CPU Scheduling

Administrative

- Midterm
  – Mar. 11, 2016
  – Closed book, in-class
  – Review class: Mar. 9, 2016

Agenda

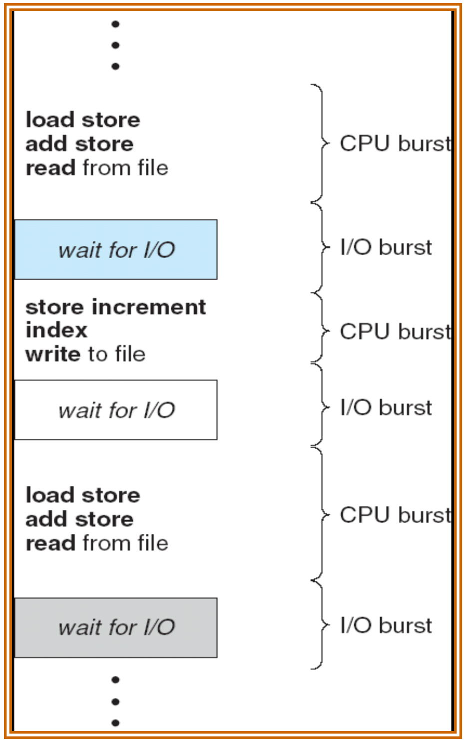
- Introduction to CPU scheduling
- Classical CPU scheduling algorithms

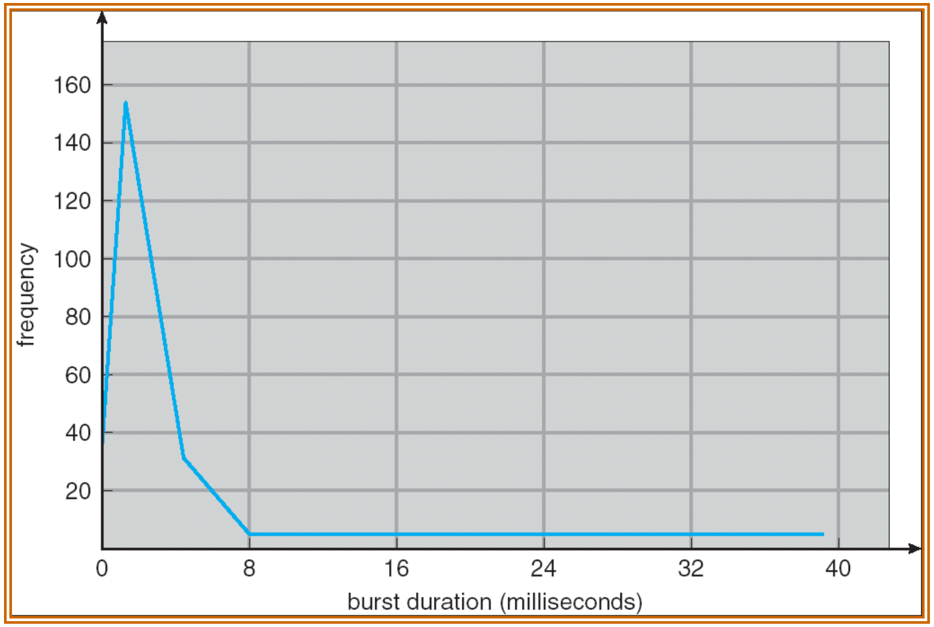
CPU Scheduling

- CPU scheduling is a **policy** to decide
  - **Which** thread to run next?
  - **When** to schedule the next thread?
  - **How long**?

- Context switching is a **mechanism**
  - To change the running thread

Assumption: CPU Bursts

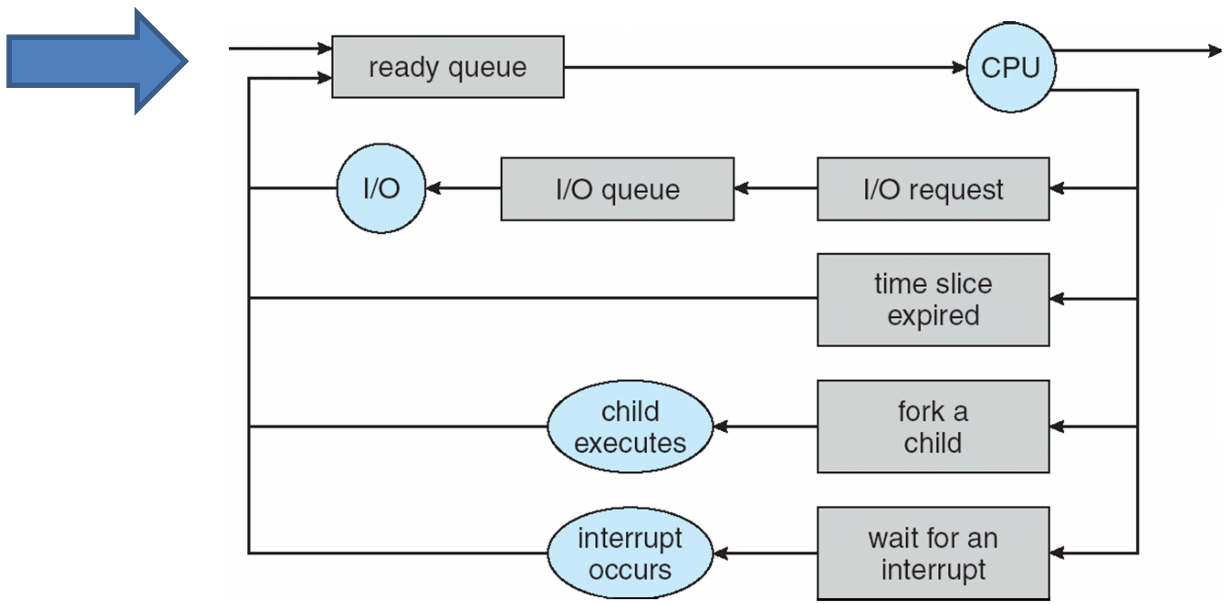




- Execution model
  - Program uses the CPU for a while and the does some I/O, back to use CPU, …, keep alternating

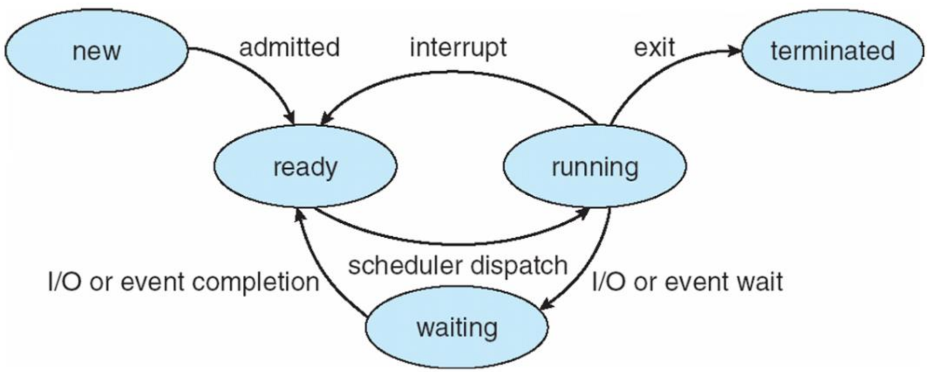
CPU Scheduler

- An OS component that determines which thread to run, at what time, and how long
  – Among threads in the **ready queue**



CPU Scheduler

- When the scheduler runs?



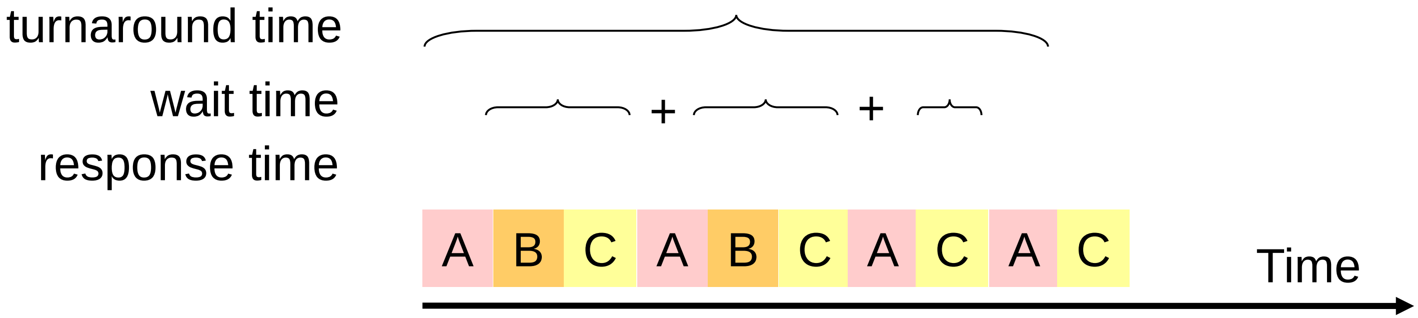
  - The running thread finishes
  - The running thread voluntarily gives up the CPU
    - yield, block on I/O, …
  - The OS **preempts** the current running thread
    - quantum expire (timer interrupt)

Performance Metrics for CPU Scheduling

- CPU utilization
  - % of time the CPU is busy doing something
- Throughput
  - #of jobs done / unit time
- **Turnaround time**
  - Time to complete a task (ready -> complete)
- **Waiting time**
  - Time spent on waiting in the ready queue
- **Response time**
  - Time to schedule a task (ready -> first scheduled)

Example

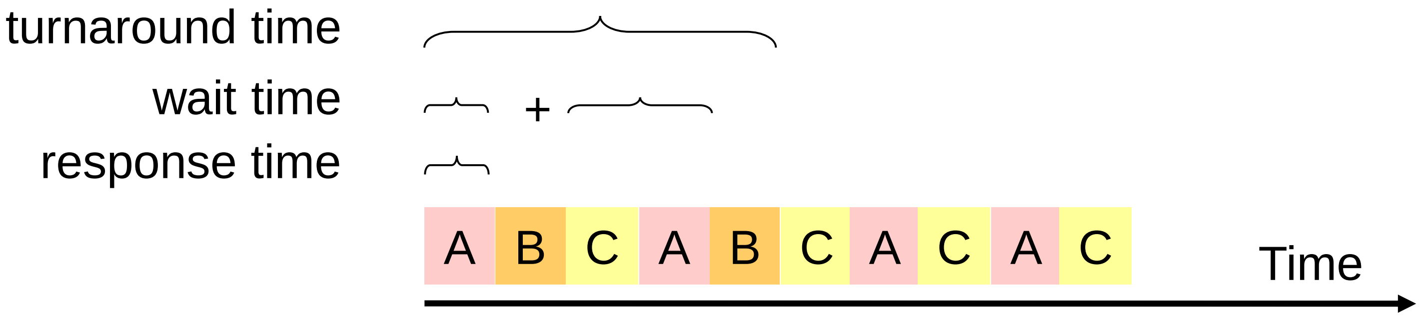
- Assumption: A, B, C are released at time 0



