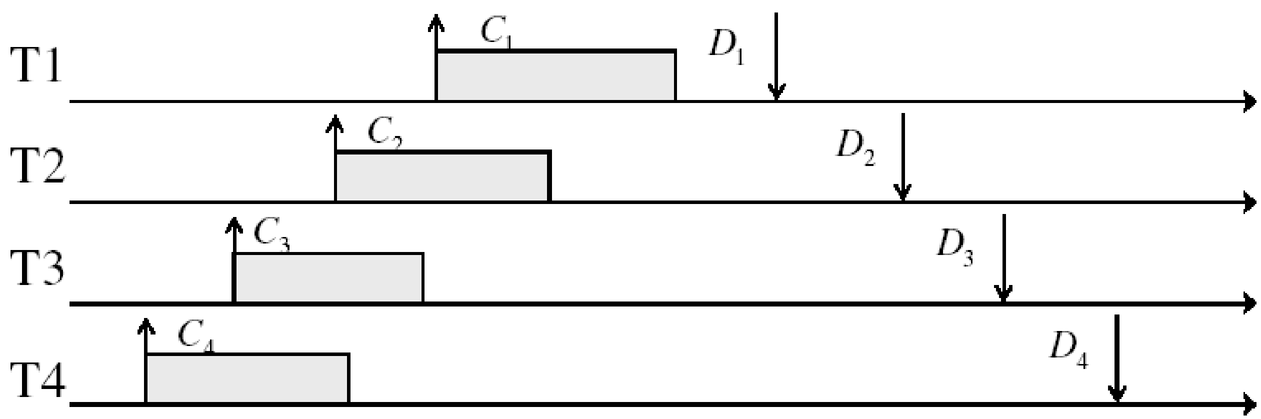

- Additionally: OS informs a parallel program how many processors its threads are scheduled on (*Scheduler Activations*)
  - Application adapts to number of cores that it has scheduled
  - "Space sharing" with other parallel programs can be more efficient, because parallel speedup is often sublinear with the number of cores

# Real-Time Scheduling

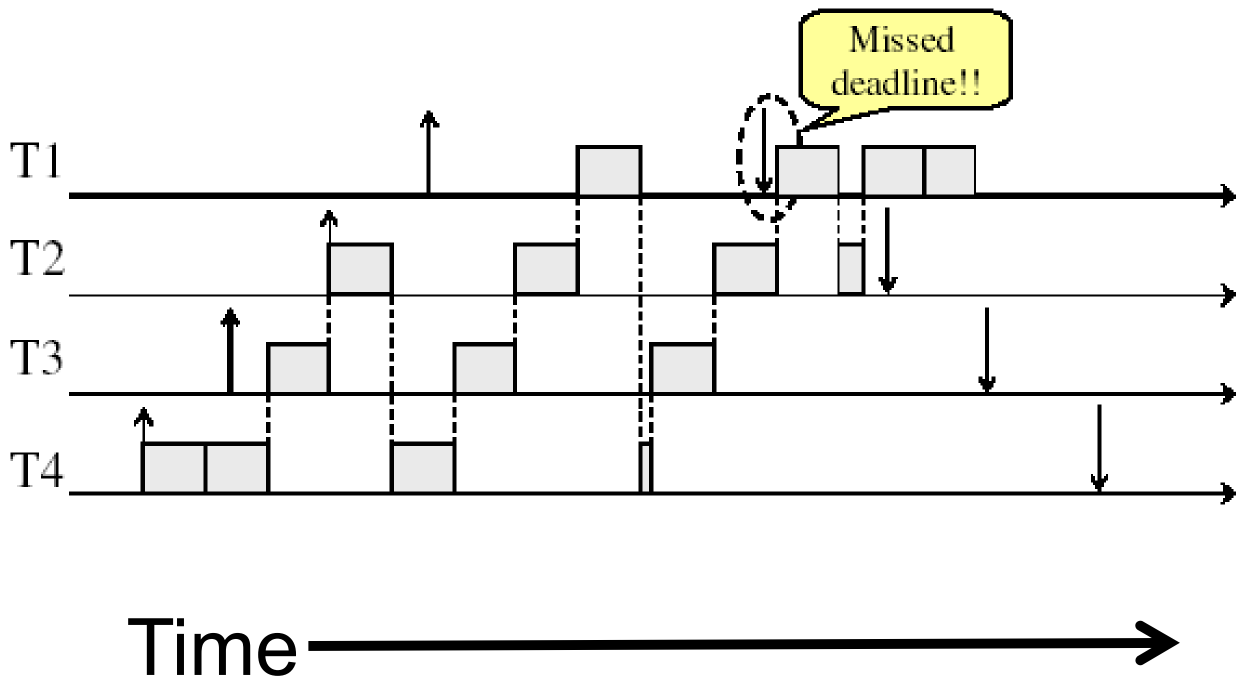
- Goal: Predictability of Performance!
  - We need to predict with confidence worst case response times for systems!
  - In RTS, performance guarantees are:
    - » Task- and/or class centric and often ensured a priori
  - In conventional systems, performance is:
    - » System/throughput oriented with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

