Scheduling (ch 7+8+9)

Operating Systems
Based on: Three Easy Pieces by Arpaci-Dusseaux

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Scheduling Policy

- How to switch processes? **mechanism**
- When to switch? **policy**

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- When to switch? **policy**

- **Scheduling policy**

On context switch, which process to run next?

Definitions

- **Job**: what we schedule (i.e., processes)
- **Workload**: set of job descriptions
- **Scheduler**: logic that decides when jobs run
- **Metric**: measurement of scheduling quality

Scheduling Metrics

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  - $T_{turnaround} = T_{completion} - T_{arrival}$

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- **Turnaround time**
  - Time from job **arrival** to **completion**
  - $T_{turnaround} = T_{completion} - T_{arrival}$
- **Fairness**
  - Jobs get same amount of CPU
  - Performance and fairness are often at odds

Workload Assumptions

(Assumption are not realistic)

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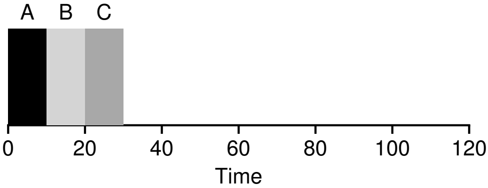
2. All jobs arrive at the same time
3. Once started, each job runs to completion
4. All jobs only use the CPU (i.e., no I/O)
5. The run-time of each job is known

First In, First Out (FIFO)

- Also: **First Come, First Served (FCFS)**
  - Simple and easy to implement
- Example: A, B, and C run for 10 seconds each



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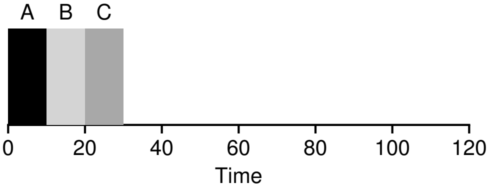

- What is the average turnaround time?

Average turnaround $= \frac{10+20+30}{3} = 20$ sec

First In, First Out (FIFO)

- Relax assumption 1 (~~each job runs for the same amount of time~~)
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Average turnaround $= \frac{100+110+120}{3} = 110$ sec

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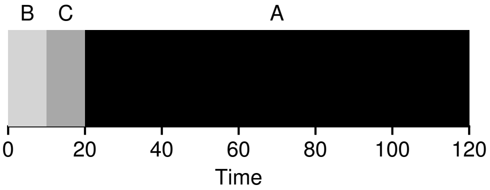
Average turnaround $= \frac{100+110+120}{3} = 110$ sec

Ideal turnaround $= \frac{10+20+120}{3} = 50$ sec

- What should we do?

Shortest Job First (SJF)

- Run shortest job first, then next shortest, and so on
- Previous example:



Average turnaround $= \frac{10+20+120}{3} = 50$ sec

Shortest Job First (SJF)

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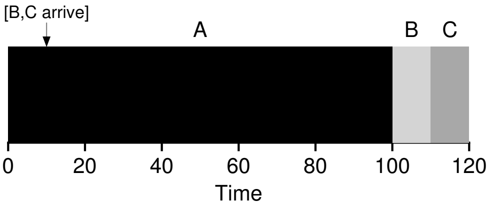
- Example:

Shortest Job First (SJF)

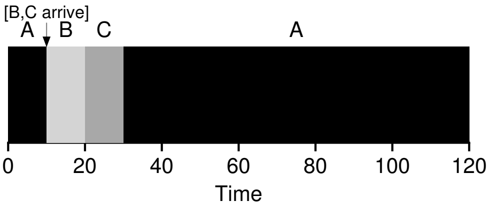
- Relax assumption 2 (~~all jobs arrive at the same time~~)
- Example:
  - A arrives at $t = 0$, needs to run for 100 seconds
  - B & C arrive at $t = 10$, need to run for 10 seconds each



Average turnaround $= \frac{100+100+110}{3} = 103.33$ sec

Shortest Time-to-Completion First (STCF)

- Relax assumption 3 (~~once started, each job runs to completion~~)
- When a new job arrives: schedule job with least time left
- STCF is a **preemptive** scheduler
  - Can **preempt** A to run another job, continuing A later
  - In contrast, SJF is **non-preemptive** (by definition)



Average turnaround $= \frac{120+10+20}{3} = 50$ sec

New Scheduling Metric

- **Response time**
  - Time from job arrival to first scheduling
  - $T_{response} = T_{firstrun} - T_{arrival}$
  - Important for interactive performance (user interaction)
- STCF: not good for response time

How can we build a scheduler that is sensitive to response time?