- The times of Process **A**
  - Turnaround time: 9
  - Wait time: 5
  - Response time: 0

Example

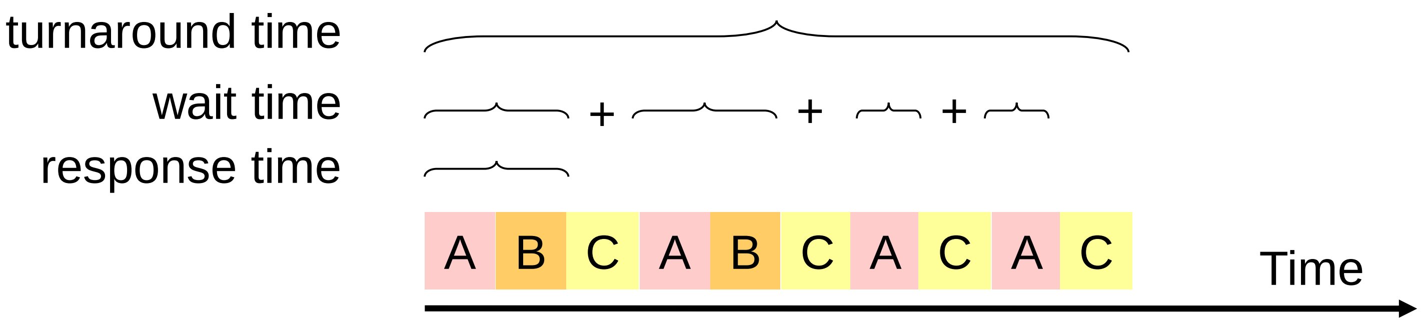
- Assumption: A, B, C are released at time 0



- The times of Process **B**
  - Turnaround time: 5
  - Wait time: 3
  - Response time: 1

Example

- Assumption: A, B, C are released at time 0



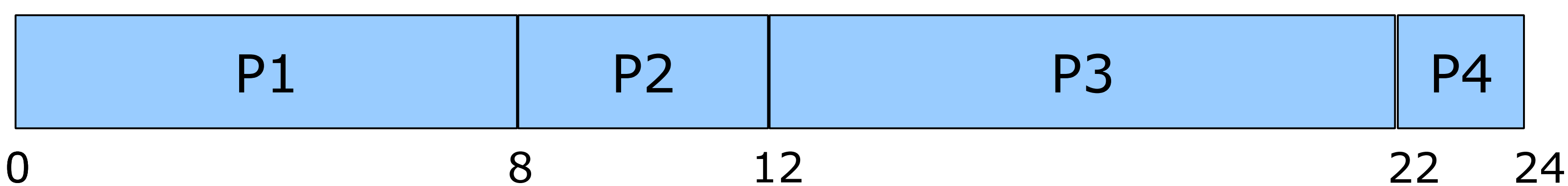
- The times of Process **C**
  - Turnaround time: 10
  - Wait time: 6
  - Response time: 2

Workload Model and Gantt Chart

- Workload model

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	1	10
P4	6	2

- Gantt chart
  - bar chart to illustrate a particular schedule



Scheduling Policy Goals

- Maximize throughput
  - High throughput (#of jobs done / time) is always good
- Minimize response/completion time
  - Important to interactive applications (games, editor, …)
- Fairness
  - Make all threads progress equally

- Goals often conflicts
  - Frequent context switching may be good for reducing response time, but not so much for maximizing throughput

First-Come, First-Served (FCFS)

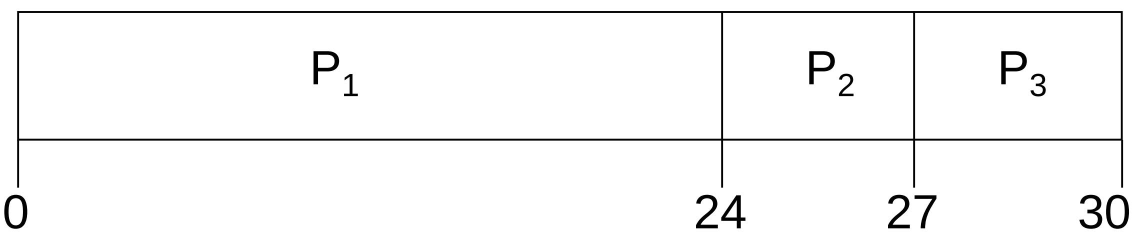
- FCFS
  - Assigns the CPU based on the order of the requests.
  - Implemented using a FIFO queue.

FCFS

- Example

Process	Arrival Time	Burst Time
P1	0	24
P2	0	3
P3	0	3

  - Suppose that the processes arrive in the order: P_1 , P_2 , P_3



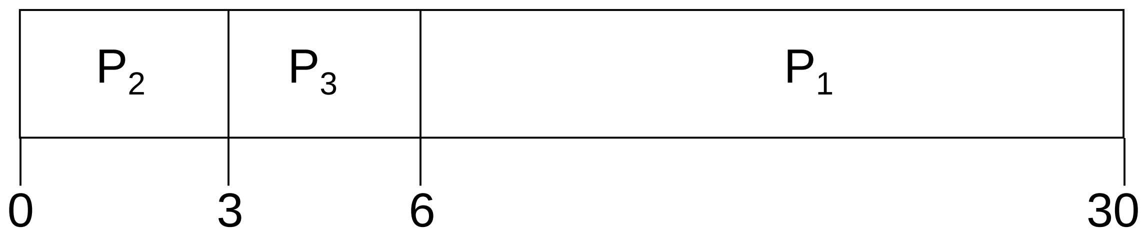
  - Waiting time?
    - P1 = 0; P2 = 24; P3 = 27
  - Average waiting time
    - (0 + 24 + 27)/3 = 17

FCFS

- Example 2

Process	Arrival Time	Burst Time
P1	0	24
P2	0	3
P3	0	3

– Suppose that the processes arrive in the order: P_2 , P_3, P_1



– Waiting time?

- P1 = 6; P2 = 0; P3 = 3

– Average waiting time

- (6 + 0 + 3)/3 = 3

– Much better than previous case → performance varies greatly depending on the scheduling order

Shortest Job First (SJF)

- Can we always do the best FIFO?
  - Yes: **if** you know the tasks' CPU burst times

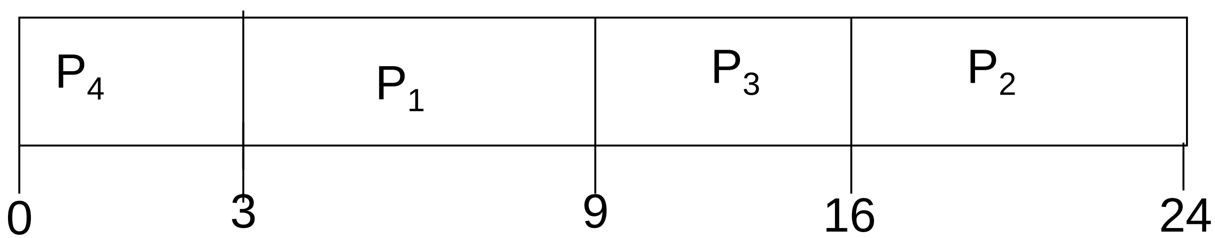
- Shortest Job First (SJF)
  - Order jobs based on their burst lengths
  - Executes the job with the shortest CPU burst first
  - SJF is optimal
    - Achieves minimum average waiting time

Shortest Job First (SJF)

- Example

Process	Arrival Time	Burst Time
P1	0	6
P2	0	8
P3	0	7
P4	0	3

  - Gantt chart



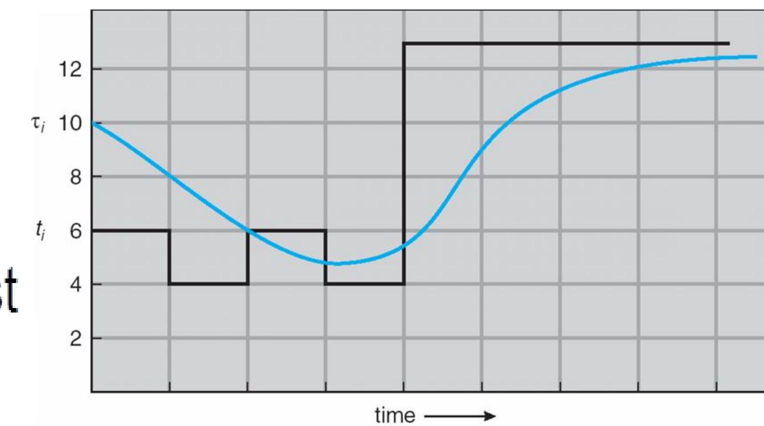
  - Average waiting time?
    - (3 + 16 + 9 + 0) / 4 = 7

- How to know the CPU burst time **in advance**?

Determining CPU Burst Length

- Can only estimate the length
  - Next CPU burst similar to previous CPU bursts ?
  - Predict based on the past history
- Exponential weighted moving average (EWMA)
  - of past CPU bursts

1. $t_n =$ actual length of n^{th} CPU burst
2. $\tau_{n+1} =$ predicted value for the next CPU burst
3. $\alpha, 0 \le \alpha \le 1$
4. Define: $\tau_{n=1} = \alpha\, t_n + (1-\alpha)\tau_n.$



CPU burst (t_i)		6	4	6	4	13	13	13 …
"guess" (τ_i)	10	8	6	6	5	9	11	12 …

Recap

- CPU Scheduling
  - Decides which thread, when, and how long?
- Metrics
  - Turnaround time
    - Time to complete a task (ready -> complete)
  - Waiting time
    - Time spent on waiting in the ready queue
  - Response time
    - Time to schedule a task (ready -> first scheduled)
- FIFO
- SJF

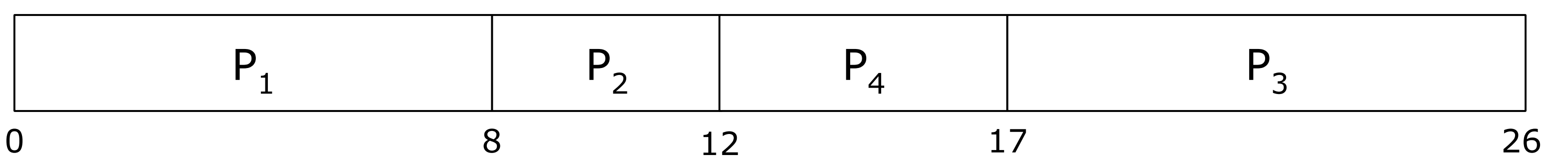
Administrivia

- Project 1 grading policy is updated.
  - Deadline: Tonight
- Quiz1 is posted
  - Chapter 1-4
  - Due: Friday

Shortest Job First (SJF)

- What if jobs don't arrive at the same time?