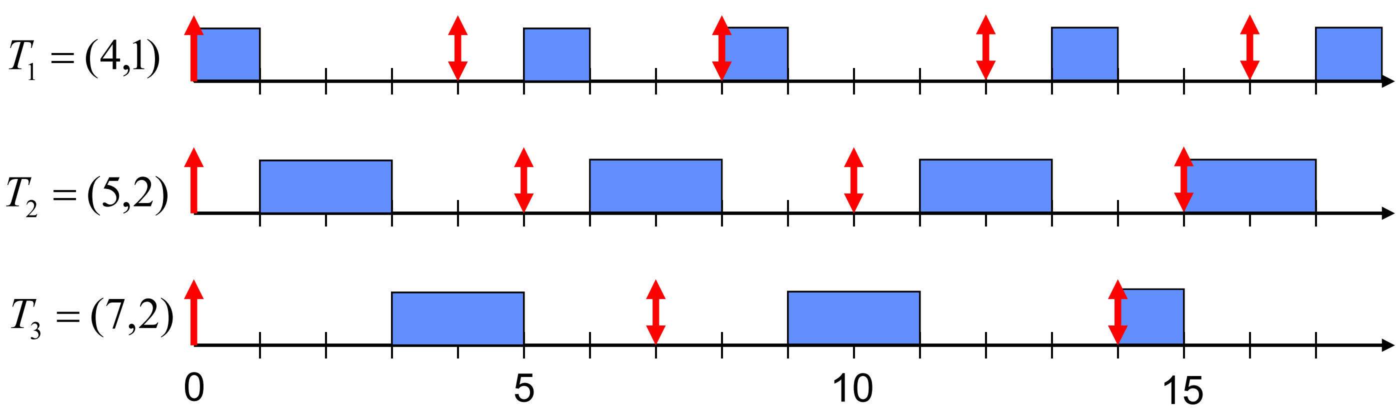


# Example: Round-Robin Scheduling Doesn't Work



# 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

- Even EDF won't work if you have too many tasks
- For $n$ tasks with computation time $C$ and deadline $D$, a feasible schedule exists if:

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

# Ensuring Progress

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

- Starvation ≠ Deadlock 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…

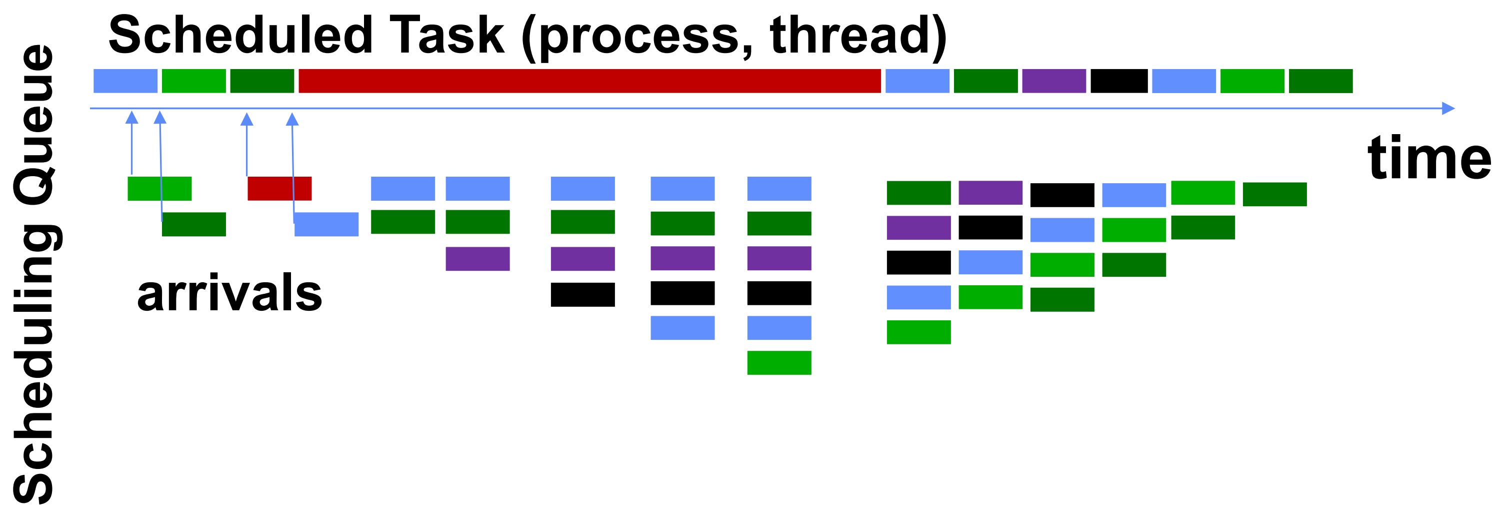
# Strawman: Non-Work-Conserving Scheduler

- 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

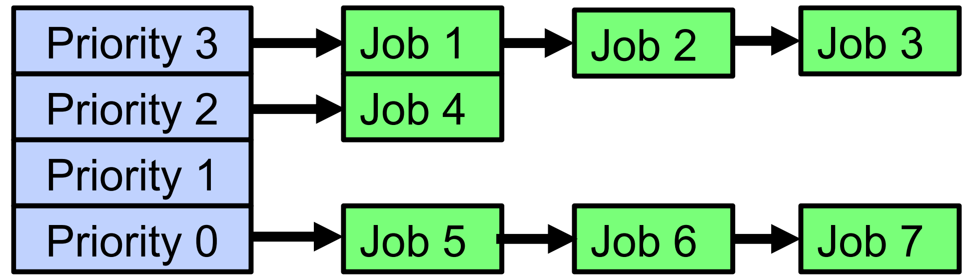
# Is Round Robin (RR) Prone to Starvation?

- 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… (if you give up your time slot early, you don't get the time back!)

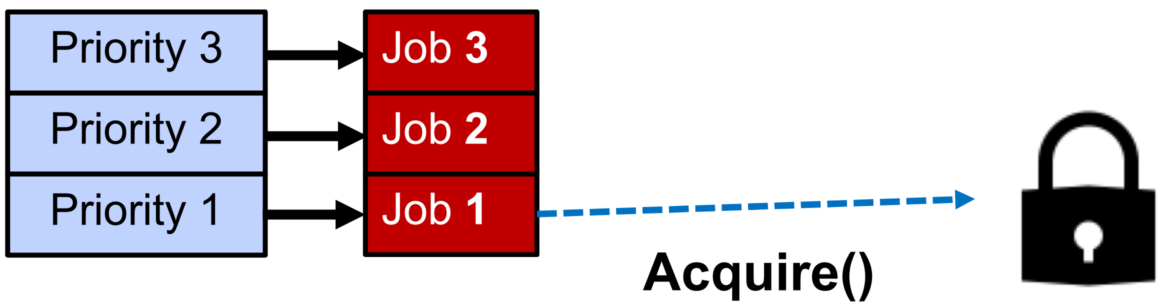
# Is Priority Scheduling Prone to Starvation?

