Scheduling: Introduction
How to develop a scheduling policy

• How should we develop a basic framework for thinking about scheduling policies?
• What are the key assumptions?
• What metrics are important?
• What basic approaches have been used in the past?
Initial workload assumptions (we’ll relax these assumptions later):

1. Each job runs for the **same amount of time**
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., they don’t perform no I/O)
5. The **run-time** of each job is known
Scheduling Metrics

• Performance metric: Turnaround time
  • The time at which the job completes minus the time at which the job arrived in the system

\[ T_{\text{turnaround}} = T_{\text{completion}} - T_{\text{arrival}} \]

• Another metric is fairness (e.g., Jain’s Fairness Index)
  • Maximum when all jobs receive the same share of CPU allocation

• Performance and fairness are often at odds in scheduling
First In, First Out (FIFO)

• First Come, First Served (FCFS)
  • Very simple and easy to implement

• Example:
  • A arrived just before B which arrived just before C
  • Each job runs for 10 seconds

\[ \text{Average turnaround time} = \frac{10 + 20 + 30}{3} = 20 \text{ sec} \]
Why FIFO is not that great? – Convoy effect

- Let’s relax assumption #1 (all jobs run for the same time)
  - Each job **no longer** runs for the same amount of time

- Example:
  - A arrived just before B which arrived just before C
  - A runs for 100 seconds, B and C run for 10 each

\[
\text{Average turnaround time} = \frac{100 + 110 + 120}{3} = 110 \text{ sec}
\]
Shortest Job First (SJF)

• Run the shortest job first, then the next shortest, and so on
  • Non-preemptive scheduler (no interrupting a running job)

• Example:
  • A arrived just before B which arrived just before C
  • A runs for 100 seconds, B and C run for 10 each

\[
\text{Average turnaround time } = \frac{10 + 20 + 120}{3} = 50 \text{ sec}
\]
SJF with Late Arrivals from B and C

• Let’s relax assumption #2 (all jobs arrive at the same time)
  • Jobs can now arrive at any time

• Example:
  • A arrives at t=0 and needs to run for 100 seconds
  • B and C arrive at t=10 and each need to run for 10 seconds

\[
\text{Average turnaround time} = \frac{100 + (110 - 10) + (120 - 10)}{3} = 103.33 \text{ sec}
\]
Shortest Time-to-Completion First (STCF)

• Let’s relax assumption #3 (once started, each job runs to completion)
• Add preemption to SJF
  • Also knows as Preemptive Shortest Job First (PSJF)
• When a new job enters the system:
  • Determine the time to complete the remaining jobs and new job
  • Schedule the job which has the least remaining time left
• Provably optimal with regard to minimizing turnaround time
Shortest Time-to-Completion First (STCF)

• Example:
  • A arrives at t=0 and needs to run for 100 seconds
  • B and C arrive at t=10 and each need to run for 10 seconds

Average turnaround time = \( \frac{(120 - 0) + (20 - 10) + (30 - 10)}{3} \) = 50 sec
New scheduling metric: Response time

• The time from \textit{when the job arrives} to the \textit{first time it is scheduled}

\[ T_{\text{response}} = T_{\text{firstrun}} - T_{\text{arrival}} \]

• STCF and related disciplines are not particularly good for response time

How can we build a scheduler that is sensitive to response time?
Round Robin (RR) Scheduling

- Time slicing Scheduling
  - Run a job for a time slice and then switch to the next job in the run queue until the jobs are finished
    - Time slice is sometimes called a scheduling quantum
  - It repeatedly does so until the jobs are finished
  - The length of a time slice must be a multiple of the timer-interrupt period

RR is fair, but performs poorly on metrics such as turnaround time
RR Scheduling Example

• A, B and C arrive at the same time
• They each wish to run for 5 seconds

![Diagram](image)

\[ T_{\text{average response}} = \frac{0 + 5 + 10}{3} = 5\text{sec} \]

\[ T_{\text{average response}} = \frac{0 + 1 + 2}{3} = 1\text{sec} \]
The length of the time slice is critical

• The shorter time slice
  • Better response time
  • The cost of context switching will dominate overall performance

• The longer time slice
  • Amortize the cost of switching
  • Worse response time

Deciding on the length of the time slice presents a trade-off to a system designer
Incorporating I/O

- Let’s relax assumption #4 (all jobs only use the CPU)
  - Jobs can now perform I/O

- Example:
  - Jobs A and B need 50ms of CPU time each
  - A runs for 10ms and then issues an I/O request
    - I/Os each take 10ms
  - B simply uses the CPU for 50ms and performs no I/O
  - The scheduler runs A first, then B after
Incorporating I/O (Cont.)