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	2	9
P4	3	5

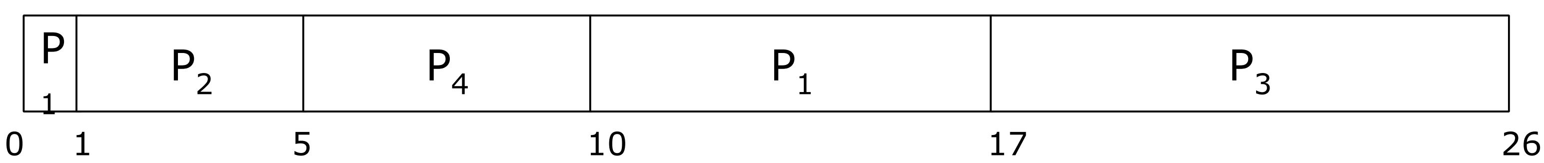


– Average waiting time
  - (0+7+15+8)/4 = 7.5

Shortest Remaining Time First (SRTF)

- Preemptive version of SJF
- New shorter job preempt longer running job

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	2	9
P4	3	5



- Average waiting time
  - (9 + 0 + 15 + 2) / 4 = 6.5

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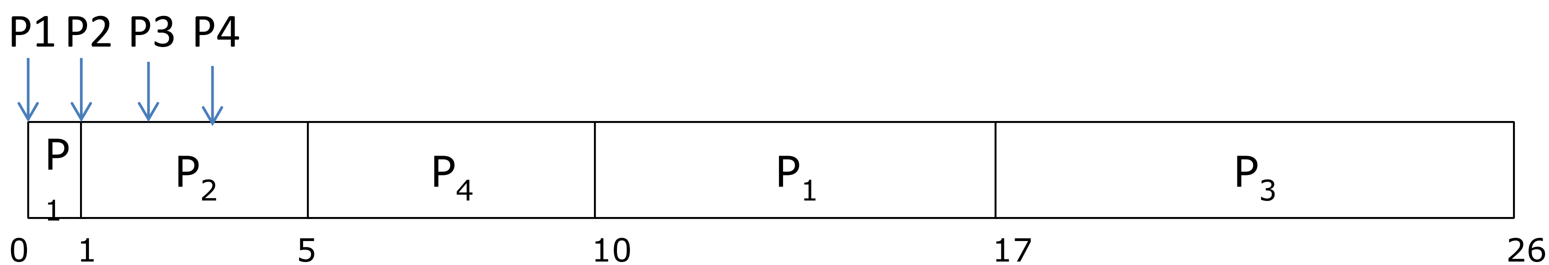
Quiz: SRTF

- Average waiting time?

Process	Arrival Time	Burst Time
P1	0	8
P2	1	4
P3	2	9
P4	3	5



- (9 + 0 + 15 + 2) / 4 = 6.5

Summary

- FIFO
  - In the order of arrival
  - Non-preemptive
- SJF
  - Shortest job first.
  - Non preemptive
- SRTF
  - Preemptive version of SJF

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Issues

- FIFO
  - Bad average turn-around time
- SJF/SRTF
  - Good average turn-around time
  - IF you know or can predict the future
- Time-sharing systems
  - Multiple users share a machine
  - Need high interactivity → low **response time**

Round-Robin (RR)

- FIFO with preemption
- Simple, fair, and easy to implement
- Algorithm
  - Each job executes for a fixed time slice: **quantum**
  - When quantum expires, the scheduler preempts the task
  - Schedule the next job and continue...

Round-Robin (RR)

- Example
  - Quantum size = 4

Process	Burst Times
P1	24
P2	3
P3	3

  - Gantt chart

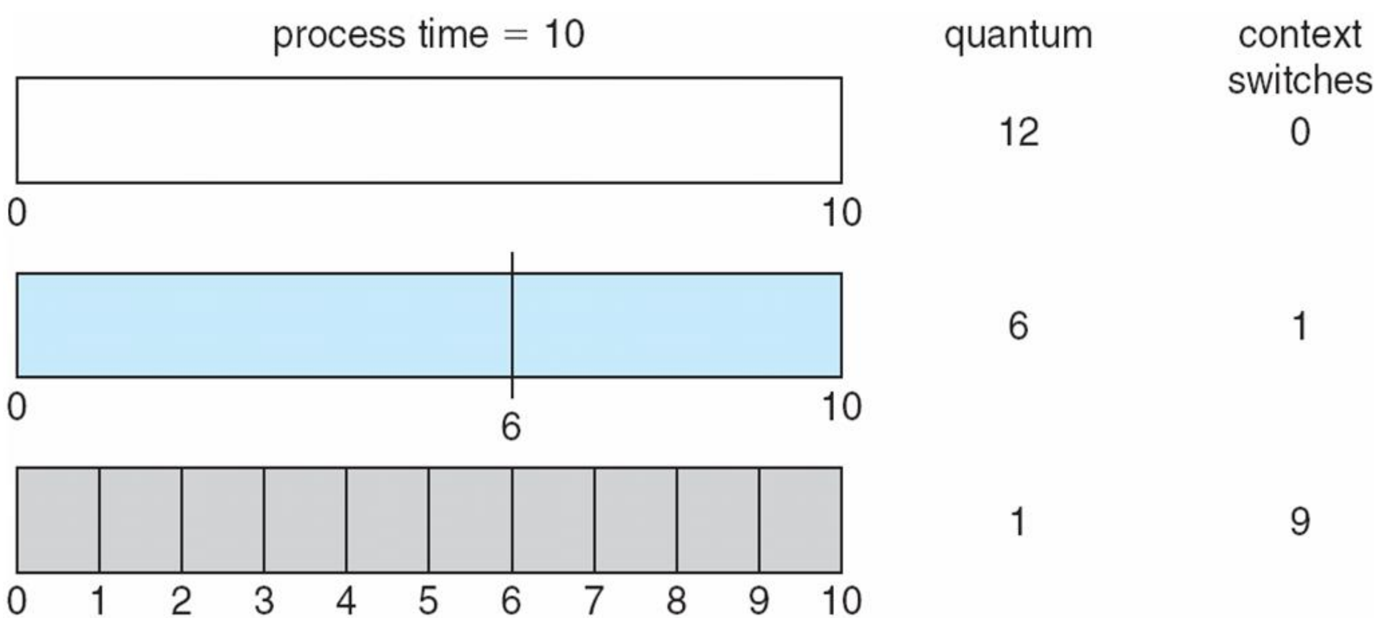
P_1	P_2	P_3	P_1	P_1	P_1	P_1	P_1

0 4 7 10 14 18 22 26 30

  - Response time (between ready to first schedule)
    - P1: 0, P2: 4, P3: 7. average response time = (0+4+7)/3 = 3.67
  - Waiting time
    - P1: 6, P2: 4, P3: 7. average waiting time = (6+4+7)/3 = 5.67

How To Choose Quantum Size?

- Quantum length
  - Too short → high overhead (why?)
  - Too long → bad response time
    - Very long quantum → FIFO

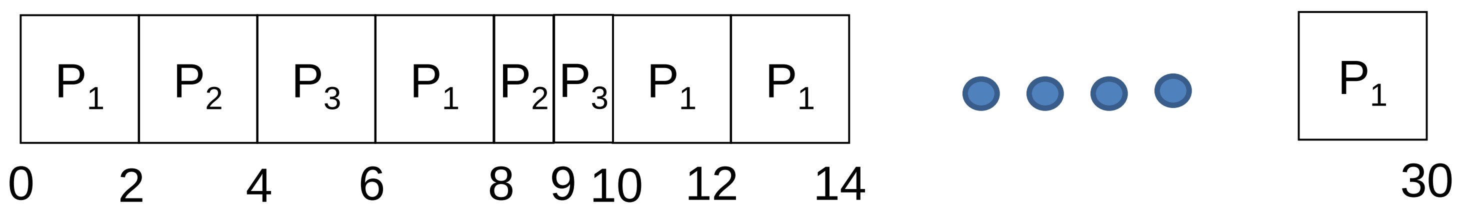


Round-Robin (RR)

- Example
  - Quantum size = 2

Process	Burst Times
P1	24
P2	3
P3	3

  - Gantt chart



  - Response time (between ready to first schedule)
    - P1: 0, P2: 2, P3: 4. average response time = (0+2+4)/3 = 2
  - Waiting time
    - P1: 6, P2: 6, P3: 7. average waiting time = (6+6+7)/3 = 6.33

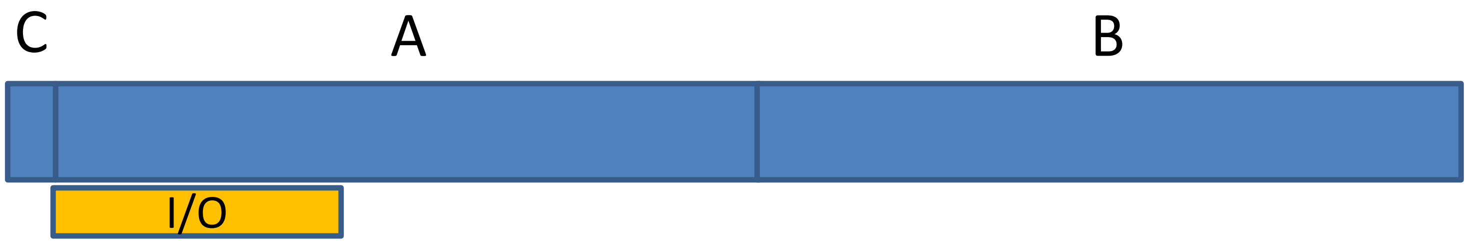
Discussion

- Comparison between FCFS, SRTF(SJF), and RR
  - What to choose for smallest average waiting time?
    - SRTF (SFJ) is the optimal
  - What to choose for better interactivity?
    - RR with small time quantum (or SRTF)
  - What to choose to minimize scheduling overhead?
    - FCFS

