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Operating Systems

Scheduling

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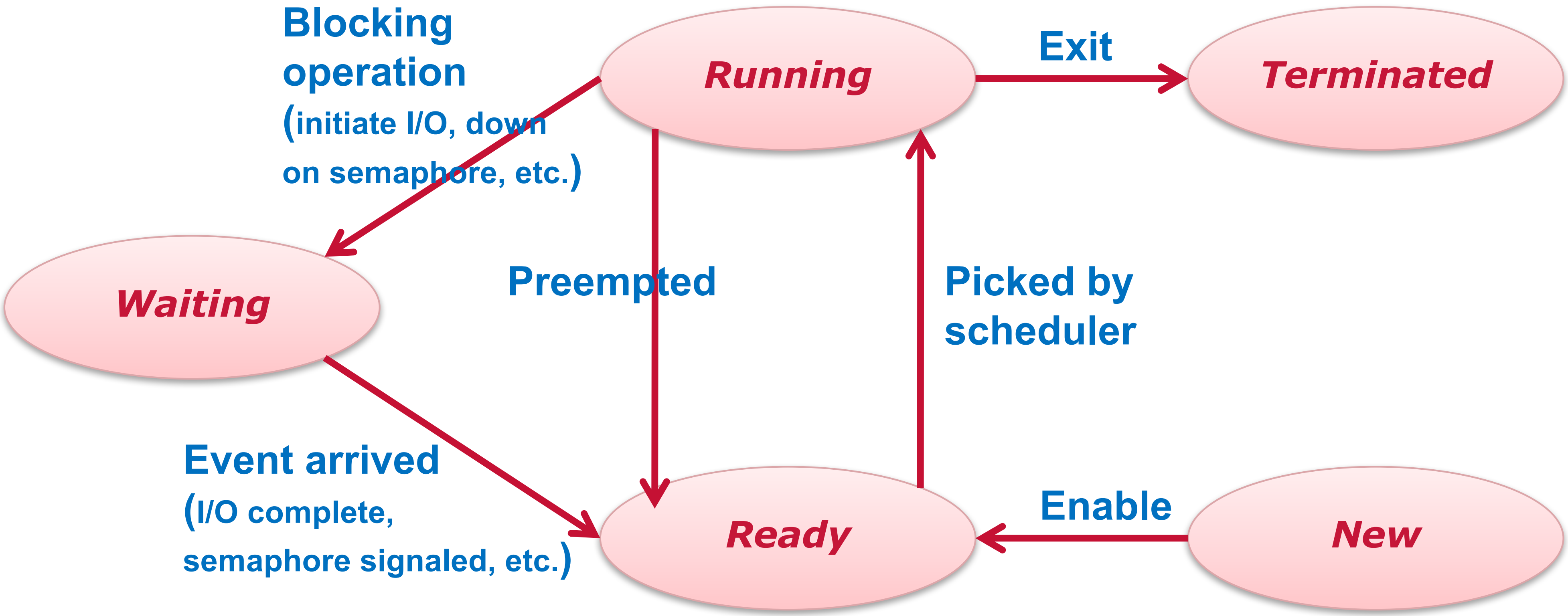
Process States



- **New**: the process is being created
- **Ready**: runnable and waiting for processor
- **Running**: executing on a processor
- **Waiting/Blocked**: waiting for an event
- **Terminated**: process is being deleted

If multiple processes are ready, which one should be run?

Goals of Scheduling Algorithms

- Ensure fairness
  - Comparable processes should get comparable services
- Avoid indefinite postponement
  - No process should starve
- Enforce policy
  - E.g., priorities
- Maximize resource utilisation
  - CPU, I/O devices
- Minimize overhead
  - From context switches, scheduling decisions

Goals of Scheduling Algorithms

- **Batch systems:**
  - Throughput
    - Jobs per unit of time
  - Turnaround time
    - Time between job submission and termination
- **Interactive systems:**
  - Response time crucial
    - Time between request issued and first response
- **Real-time systems:**
  - Meeting deadlines
    - Soft deadlines: e.g., leads to degraded video quality
    - Hard deadline: e.g., leads to plane crash

Preemptive vs. Non-Preemptive Scheduling

- **Non-preemptive**
  - Let process run until it blocks or voluntarily releases the CPU

- **Preemptive:**
  - Let process run for a maximum amount of fixed time
  - Requires clock interrupt

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CPU-bound vs. I/O-bound Processes

- **CPU-bound processes**
  - Spend most of their time using the CPU
- **I/O-bound processes**
  - Spend most of their time waiting for I/O
  - Tend to only use CPU briefly before issuing I/O request