Round Robin

- Run job for a **time slice** (**scheduling quantum**)
- Then switch to the next job
- Repeat until jobs are finished

Good for response time and fairness,
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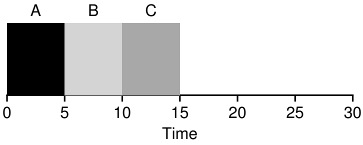
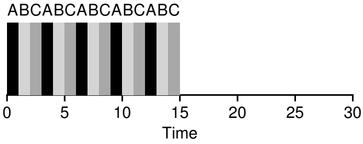
- Example: A, B and C arrive at the same time
- Each wish to run for 5 seconds

Round Robin



SJF (Bad for Response Time)



RR (Good for Response Time)

Round Robin

- Shorter time slice
  - Better response time
  - Cost of context switch dominates performance
- Longer time slice
  - Amortize cost of switching
  - Worse response time

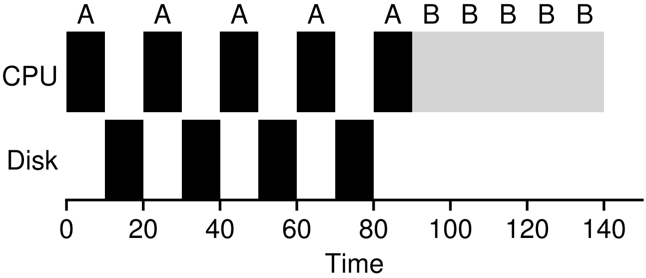
Incorporating I/O

- Relax assumption 4 (~~All jobs only use the CPU~~)
- A job initiates an I/O request
  - Won't be using the CPU; it is **blocked**
  - Scheduler should probably schedule another job
- When the I/O completes
  - An interrupt is raised
  - Moves from **blocked** to **ready**

- Example:
  - A and B need 50ms of CPU time each
  - Each 10ms, A issues an I/O request of 10ms
  - B performs no I/O

Incorporating I/O

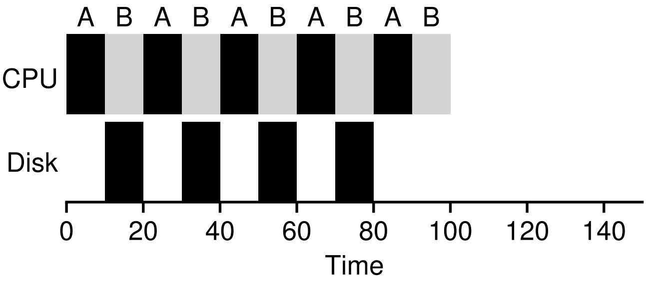
- A runs first, then B after:



Poor use of resources

Incorporating I/O

- STCF scheduler
  - Common approach: treat each sub-job as independent job
  - A is broken up into five 10ms jobs
  - Allows for **overlap** of jobs



Overlap allows better use of resources

No More Oracle

- Relax final assumption (~~the run-time of each job is known~~)
  - Likely the worst assumption we made
  - OS usually knows very little about the length of each job

  - Use recent past to predict the future

Multi-Level Feedback Queue

- Optimize **turnaround time**
  - By running shorter jobs first
  - But the OS doesn't know how long a job will run for
- Make the system feel responsive
  - Minimize **response time**
  - But Round Robin is terrible for turnaround time

How can we design a scheduler without *a priori* knowledge of job length?

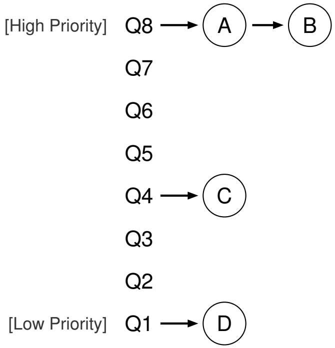
Multi-Level Feedback Queue

- A number of **queues**
- Each assigned a different **priority level**
- Each **ready** job is on a single queue
- MLFQ chooses to run a job with higher priority
  - On a higher queue
  - Round-robin scheduling among jobs with same priority