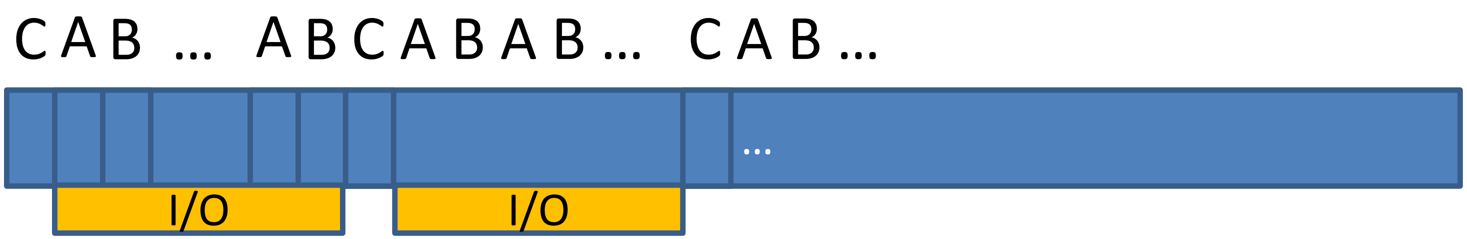
Example

- Task A and B
  - CPU bound, run an hour
- Task C
  - I/O bound, repeat(1ms CPU, 9ms disk I/O)
- FCFS?
  - If A or B is scheduled first, C can begins an hour later
- RR and SRTF?

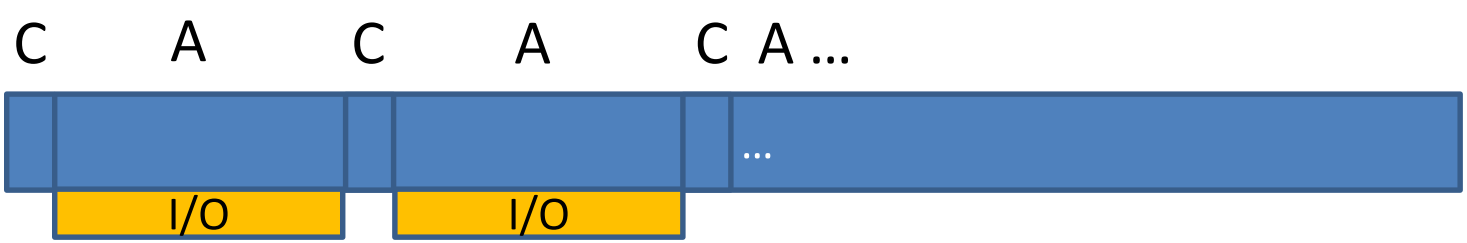
Example Timeline



RR with 100ms time quantum



RR with 1ms time quantum



SRTF

Summary

- First-Come, First-Served (FCFS)
  - Run to completion in order of arrival
  - Pros: simple, low overhead, good for batch jobs
  - Cons: short jobs can stuck behind the long ones
- Round-Robin (RR)
  - FCFS with preemption. Cycle after a fixed time quantum
  - Pros: better interactivity (optimize response time)
  - Cons: performance is dependent on the quantum size
- Shortest Job First (SJF)/ Shorted Remaining Time First (SRTF)
  - Shorted job (or shortest remaining job) first
  - Pros: optimal average waiting time (turn-around time)
  - Cons: you need to know the future, long jobs can be starved by short jobs

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Agenda

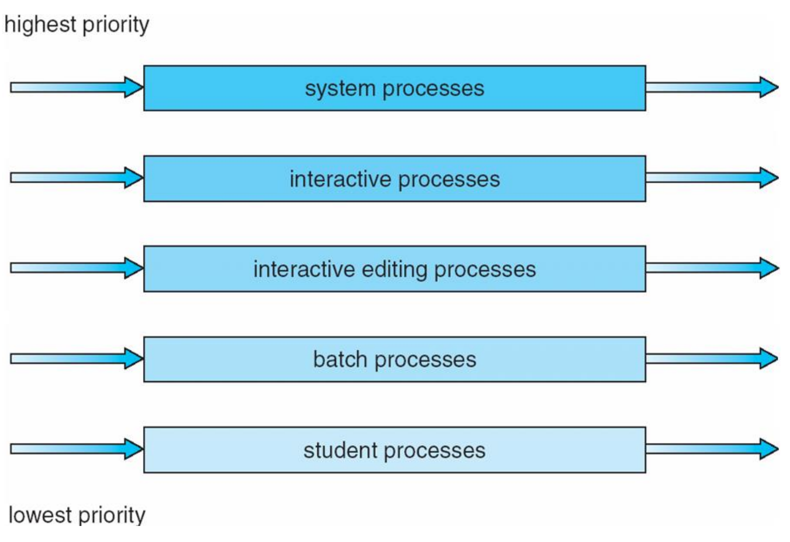
- **Multi-level queue scheduling**
- **Fair scheduling**
- Real-time scheduling
- Multicore scheduling

Multiple Scheduling Goals

- Optimize for interactive applications
  – Round-robin
- Optimize for batch jobs
  – FCFS
- Can we do both?

Multi-level Queue

- Ready queue is partitioned into separate queues
  - Foreground: interactive jobs
  - Background: batch jobs
- Each queue has its own scheduling algorithm
  - Foreground : RR
  - Background: FCFS
- Between the queue?

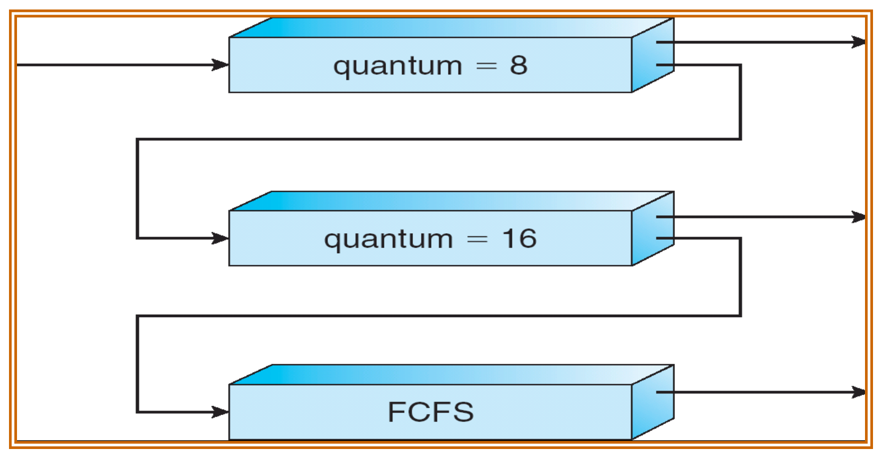


Multi-level Queue Scheduling

- Scheduling between the queues
  - Fixed priority
    - Foreground first; schedule background only when no tasks in foreground
    - Possible starvation
  - Time slicing
    - Assign fraction of CPU time for each queue
    - 80% time for foreground; 20% time for background

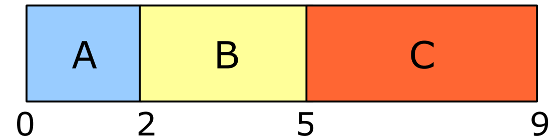
Multi-level Feedback Queue

- Each queue has a priority
- Tasks migrate across queues
  - Each job starts at the highest priority queue
  - If it uses up an entire quantum, drop one-level
  - If it finishes early, move up one-level (or stay at top)
- Benefits
  - Interactive jobs stay at high priority queues
  - Batch jobs will be at the low priority queue
  - **Automatically!**



Example of Multilevel Feedback Queues

time = 0

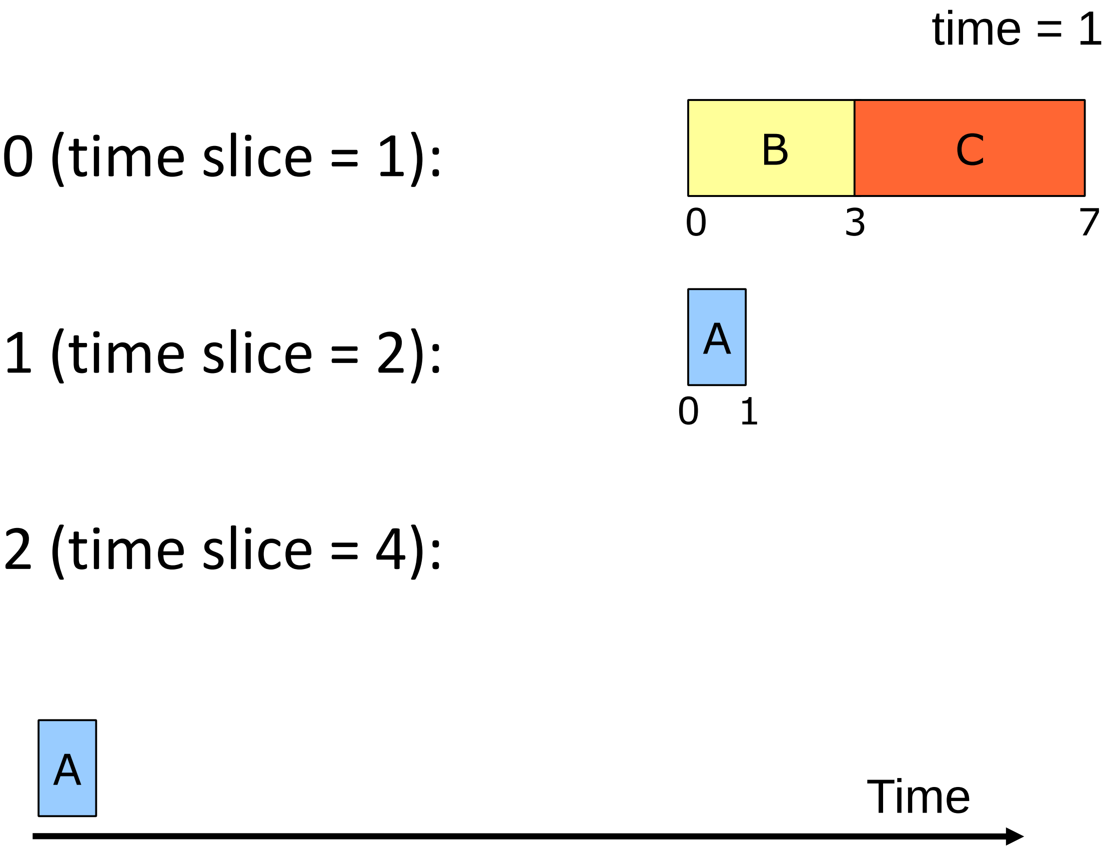


- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):