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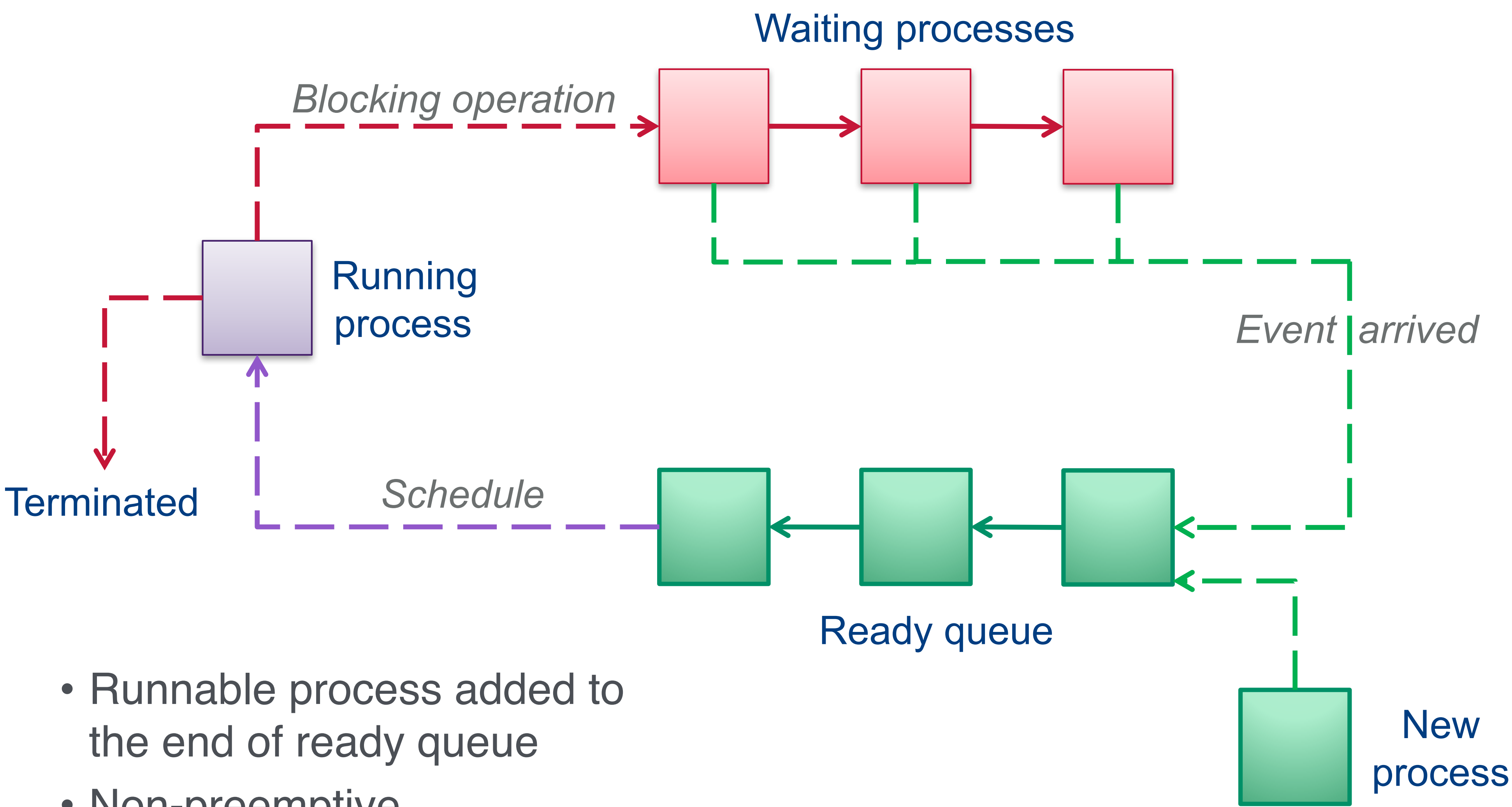
First-Come First-Served (FCFS) (non-preemptive)



- Runnable process added to the end of ready queue
- Non-preemptive

FCFS Advantages

- No indefinite postponement
  - All processes are eventually scheduled

- Really easy to implement

FCFS Disadvantages

- What happens if a long job is followed by many short jobs?
  - E.g., 1h, 1s, 1s, 1s, with jobs 2-4 submitted just after job 1