- Recall: Priority Scheduler always runs the thread with highest priority
  - Low priority thread might never run!
  - Starvation…



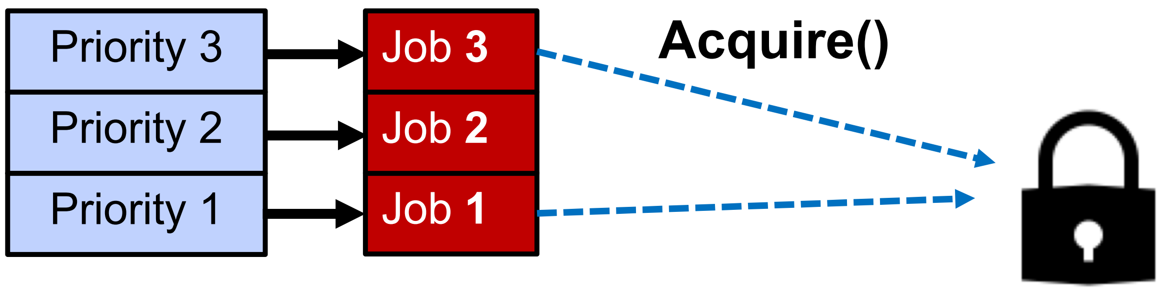

- But there are more serious problems as well…
  - Priority inversion: even high priority threads might become starved

# Priority Inversion



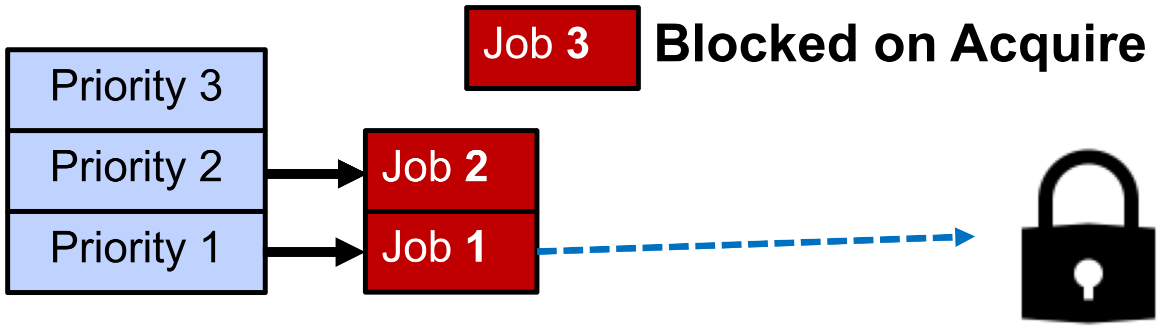

- **At this point, which job does the scheduler choose?**
- Job 3 (Highest priority)

# 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"?

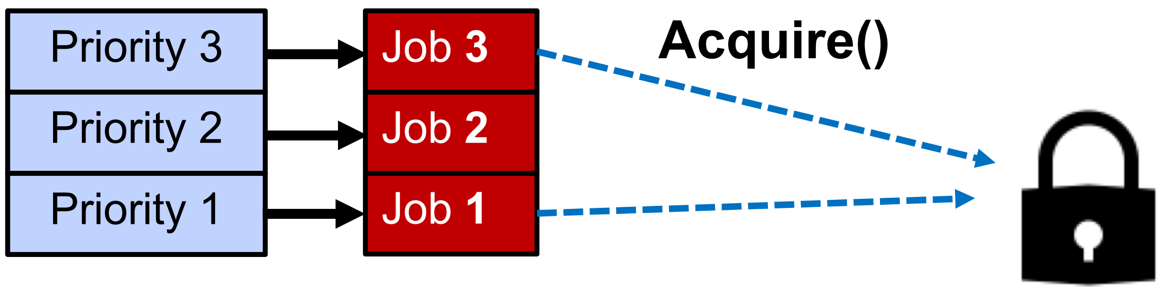
**High Priority**

```
while (try_lock) {
…
}
```