Time

Example of Multilevel Feedback Queues

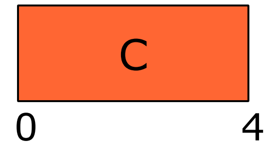
- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):



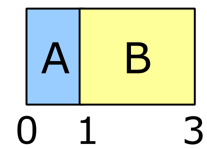
Example of Multilevel Feedback Queues

time = 2

- Priority 0 (time slice = 1):



- Priority 1 (time slice = 2):

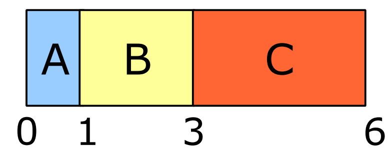


- Priority 2 (time slice = 4):

Example of Multilevel Feedback Queues

time = 3

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):

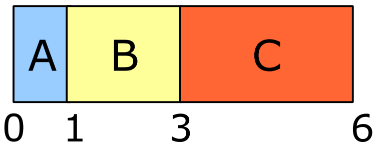


- Priority 2 (time slice = 4):

Example of Multilevel Feedback Queues

time = 3

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):



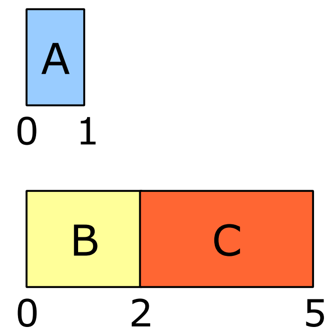
- Priority 2 (time slice = 4):

Suppose A is blocked on I/O

Example of Multilevel Feedback Queues

time = 3

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):

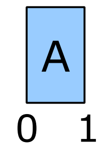


Suppose A is blocked on I/O

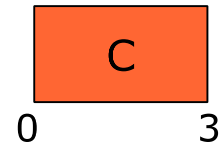
Example of Multilevel Feedback Queues

time = 5

- Priority 0 (time slice = 1):



- Priority 1 (time slice = 2):



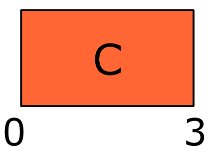
- Priority 2 (time slice = 4):

Suppose A is returned from I/O

Example of Multilevel Feedback Queues

time = 6

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):

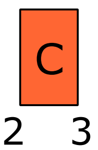


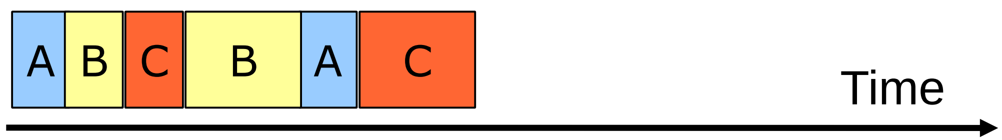
- Priority 2 (time slice = 4):

Example of Multilevel Feedback Queues

time = 8

- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):

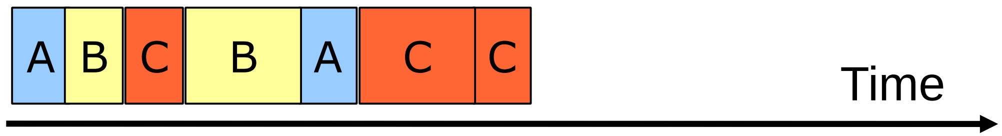




Example of Multilevel Feedback Queues

time = 9

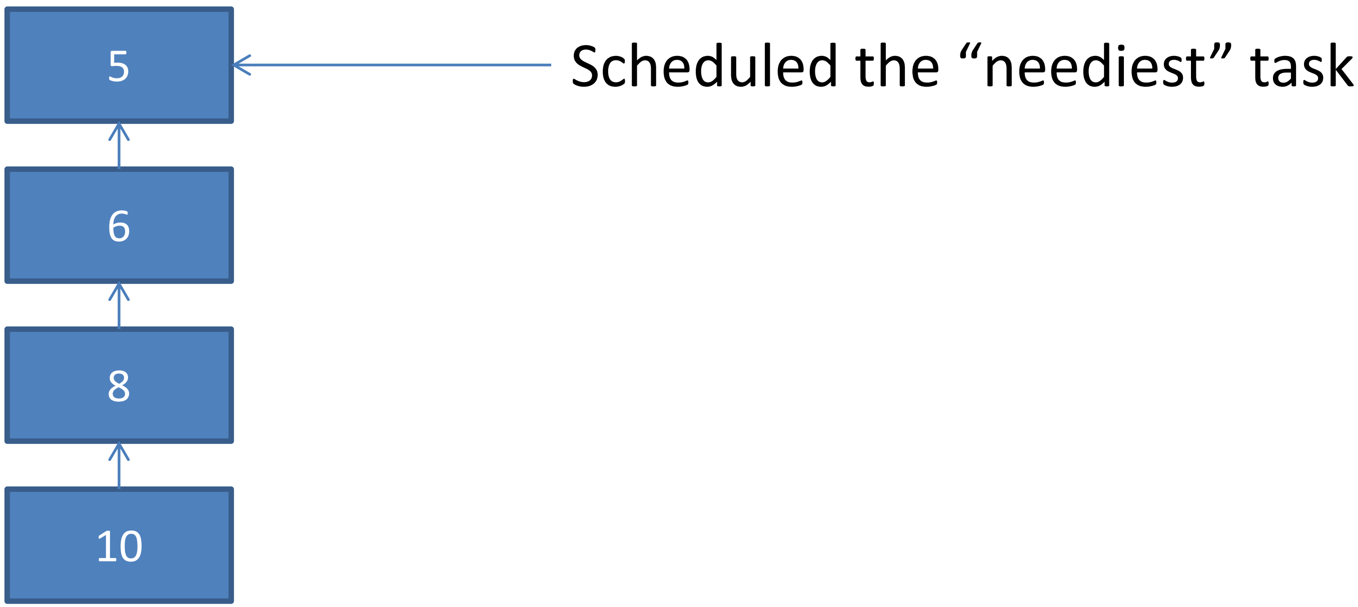
- Priority 0 (time slice = 1):
- Priority 1 (time slice = 2):
- Priority 2 (time slice = 4):



Completely Fair Scheduler (CFS)

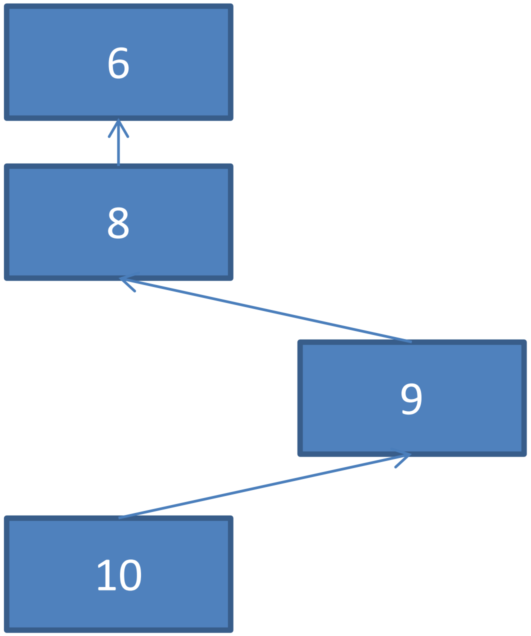
- Linux default scheduler, focusing on **fairness**
- Each task owns a fraction of CPU time share
  - E.g.,) A=10%, B=30%, C=60%
- Scheduling algorithm
  - Each task maintains its virtual runtime
    - Virtual runtime = executed time (x weight)
  - Pick the task with the **smallest virtual runtime**
    - Tasks are sorted according to their virtual times
  - Time slice varies depending on the #of tasks
    - Slice = target_latency / #of tasks

CFS Example



- Tasks are sorted according to their virtual times

CFS Example



On a next scheduler event **re-sort** the list

But list is inefficient.