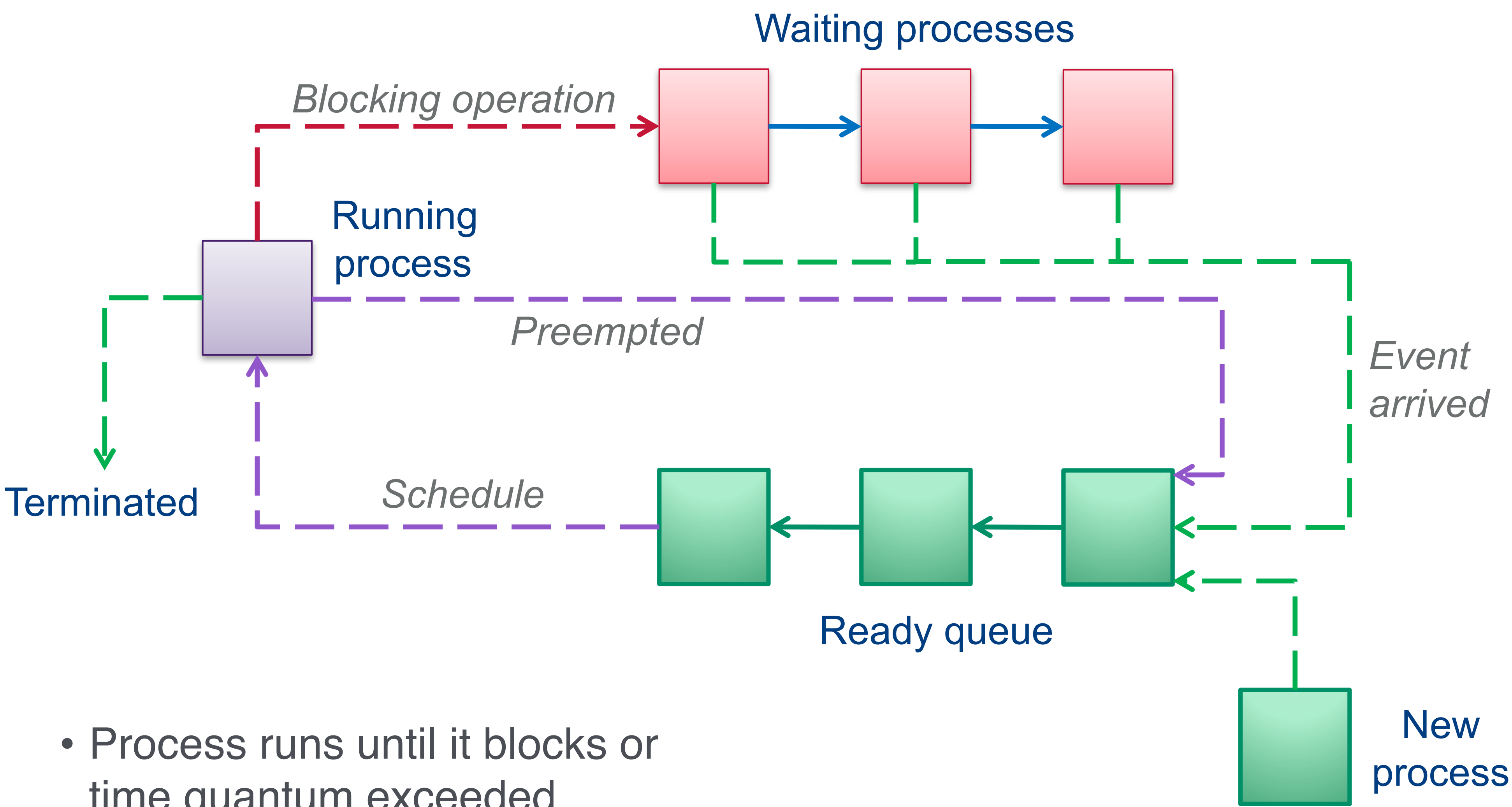
3600s	*1s*	*1s*	*1s*

  - Throughput?
  - Average turnaround time?

1s	*1s*	*1s*	*3600s*

  - Throughput?
  - Average turnaround time?