Rule 1: If Priority(A) $>$ Priority(B), A runs (B doesn't)
Rule 2: If Priority(A) $=$ Priority(B), A & B run in RR

Multi-Level Feedback Queue

- The key: how the scheduler sets priorities
  - Job repeatedly waits for keyboard input:
    - Priority high, interactive process
  - Job uses the CPU intensively for long periods
    - Reduce its priority

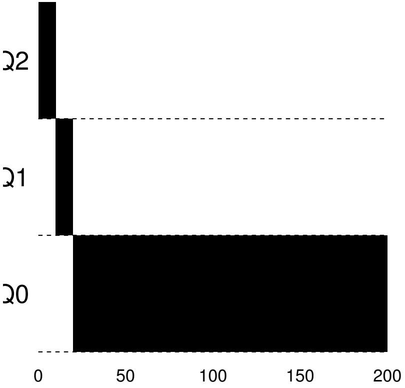


How To Change Priority

- Let's attempt the following:
  - **Rule 3**: A job enters the system $\rightarrow$ highest priority
  - **Rule 4a**: Job uses entire time slice $\rightarrow$ reduce priority
  - **Rule 4b**: Job gives up CPU $\rightarrow$ stay at the same priority

A Single, Long-Running Job

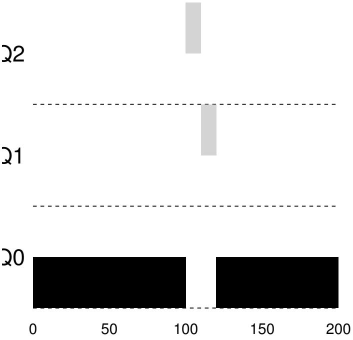
- Three-queue scheduler, 10ms time slice



Along Came A Short Job

MLFQ approximates SJF:

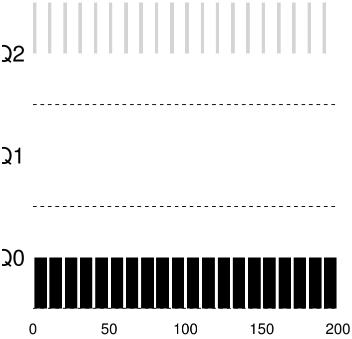
- B: short-running interactive job



- Assume short job, slowly move down the queues if not

What About I/O?

- B needs the CPU for 1ms before performing I/O
  - Same priority by Rule 4b



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    - Before time slice is over, issue I/O operation
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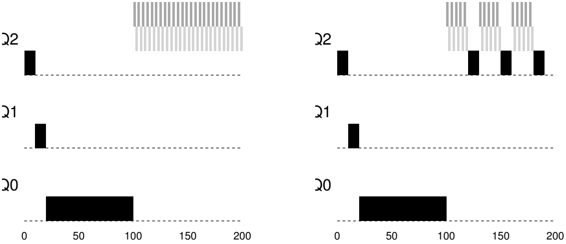
- This approach has serious flaws
  - **Starvation**
    - Too many interactive jobs consume all CPU time
  - **Game the scheduler**
    - Before time slice is over, issue I/O operation
    - Remain in same queue, gain higher percentage of CPU time
  - Change behavior over time
    - Start as CPU-bound, transition to interactivity

The Priority Boost

- Let's make another attempt:
  - **Rule 5**: After some time period, all jobs $\rightarrow$ topmost queue
- Solves two problems at once:
  - Guaranteed not to starve
  - CPU-bound job that becomes interactive is treated properly

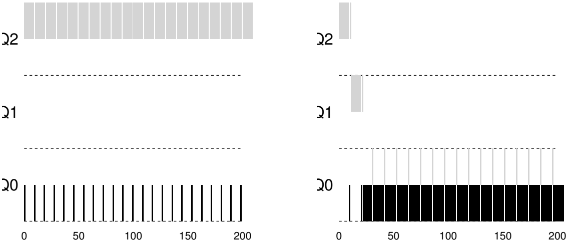


Without (Left) and With (Right) Priority Boost

Better Accounting

- How to prevent gaming of our scheduler?
  - Rules 4a and 4b are the culprits
  - Perform better **accounting** of CPU time