- Tasks are sorted according to their virtual times

Red-black Tree

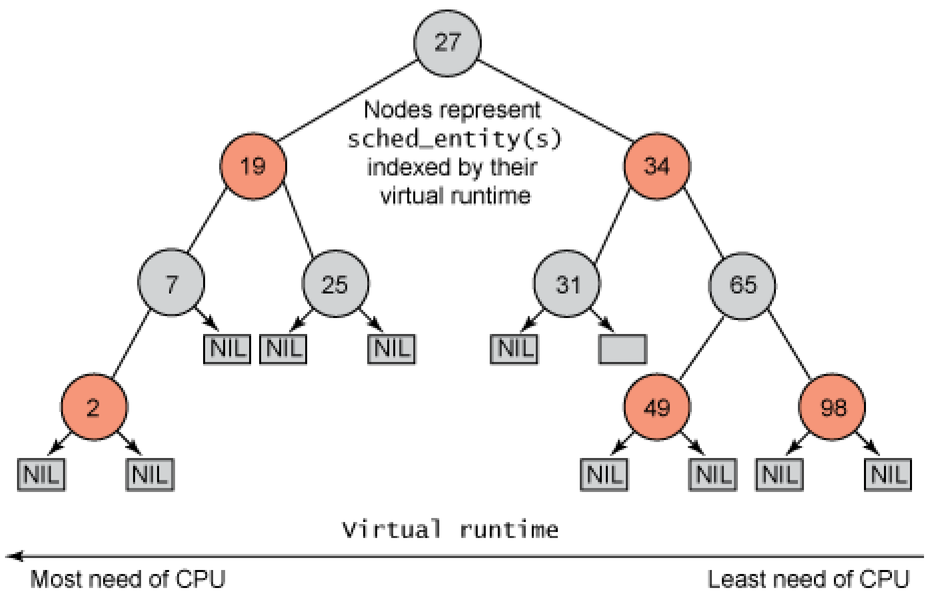
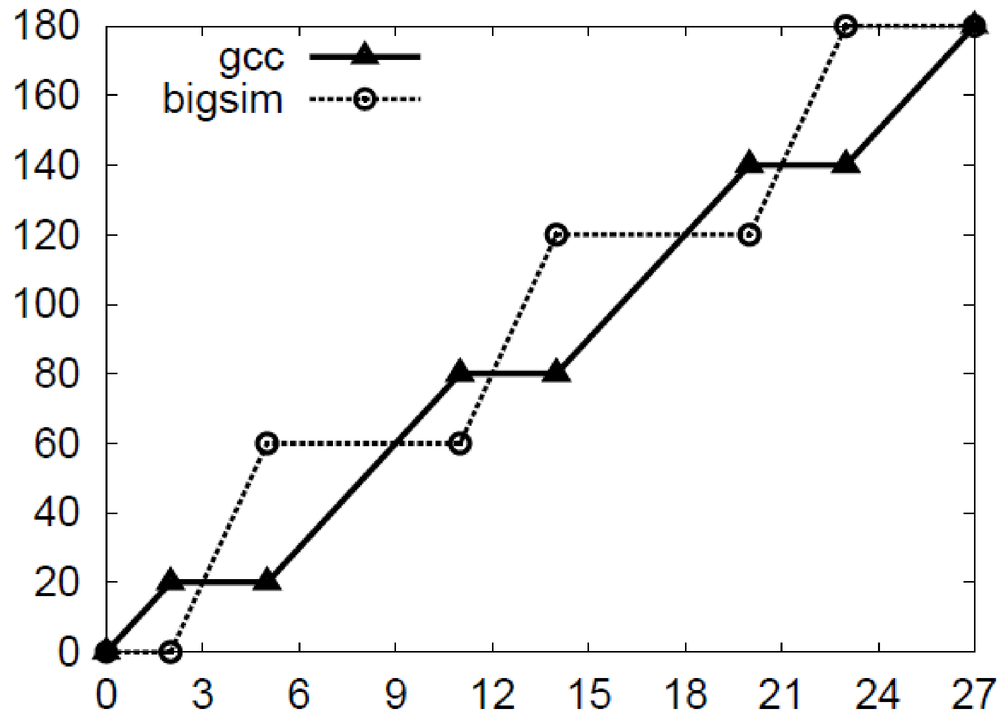


Figure source: M. Tim Jones, [“Inside the Linux 2.6 Completely Fair Scheduler”](), IBM developerWorks

– Self-balancing binary search tree
– Insert: O(log N), Remove: O(1)

Weighed Fair Sharing: Example



Weights: gcc = 2/3, bigsim=1/3

X-axis: mcu (tick), Y-axis: virtual time

Fair in the long run

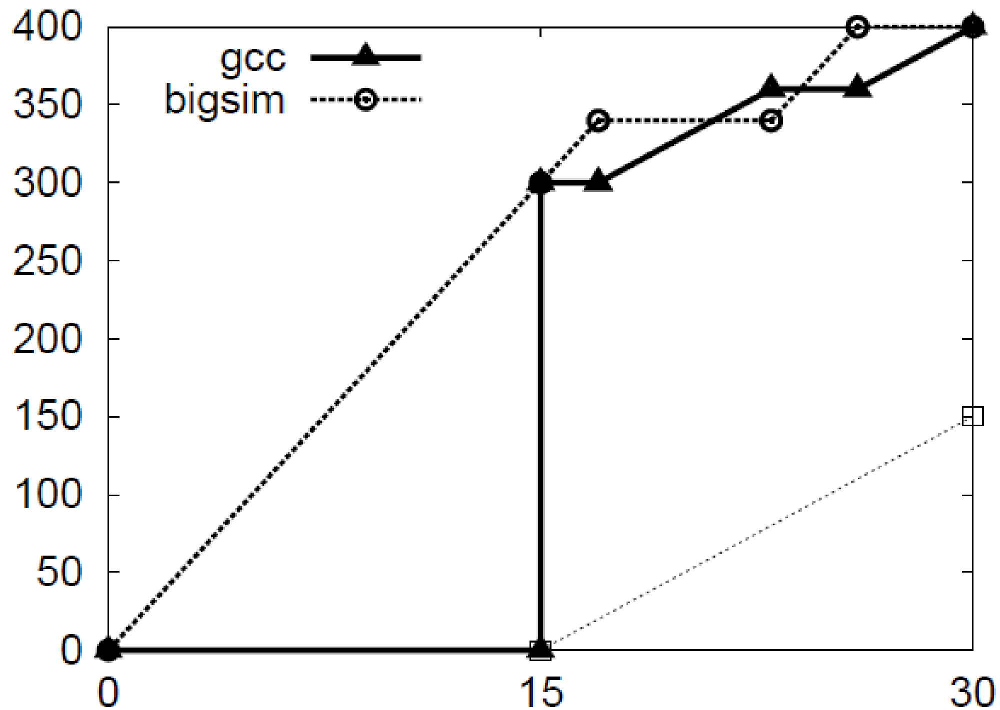
Recap

- Multi-level queue scheduling
  - Multiple scheduling policies
    - RR for interactive tasks
    - FCFS for batch tasks
  - Multi-level feedback queue scheduling
    - Tasks automatically migrate among the queues
- CFS
  - Fair sharing of CPU time
  - Based on (virtual) runtime of each task

Some Edge Cases

- How to set the virtual time of a new task?
  - Can’t set as zero. Why?
  - System virtual time (SVT)
    - The minimum virtual time among all active tasks
    - cfs_rq->min_vruntime
  - The new task can “catch-up” tasks by setting its virtual time with SVT

Weighed Fair Sharing: Example 2



Weights: gcc = 2/3, bigsim=1/3

X-axis: mcu (tick), Y-axis: virtual time

gcc slept 15 mcu

Real-Time Systems

- The correctness of the system depends not only on the logical result of the computation but also on the time at which the results are produced.
- **A correct value at the wrong time is a fault.**

- Processes attempt to control or react to events that take place in the outside world
- These events occur in “real time” and tasks must be able to keep up with them
- Processes are associated with timing constraints (deadlines)

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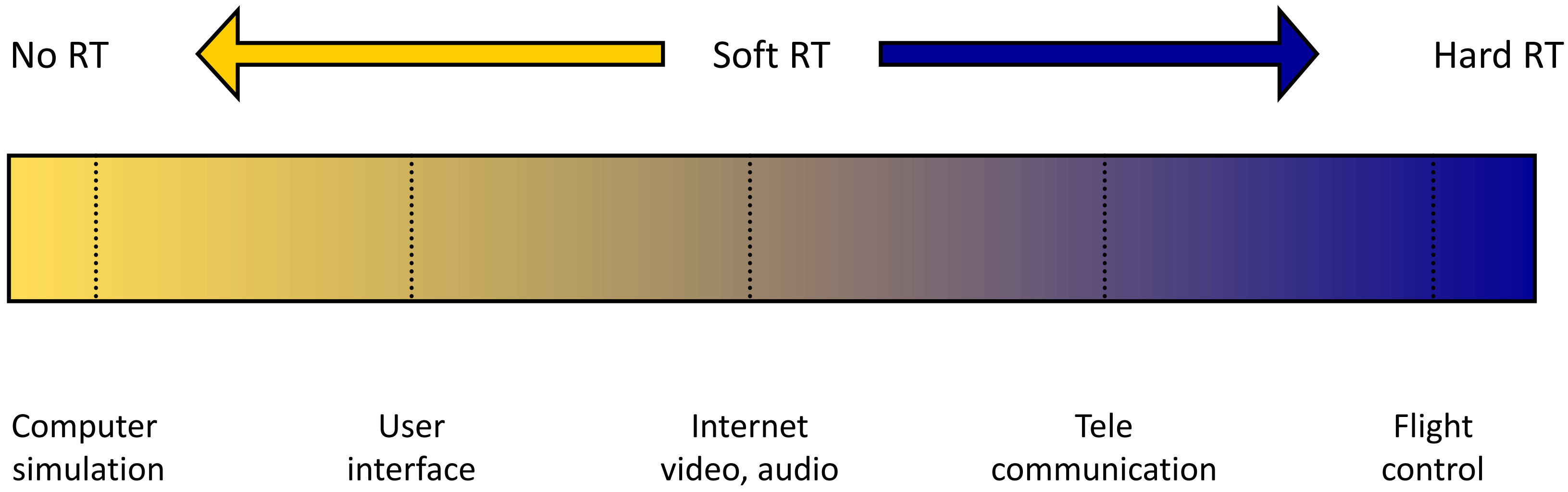
Real-Time Spectrum