**Low Priority**

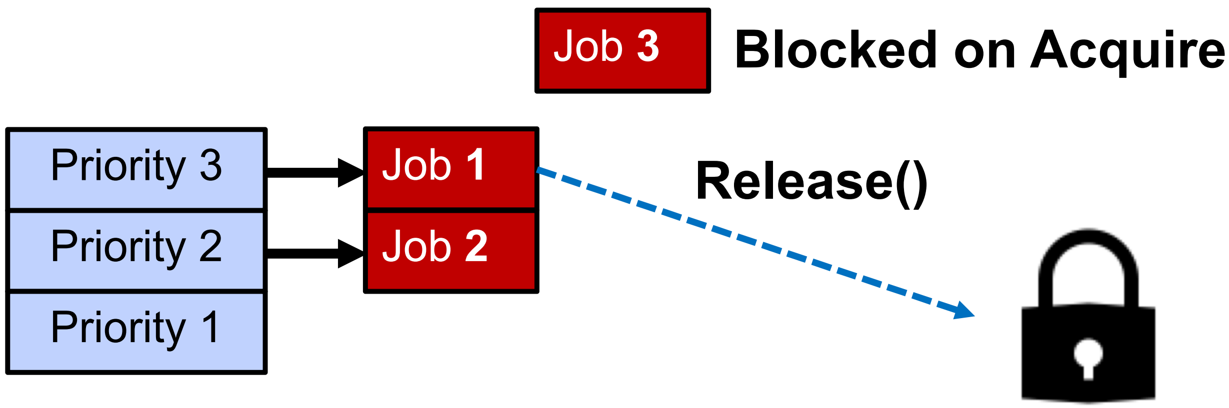
```
lock.acquire(…)
…
lock.release(…)
```

# One Solution: Priority Donation/Inheritance



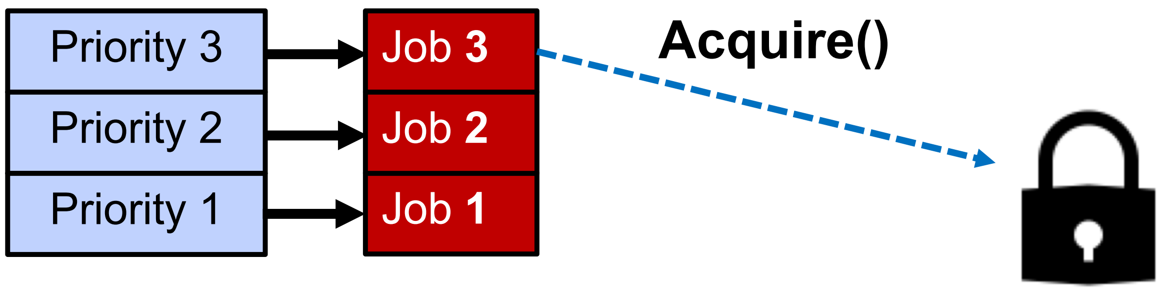

- Job 3 temporarily grants Job 1 its “high priority” to run on its behalf

# One Solution: Priority Donation/Inheritance




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

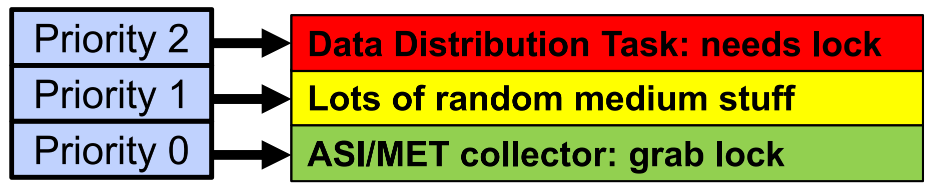
# One Solution: Priority Donation/Inheritance




- Job 1 completes critical section and releases lock
- Job 3 acquires lock, runs again
- How does the scheduler know?

