# Operating Systems (Honor Track)

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

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Acknowledgments: Ion Stoica, Berkeley CS 162

# Recap: 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

# Recap: *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
  - So – really want to use `test&test&set()` !
- 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)

- Alternative: 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

# 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)

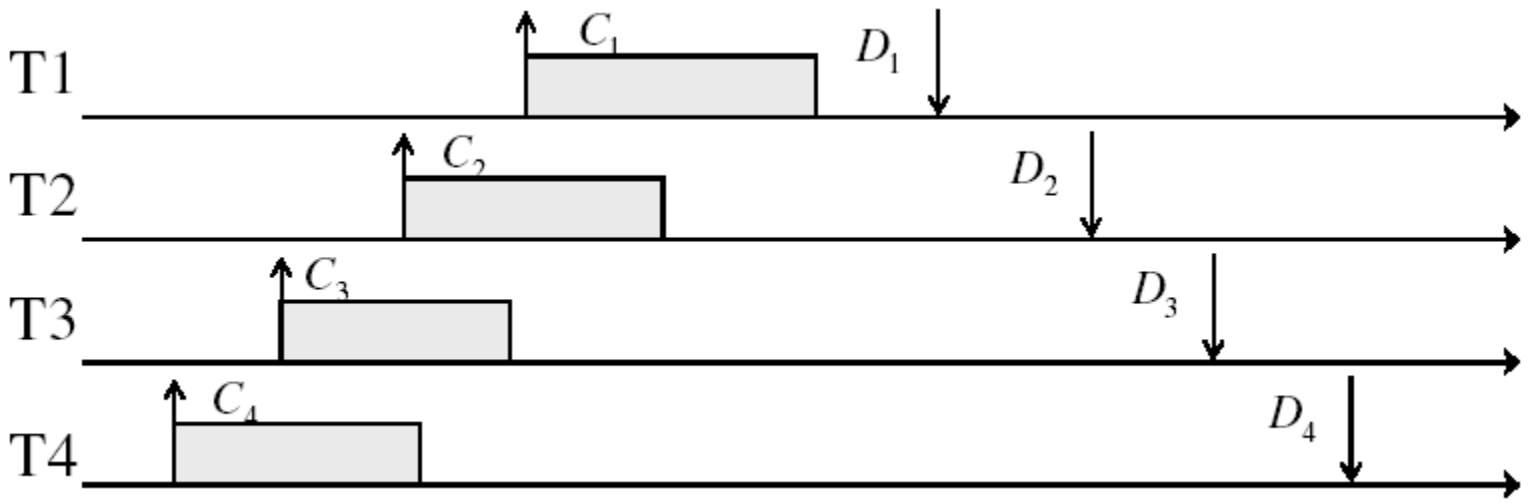
- One point to notice: switching threads vs. switching processes incurs different costs:
  - Switch threads: Save/restore registers
  - Switch processes: Change active address space too!
    - » Expensive
    - » Disrupts caching