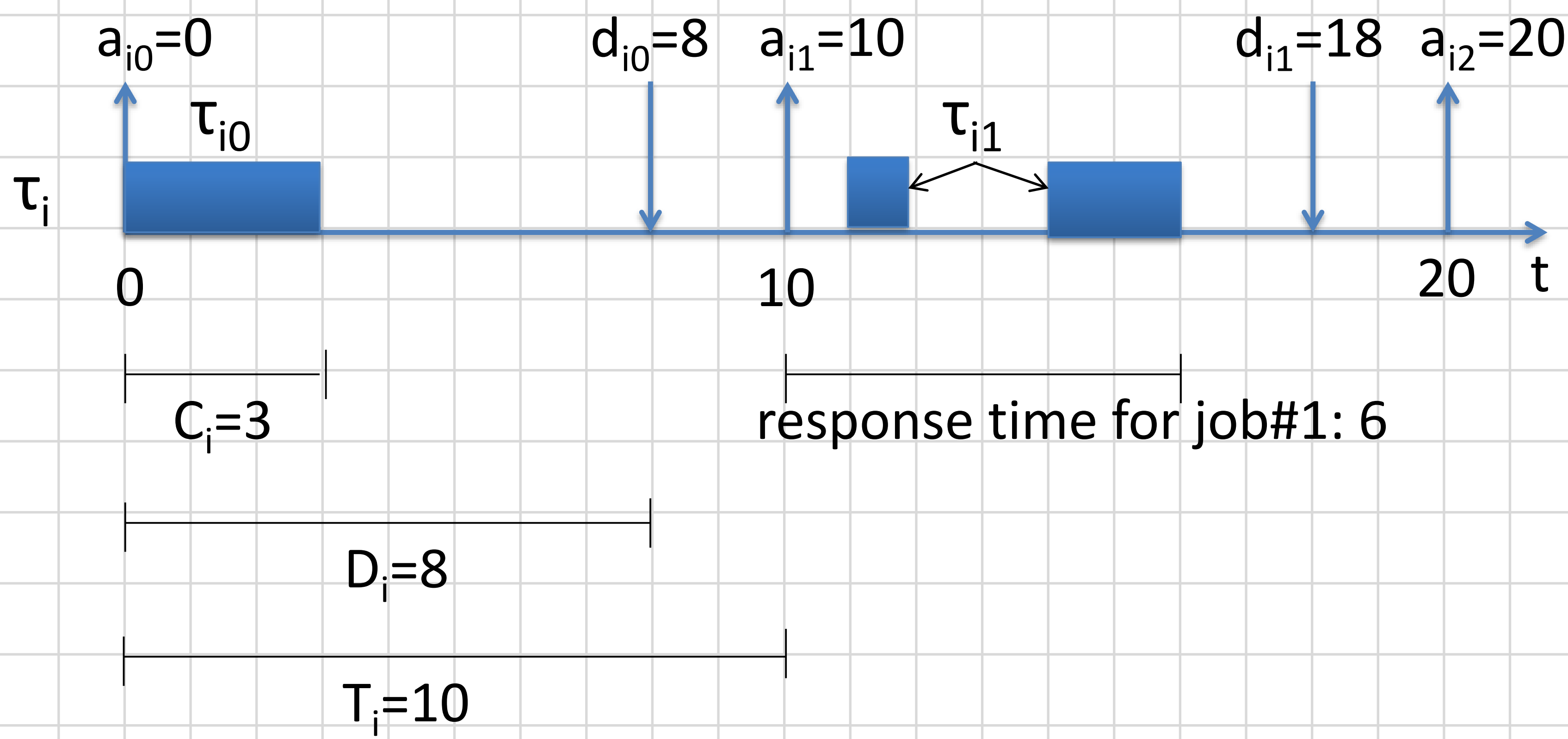
Real-Time Scheduling

- Goal: meet the deadlines of important tasks
  - **Soft** deadline: game, video decoding, …
  - **Hard** deadline: engine control, anti-lock break (ABS)
    - 100 ECUs (processors) in BMW i3 [*]

- Priority scheduling
  - A high priority task preempts lower priority tasks
  - Static priority scheduling
  - Dynamic priority scheduling

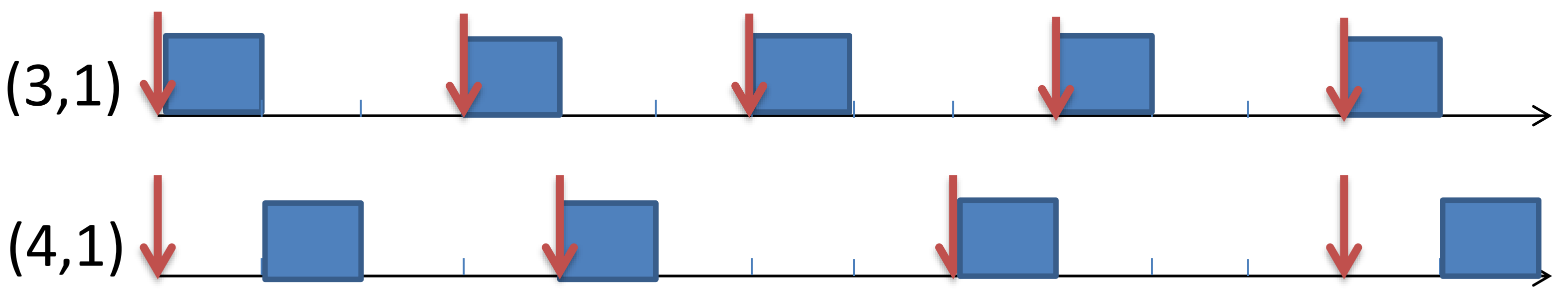
[*] Robert Leibinger, "Software Architectures for Advanced Driver Assistance Systems (ADAS)", OSPERT'15 keynote

Periodic Task Model



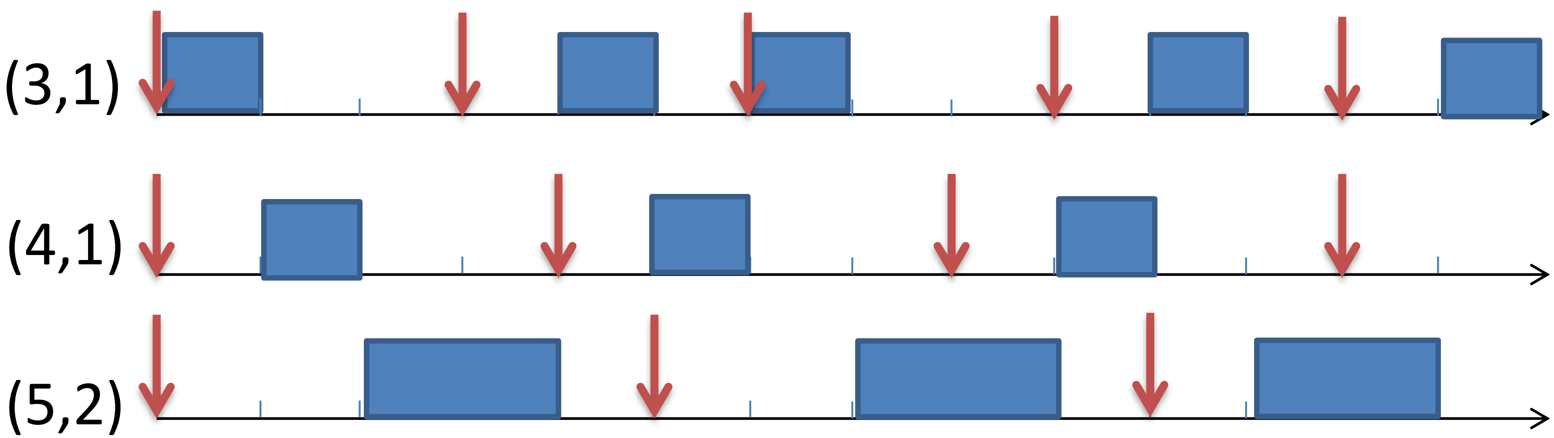
Rate Monotonic (RM)

- Priority is assigned based on **periods**
  - Shorter period -> higher priority
  - Longer period -> lower priority
- Optimal static-priority scheduling

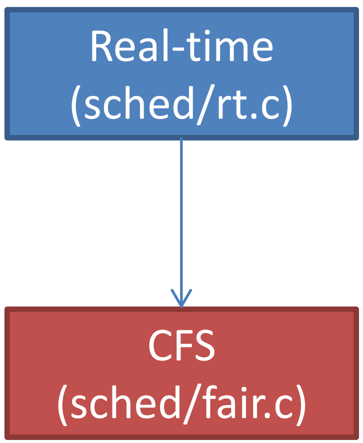


Earliest Deadline First (EDF)

- Priority is assigned based on deadline
  - Shorter deadline → higher priority
  - Longer deadline → lower priority
- Optimal dynamic priority scheduling



Linux Scheduling Framework



- First, schedule real-time tasks
  - Real-time schedulers: (1) Priority based, (2) deadline based
- Then schedule normal tasks
  - Completely Fair Scheduler (CFS)

- Two-level queue scheduling
  - Between queues?

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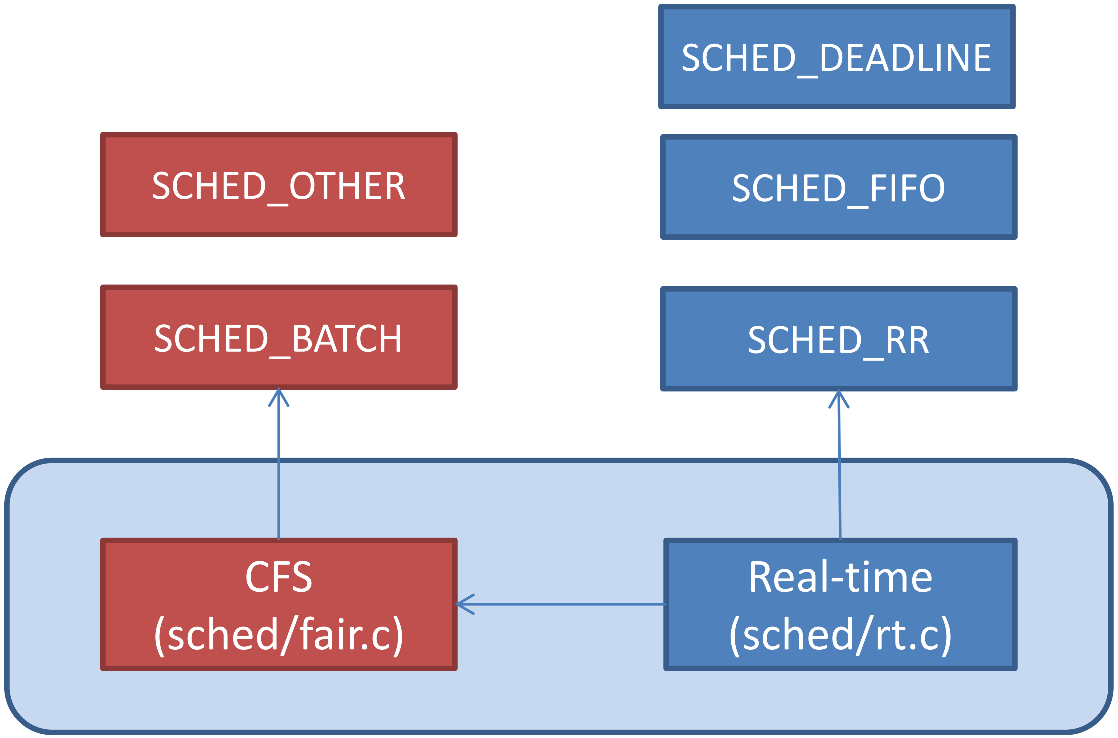
Linux Scheduling Framework