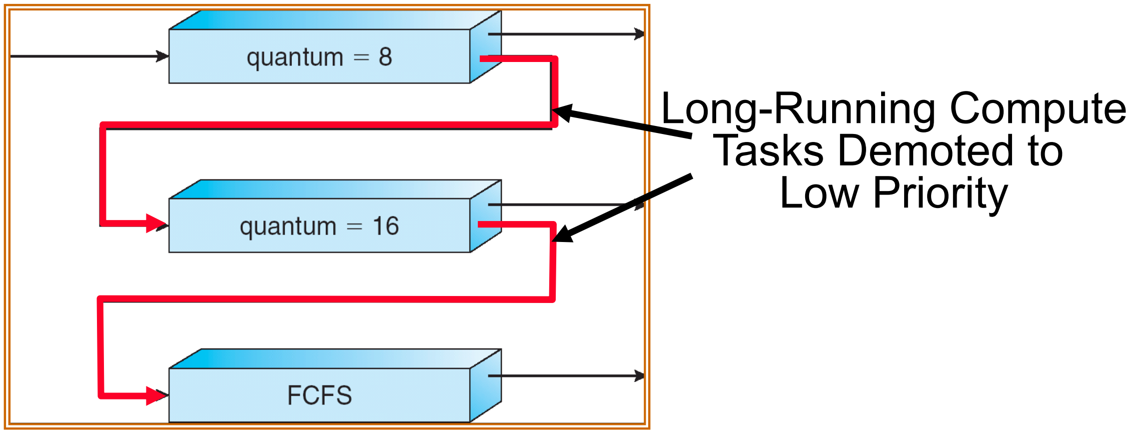
# Case Study: Martian Pathfinder Rover

- July 4, 1997 – Pathfinder lands on Mars
  - First US Mars landing since Vikings in 1976; first rover
  - Novel delivery mechanism: inside air-filled balloons bounced to stop on the surface from orbit!
- 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:




  - 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
- Solution: Turn priority donation back on and upload fixes!
- Original developers turned off priority donation (also called priority inheritance)
  - Worried about performance costs of donating priority!

# 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

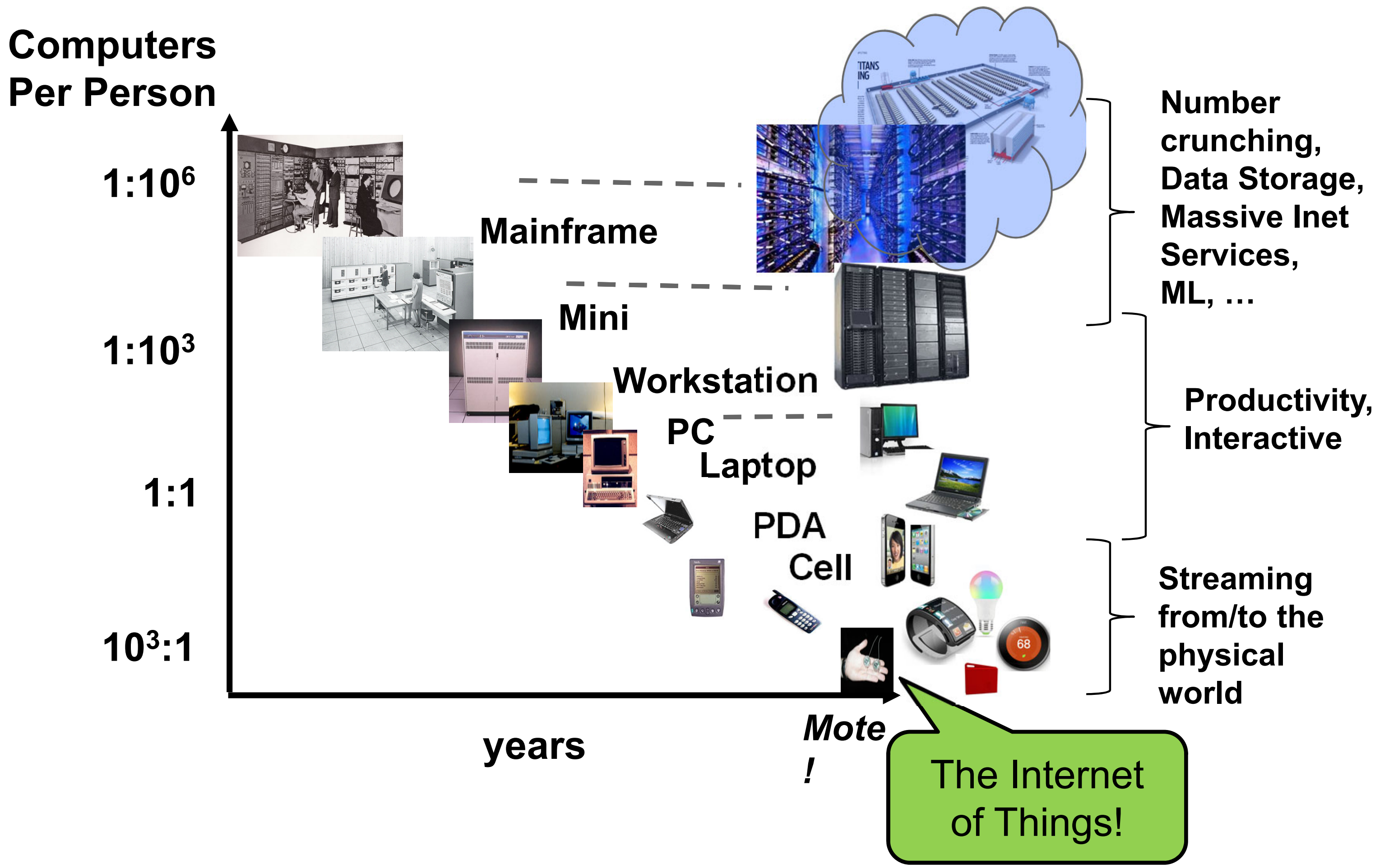
# Cause for Starvation: Priorities?