# Real-Time Scheduling

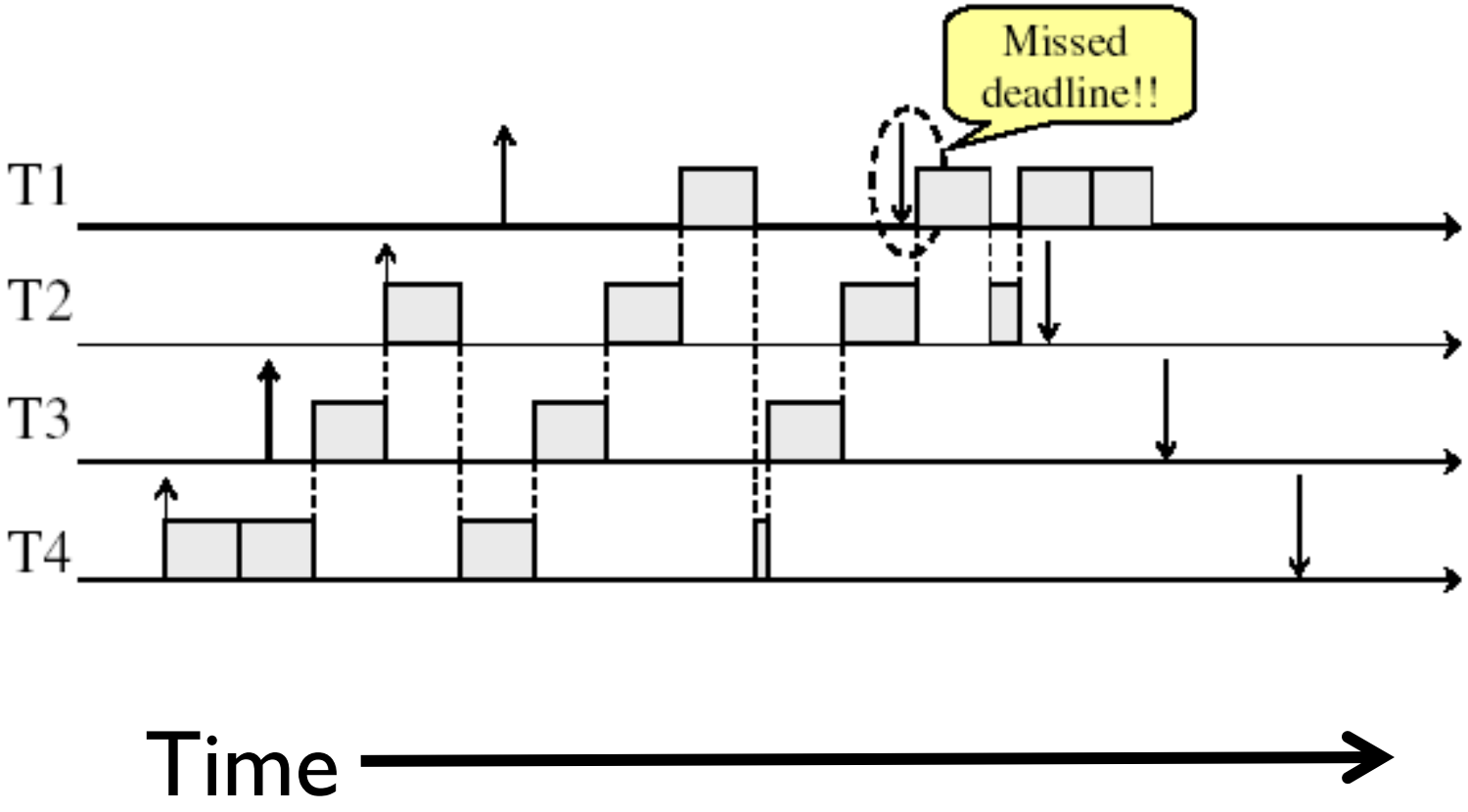
- Goal: Predictability of Performance!
  - We need to predict with confidence worst case response times for systems!
  - In RTS, performance guarantees are:
    - » Task- and/or class centric and often ensured a priori
  - In conventional systems, performance is:
    - » System/throughput oriented with post-processing (… wait and see …)
  - Real-time is about enforcing *predictability*; 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 (admission control)
  - Earliest Deadline First (EDF)
    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:

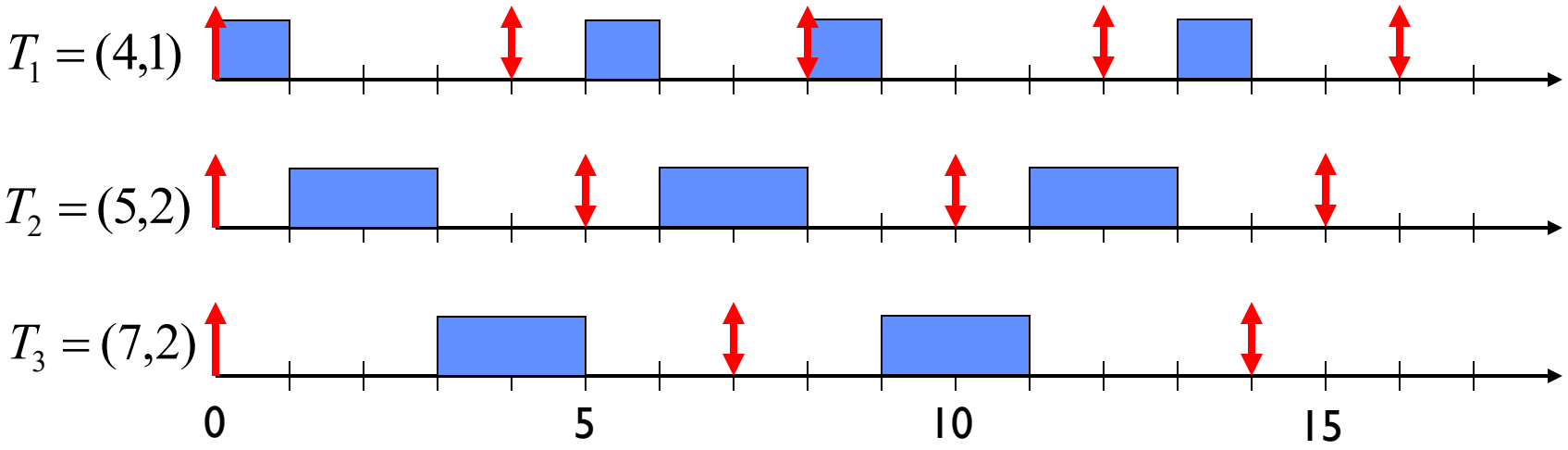


# Example: Round-Robin Scheduling Doesn't Work



# Earliest Deadline First (EDF)

- Tasks $i$ is periodic with period $P_i$ and computation $C_i$ 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 $C_i$ and deadline $D_i$, a feasible schedule exists if:

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

$$\frac{1}{4} + \frac{2}{5} + \frac{2}{7} = 0.936 \leq 1$$

# 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…

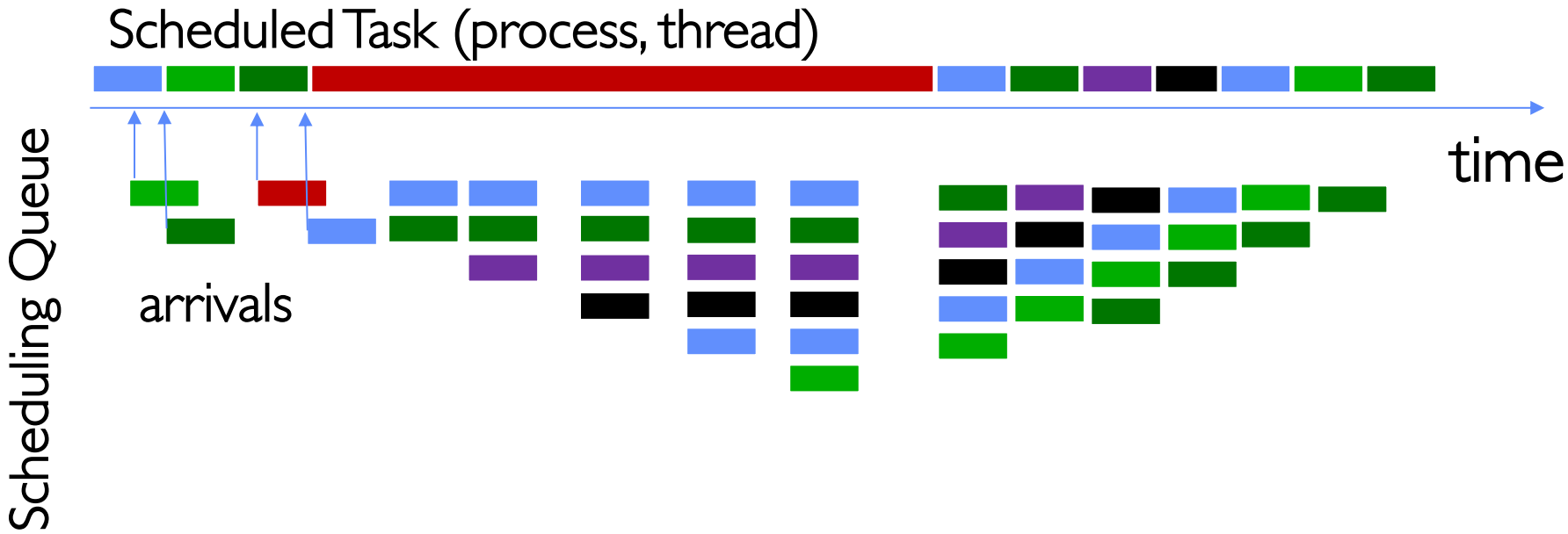
# Strawman: Non-Work-Conserving Scheduler