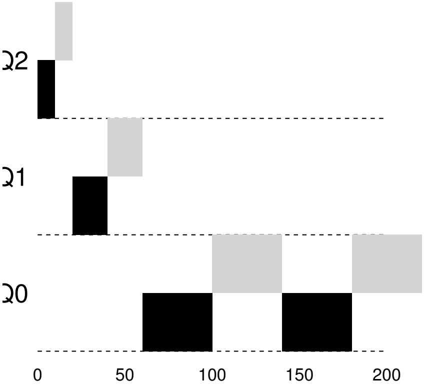
  - **Rule 4**: Job used up time allotment → reduce priority
    - Regardless of how many times it has given up the CPU



Without (Left) and With (Right) Gaming Tolerance

Tuning

- Varying time-slice lengths
  - High priority queues: short time slices
  - Low priority queues: longer time slices



MLFQ: Summary

- **Rule 1**: If Priority(A) $>$ Priority(B), A runs (B doesn't)
- **Rule 2**: If Priority(A) $=$ Priority(B), A & B run in RR
- **Rule 3**: A job enters the system $\rightarrow$ highest priority
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- **Rule 5**: After some time period, all jobs $\rightarrow$ topmost queue

Proportional Share Scheduler

- **Fair-share** scheduler
  - Instead of optimizing turnaround and response time
  - Try to guarantee each job a certain percentage of CPU time
- An early example: **lottery scheduling**
  - Every so often, hold a lottery to determine next process

How to design a scheduler to share the CPU in a proportional manner?

Tickets

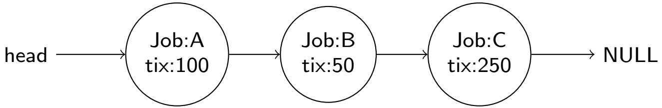
- Each job has a number of **tickets**
- Percent of tickets represents share of CPU it should receive:
  - A has 75 tickets, B has 25 tickets
  - A receives 75% of CPU, B receives 25%
- Lottery scheduling: probabilistic
  - Hold a lottery every time slice

Tickets

- **Ticket currency**
  - User allocates tickets among its jobs how they would like
  - The system converts the currency to the global value
- **Ticket transfer**
  - A job can temporarily hand off its tickets to another job
  - e.g., a client handing its tickets to a server
- **Ticket inflation**
  - A job temporarily raises or lower the number of tickets it owns
  - Only for non-competitive scenarios

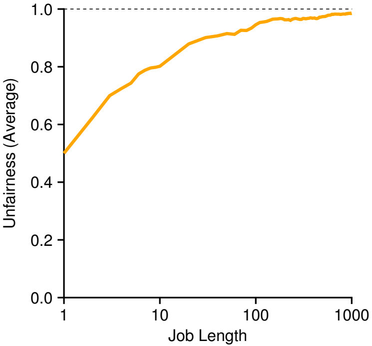
Implementation

- Example: keep processes in a list



Implementation

- **Unfairness metric**
  - The time the first job completes divided by the time the second job completes
  - For example: two jobs with runtime 10 in FCFS: $\frac{10}{20} = 0.5$



Why Not Deterministic?

- For determinism: **stride scheduling**
  - Each job has a **stride**, inverse in proportion to number of tickets
  - Each job has a **pass** value, incremented by stride each run
  - Scheduler picks job with lowest pass value
- For example:
  - A, B, C with 100, 50, 250 tickets respectively
  - Divide some large number by it, e.g., 10,000
  - A: B, C with 100, 200, 40 stride

Why Not Deterministic?

Pass(A)	Pass(B)	Pass(C)	Who runs?
0	0	0	A
100	0	0	B
100	200	0	C
100	200	40	C
100	200	80	C
100	200	120	A
200	200	160	C
200	200	200	...

- Why use lottery scheduling?
  - New job with pass value 0: monopolizes the CPU
  - Stride scheduler requires global state

Summary

- Scheduler efficiency is very important
  - In Google datacenters, scheduling uses 5% of CPU time
  - Even after aggressive optimization
- **FCFS** and **SJF** are simple, but high turnaround
- **STCF** is good for turnaround, but bad for response time
- **RR** solves is good for response time and fairness, but bad for turnaround
- **STCF** with **overlap** (sub-jobs) allows better use of resources
- Without oracle: **multi-level feedback queue**
  - Number of **queues** each assigned a different **priority level**
- **Proportional share scheduler**
  - Guarantee percentage of CPU instead of optimizing turnaround and response times