Round-Robin Scheduling (RR)



- Process runs until it blocks or time quantum exceeded

Round-Robin

- Fairness
  - Ready jobs get equal share of the CPU
- Response time
  - Good for small number of jobs
- Average turnaround time:
  - Low when run-times differ
  - Poor for similar run-times

RR Quantum (Time Slice)

- RR Overhead:
  - 4ms quantum, 1ms context switch time: 20% of time → overhead
  - 1s quantum, 1ms context switch time: only 0.1% of time → overhead

- Large quantum:
  - Smaller overhead
  - Worse response time
    - Quantum = ∞ → FCFS

- Small quantum:
  - Larger overhead
  - Better response time

RR Quantum

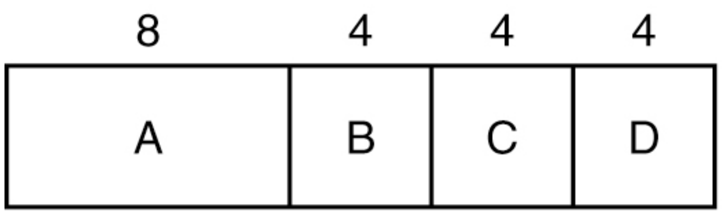
- Choosing a quantum value:
  - Should be much larger than context switch cost
  - But provide decent response time

- Typical values: 10-200ms

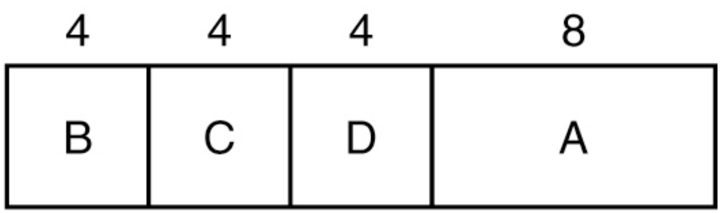
- Some example values for standard processes (values vary depending on process type and behaviour, priority, etc.):
  - Linux: 100ms
  - Windows client: 20ms
  - Windows server: 180ms

Shortest Job First (SJF)

- Non-preemptive scheduling with run-times known in advance
- Pick the shortest job first
  - Process with shortest CPU burst



FCFS turnaround time:



SJF turnaround time:

- Provably optimal when all jobs are available simultaneously

Shortest Remaining Time (SRT)

- Preemptive version of shortest job first
  - Again, runtimes have to be known in advance
- Choose process whose remaining time is shortest
  - When new process arrives with execution time less than the remaining time for the running process, run it
- Allows new short jobs to get good service

Example: 3 jobs: J_1 = 6s, J_2 = 4s, J_3 = 1s arrives after 2s

Shortest Remaining Time (SRT)

- What if a running process is almost complete and a shorter job arrives?
  - Might want to disallow preemption when remaining run-time reaches a low threshold to avoid indefinite postponement
  - What if context switch overhead is greater than the difference in remaining run-times for the two jobs?

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Knowing Run-times in Advance

- Run-times are usually not available in advance

- Compute CPU burst estimates based on various heuristics?
  - E.g., based on previous history
  - Not always applicable

- User-supplied estimates?
  - Need to counteract cheating to get higher priority
  - E.g., terminate or penalise processes after they exceed their estimated run-time

Fair-Share Scheduling

- Users are assigned some fraction of the CPU
  - Scheduler takes into account who owns a process before scheduling it
- E.g., two users each with 50% CPU share
  - User 1 has 4 processes: A, B, C, D
  - User 2 has 2 processes: E, F
- What does a fair-share RR scheduler do?
  - A, E, B, F, C, E, D, F, A, E, B, F…

Priority Scheduling

- Jobs are run based on their priority
  - Always run the job with the highest priority
- Priorities can be **externally defined** (e.g., by user) or based on some **process-specific metrics** (e.g., their expected CPU burst)
- Priorities can be **static** (i.e. they don't change) or **dynamic** (they may change during execution)

- Example: consider three processes arriving at essentially the same time with externally defined static priorities A = 4, B = 7, C = 1, where a higher value means higher priority.
  - Processes are run to completion in the order B, A, C.

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General-Purpose Scheduling

- Favour short and I/O-bound jobs
  - Get good resource utilisation
  - And short response times
- Quickly determine the nature of the job and adapt to changes
  - Processes have periods when they are I/O-bound and periods when they are CPU-bound