- 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

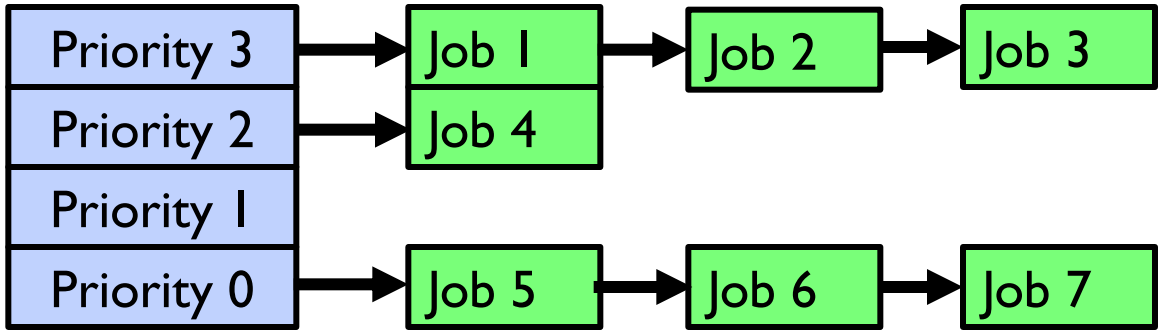
# Is Round Robin (RR) Prone to Starvation?

- 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…

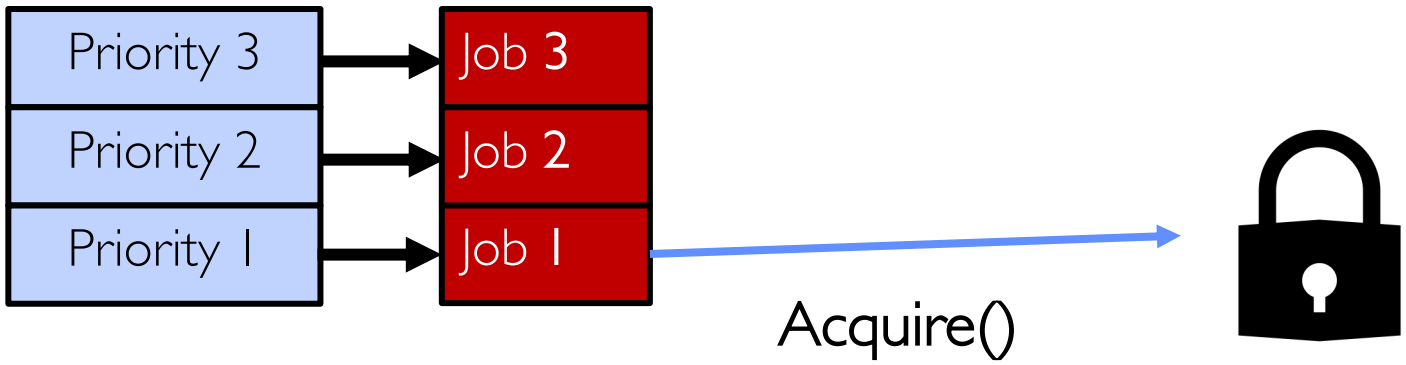
# Is Priority Scheduling Prone to Starvation?