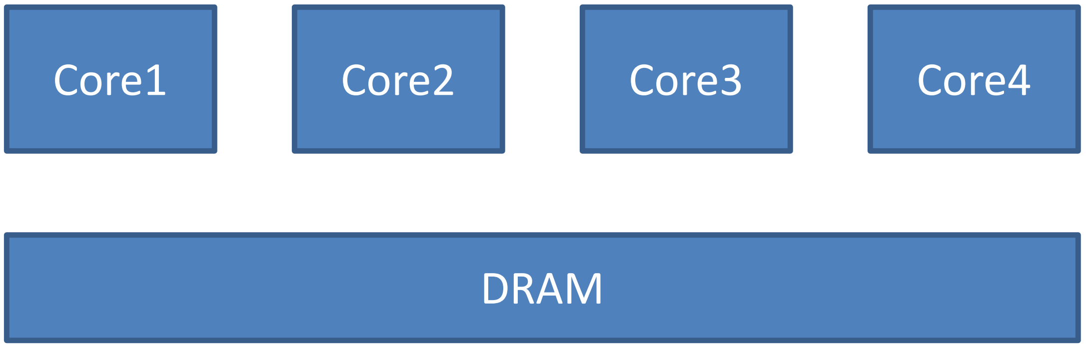


- Completely Fair Scheduler (CFS)
  - SCHED_OTHER, SCHED_BATCH
- Real-time Schedulers
  - SCHED_DEADLINE, SCHED_FIFO, SCHED_RR

Real-Time Schedulers in Linux

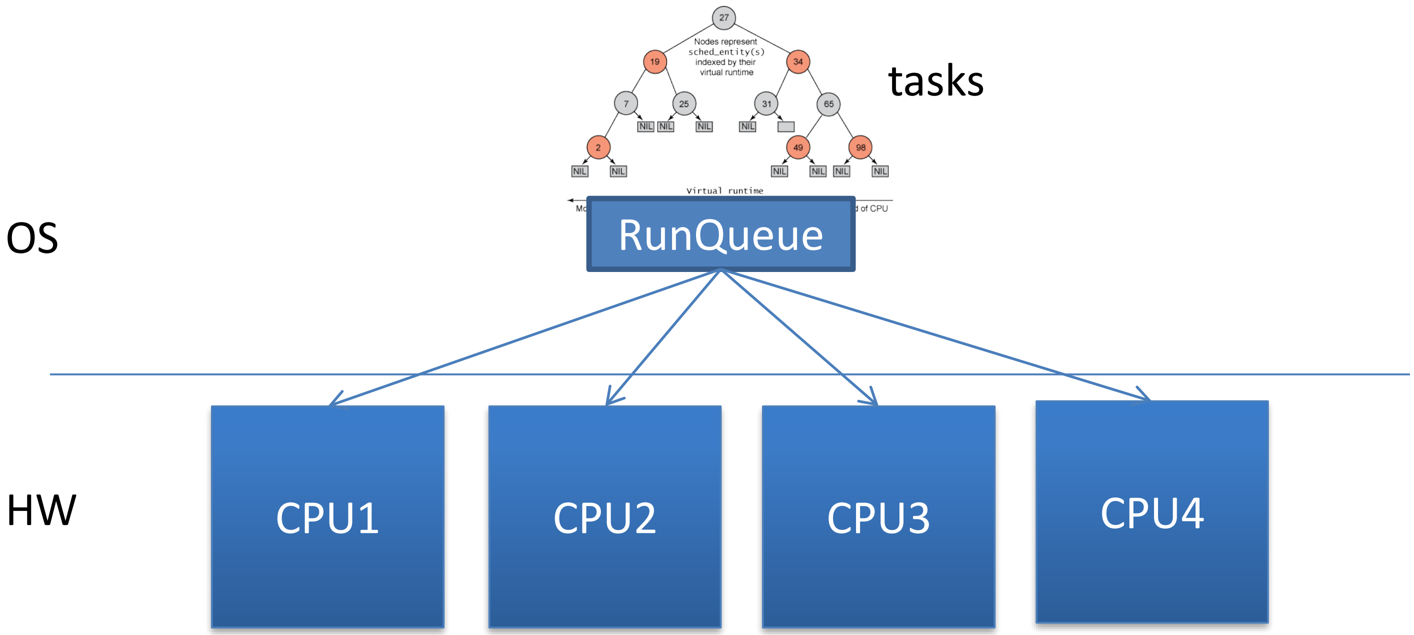
- SCHED_FIFO
  - Static priority scheduler
- SCHED_RR
  - Same as SCHED_FIFO except using RR for tasks with the same priority
- SCHED_DEADLINE
  - EDF scheduler
  - Recently merged in the Linux mainline (v3.14)

Multiprocessor Scheduling

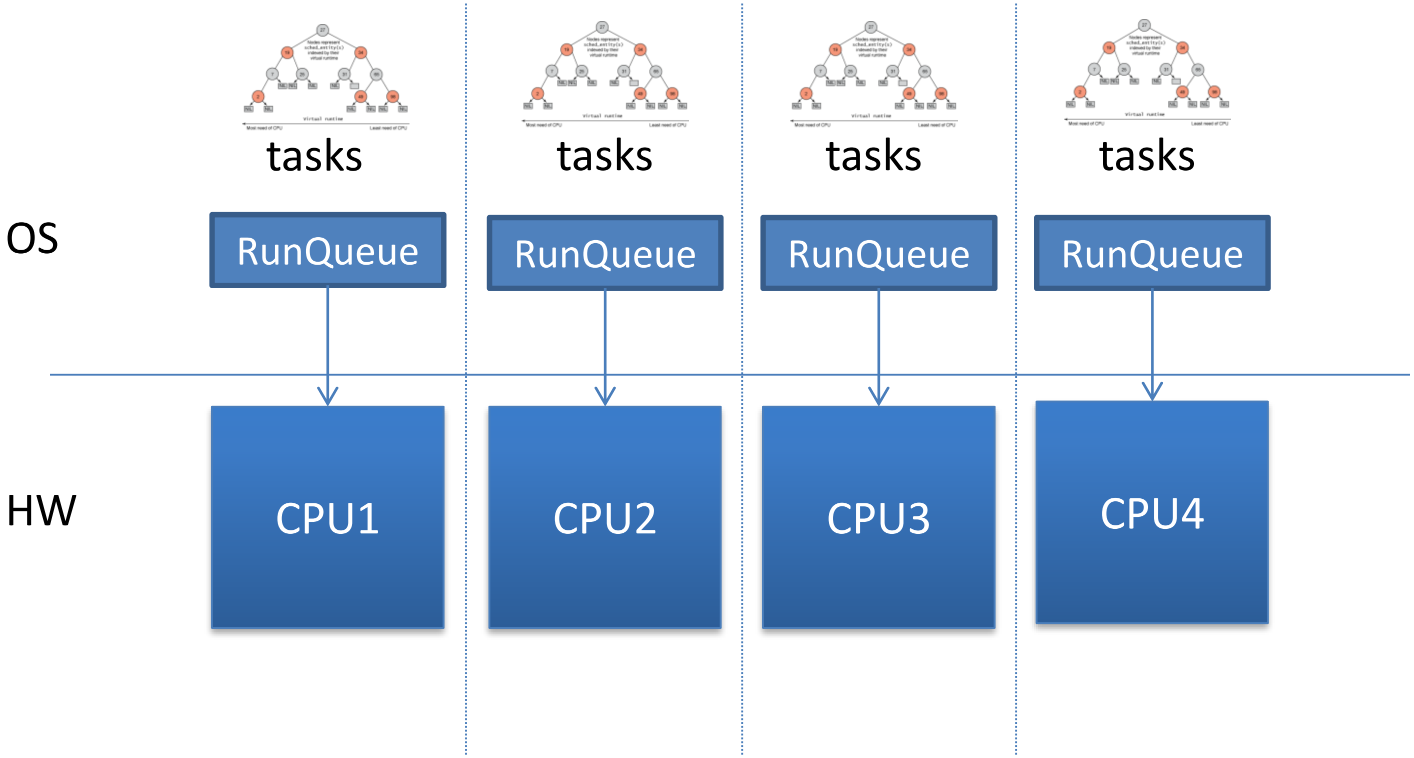


- How many scheduling queues are needed?
  - Global shared queue: all tasks are placed in a single shared queue (global scheduling)
  - Per-core queue: each core has its own scheduling queue (partitioned scheduling)

Global Scheduling



Partitioned Scheduling



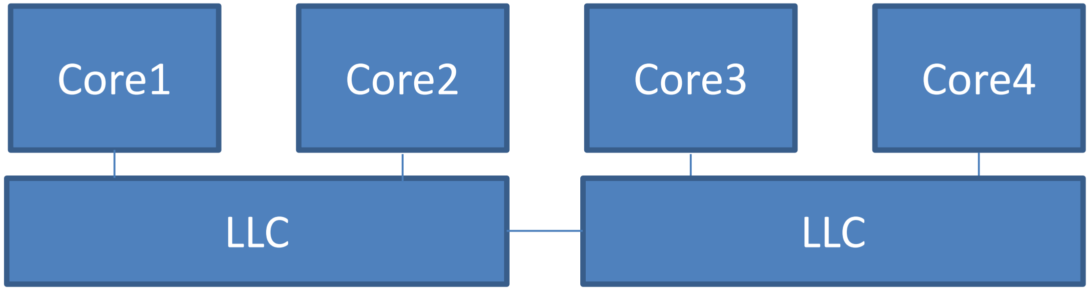
- Linux's basic design. Why?

Load Balancing

- Undesirable situation
  – Core 1’s queue: 40 tasks
  – Core 2’s queue: 0 task
- Load balancing
  – Tries to balance load across all cores.
  – Not so simple, why?
    - Migration overhead: cache warmup

Load Balancing

- More considerations
  - What if certain cores are more powerful than others?
    - E.g., ARM bigLITTLE (4 big cores, 4 small cores)
  - What if certain cores share caches while others don't?



  - Which tasks to migrate?
    - Some tasks may compete for limited shared resources

Summary

- Multi-level queue scheduling
  - Each queue has its own scheduler
  - Scheduling between the queues
- Fair scheduling (CFS)
  - Fairly allocate CPU time across all tasks
  - Pick the task with the smallest virtual time
  - Guarantee fairness and bounded response time
- Real-time scheduling
  - Static priority scheduling
  - Dynamic priority scheduling

Summary

- Multicore scheduling
  - Global queue vs. per-core queue
    - Mostly per-core queue due to scalability
  - Load balancing
    - Balance load across all cores
    - Is complicated due to
      - Migration overhead
      - Shared hardware resources (cache, dram, etc)
      - Core architecture heterogeneity (big cores vs. small cores)
      - …

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