- 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, $95^{th}$ percentile performance guarantees

# 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)

# Lottery Scheduling

- Simple Idea:
  - 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

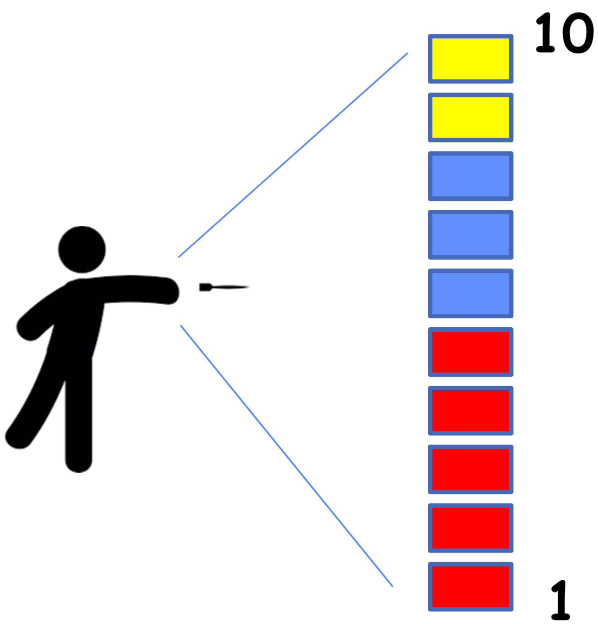
# Lottery Scheduling Example (Cont.)

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

| # short jobs/<br># 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?
    » If load average is 100, hard to make progress
    » One approach: log some user out

# Lottery Scheduling: Simple Mechanism




- $N_{ticket} = \sum N_i$
- Pick a number $d$ in $1 \,..\, N_{ticket}$ as the random "dart"
- Jobs record their $N_i$ of allocated tickets
- Order them by $N_i$
- Select the first j such that $\sum N_i$ up to j exceeds *d.*

# Unfairness

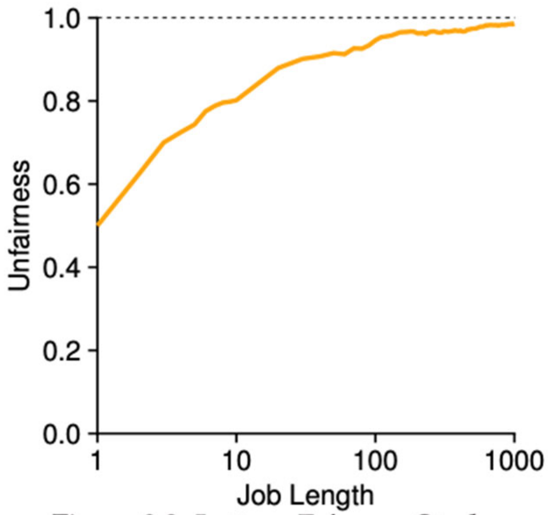


Figure 9.2: **Lottery Fairness Study**

- 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

- Achieve proportional share scheduling without resorting to randomness, and overcome the “law of small numbers” problem.
- “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 has 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
- Some messiness of counter wrap-around, new jobs, …

# Conclusion

- Multi-Level Feedback Scheduling:
  – Multiple queues of different priorities and scheduling algorithms
  – Automatic promotion/demotion of process priority in order to approximate SJF/SRTF
- 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?
- Priority Inversion
  – A higher-priority task is prevented from running by a lower-priority task
  – Often caused by locks and through the intervention of a middle-priority task
- Proportional Share Scheduling
  – 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)