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



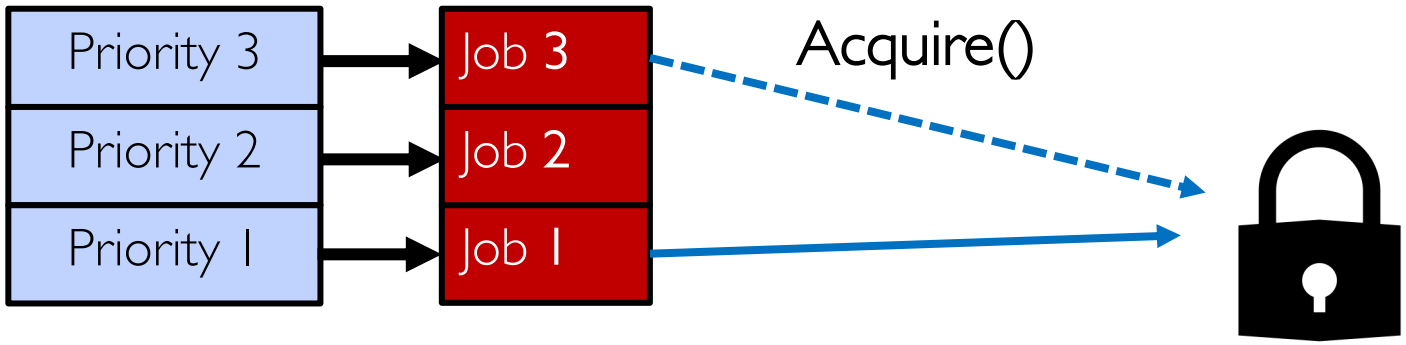

- But there are more serious problems as well…
  - Priority inversion: even high priority threads might become starved

# Priority Inversion



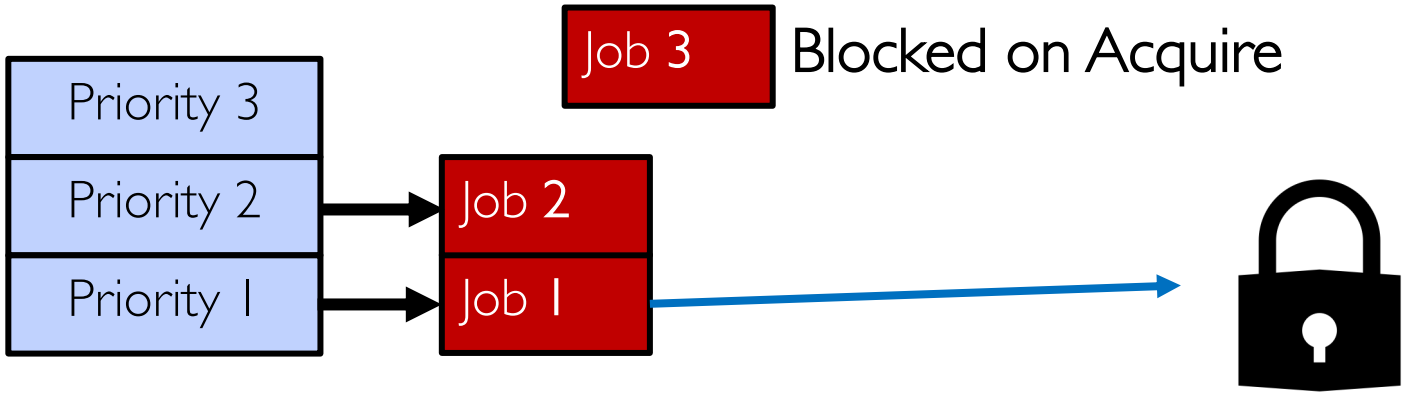

- At this point, which job does the scheduler choose?
- Job 3 (Highest priority)