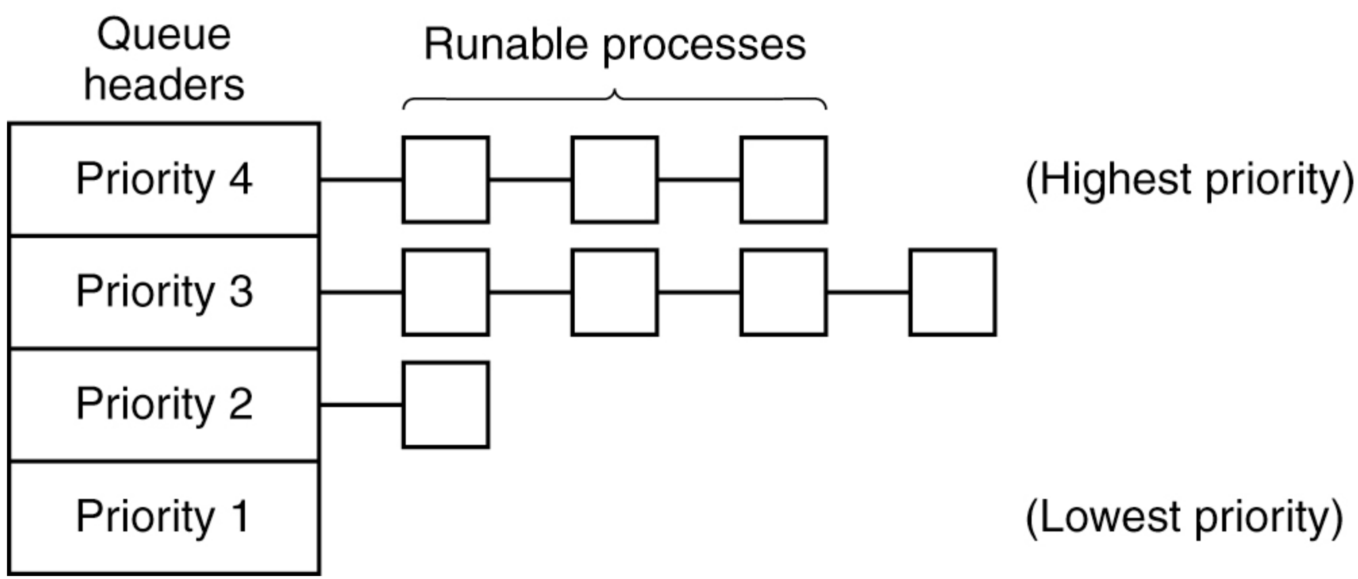
Multilevel Feedback Queues

- A form of priority scheduling
  - Shortest remaining time also a form of priority scheduling!

- Implemented by many OSs:
  - Windows Vista, Windows 7
  - Mac OS X
  - Linux 2.6 - 2.6.23
  - Pintos!

Multilevel Feedback Queues

- One queue for each priority level
  - Run job on highest non-empty priority queue
  - Each queue can use different scheduling algorithm
    - Usually round-robin



Multilevel Feedback Queues

- Need to determine current nature of job
  - I/O-bound? CPU-bound?
- Need to worry about starvation of lower-priority jobs
- Feedback mechanism:
  - Job priorities recomputed periodically, e.g., based on how much CPU they have recently used
    - Exponentially-weighted moving average
  - *Aging*: increase job's priority as it waits

Multilevel Feedback Queues

- Not very flexible
  - Applications basically have no control
  - Priorities make no guarantees
    - What does priority 15 mean?
- Does not react quickly to changes
  - Often needs *warm-up* period
    - Running system for a while to get better results
  - Problem for real-time systems, multimedia apps
- Cheating is a concern
  - Add meaningless I/O to boost priority?
- Can’t donate priority

Lottery Scheduling [Waldspurger and Weihl 1994]

- Jobs receive lottery tickets for various resources
  - E.g., CPU time
- At each scheduling decision, one ticket is chosen at random and the job holding that ticket wins

Example: 100 lottery tickets for CPU time, P1 has 20 tickets

- Chance of P1 running during the next CPU quantum: 20%
- In the long run, P1 gets 20% of the CPU time

Lottery Scheduling

- Number of lottery tickets meaningful
  - Job holding p% of tickets, gets p% of resource
  - Unlike priorities
- Highly responsive:
  - New job given p% of tickets has the p% chance to get the resource at the ***next*** scheduling decision
- No starvation
- Jobs can exchange tickets
  - Allows for priority donation
  - Allows cooperating jobs to achieve certain goals
- Adding/removing jobs affect remaining jobs proportionally
- Unpredictable response time
  - What if interactive process is unlucky for a few lotteries?

Summary

- Scheduling algorithms often need to balance conflicting goals
  - E.g., ensure fairness, enforce policy, maximize resource utilisation
- Different scheduling algorithms appropriate in different contexts
  - E.g., batch systems vs interactive systems vs real-time systems
- Well-studied scheduling algorithms include
  - First-Come First-Served FCFS, Round Robin, Shortest Job First (SJF), Shortest Remaining Time (SRT), Multilevel Feedback Queues and Lottery Scheduling