# Priority Inversion




- Job 3 attempts to acquire lock held by Job 1

# Priority Inversion



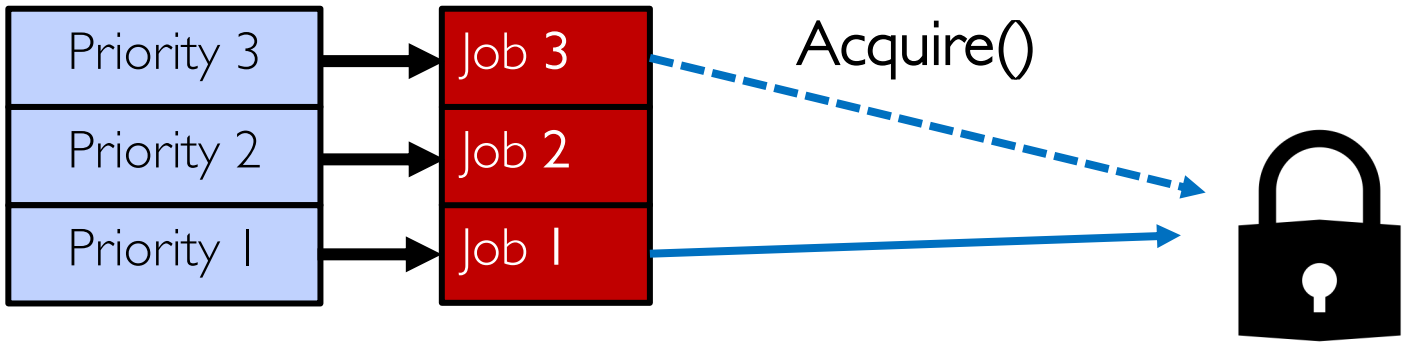

- At this point, which job does the scheduler choose?
- Job 2 (Medium Priority)
- Priority Inversion

# 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”?

# One Solution: Priority Donation/Inheritance




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

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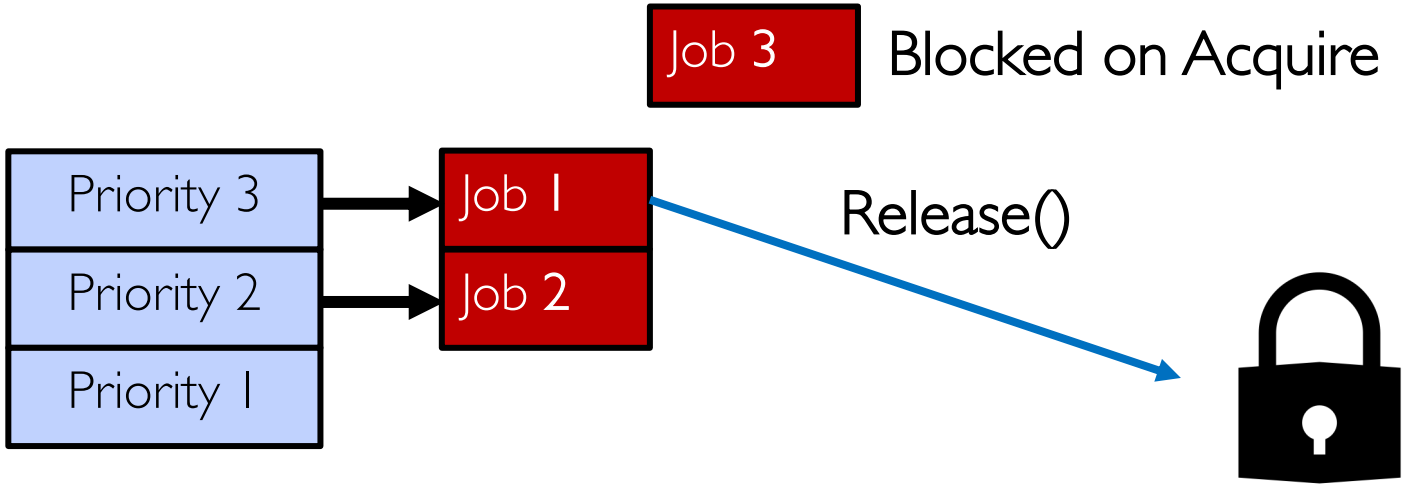


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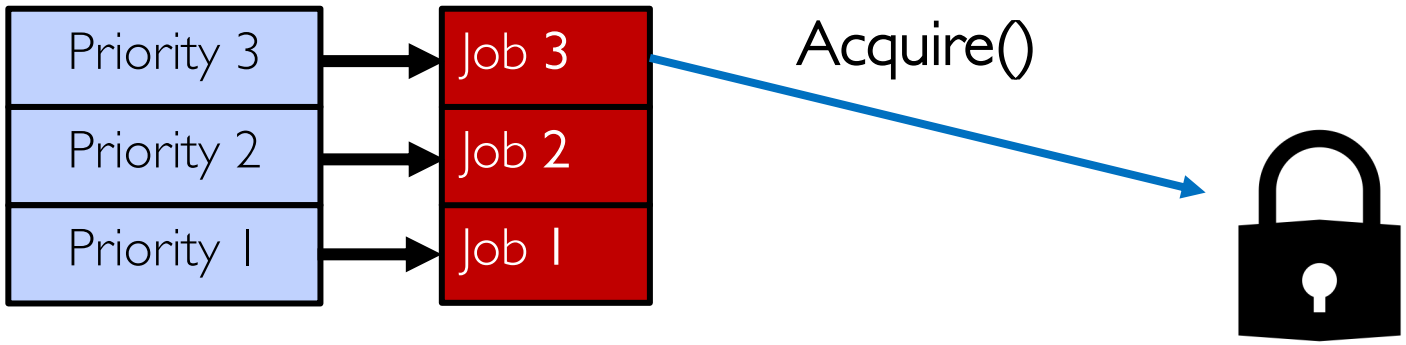
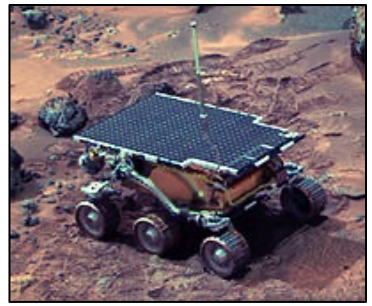


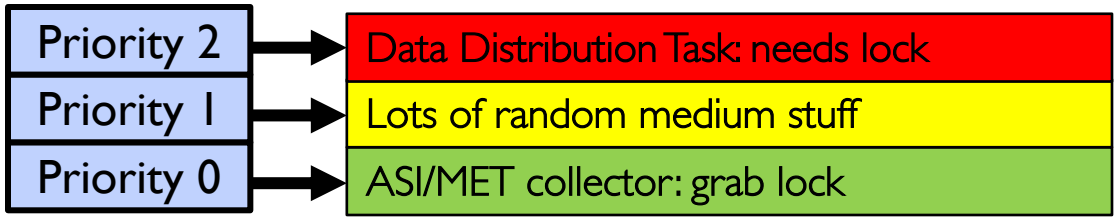

- Job 1 completes critical section and releases lock
- Job 3 acquires lock, runs again

# 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!

# Summary

- 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
- 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?