Maximize the CPU utilization

Overlap Allows Better Use of Resources

Poor Use of Resources
Incorporating I/O (Cont.)

- When a job initiates an I/O request
  - The job is blocked waiting for I/O completion
  - The scheduler should schedule another job on the CPU

- When the I/O completes
  - An interrupt is raised
  - The OS moves the process from blocked back to the ready state
What’s Next?

• Remove our final assumption: the scheduler knows the length of each job
• The OS usually knows very little about the length of each job

• How can we behave like SJF/STCF without such knowledge?
• How can we be fair and also have good response time?
Multi-Level Feedback Queue (MLFQ)

• A scheduler that learns from the past to predict the future

• Objective:
  • Optimize **turnaround time** \(\rightarrow\) Run shorter jobs first
  • Minimize **response time** without *a priori knowledge of job length*
MLFQ: Basic Rules

• MLFQ has a number of distinct *queues*
  • Each queue is assigned a different priority level

• A job that is ready to run is on a single queue
  • I.e., a job can be in only one queue at any given time
  • A job **on the highest priority queue** is chosen to run
  • Use round-robin scheduling among jobs in the same queue

**Rule 1:** If Priority(A) > Priority(B), A runs (B doesn’t)

**Rule 2:** If Priority(A) = Priority(B), A & B run in RR
MLFQ Example

[High Priority]  Q8 → A → B
Q7
Q6
Q5
Q4 → C
Q3
Q2

[Low Priority]  Q1 → D

MLFQ: Basic Rules (Cont.)

• MLFQ varies the priority of a job based on its **observed behavior**

• Example:
  • A job repeatedly relinquishes the CPU while waiting for I/O
    • Keep its priority high
    • When it runs, it doesn’t run for very long
  • A job uses the CPU intensively for long periods of time
    • Reduce its priority
MLFQ: How to Change Priority

• MLFQ priority adjustment algorithm:
  • **Rule 3**: When a job enters the system, it is placed in the highest priority queue
  • **Rule 4a**: If a job uses up an entire time slice while running, its priority is reduced (i.e., it moves down a queue level)
  • **Rule 4b**: If a job gives up the CPU before the time slice is up, it stays at the same priority level

In this manner, MLFQ approximates SJF
Example 1: A Single Long-Running Job

- A three-queue scheduler with time slice 10ms
Example 2: Along Comes a Short Job

• Assumption:
  • **Job A**: A long-running CPU-intensive job
  • **Job B**: A short-running interactive job (20ms runtime)
  • A has been running for some time, and then B arrives at time T=100.

Along Comes An Interactive Job (msec)

Q0

Q1

Q2

0 50 100 150 200

A:  
B:  

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Example 3: What About I/O?

• Assumption:
  • Job A: A long-running CPU-intensive job
  • Job B: An interactive job that need the CPU only for 1ms before performing an I/O

The MLFQ approach keeps an interactive job at the highest priority
Problems with the Basic MLFQ

• Starvation
  • If there are “too many” interactive jobs in the system
  • Long-running jobs will never receive any CPU time

• Game the scheduler
  • After running 99% of a time slice, issue an I/O operation (e.g., read(0))
  • The job gains a higher percentage of CPU time

• A program may change its behavior over time
  • CPU bound process $\rightarrow$ I/O bound process
The Priority Boost

- **Rule 5:** After some time period $S$, move all the jobs in the system to the topmost queue
  - Example:
    - A long-running job (A) with two short-running interactive job (B, C)

![Diagram showing the effect of Priority Boost](image)
Better Accounting

• How to prevent gaming of our scheduler?

• Solution:
  • **Rule 4** (Rewrite Rules 4a and 4b): Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced (i.e., it moves down on queue)

Without(Left) and With(Right) Gaming Tolerance

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Tuning MLFQ And Other Issues

- The high-priority queues → Short time slices
  - E.g., 10 or fewer milliseconds
- The Low-priority queue → Longer time slices
  - E.g., 100 milliseconds

Example: 10ms for the highest queue, 20ms for the middle, 40ms for the lowest
The Solaris MLFQ implementation

• For the Time-Sharing scheduling class (TS)
  • 60 Queues
  • Slowly increasing time-slice length
    • The highest priority: 20 msec
    • The lowest priority: A few hundred milliseconds
  • Priorities boosted around every 1 second or so
MLFQ: Summary

• The refined set of MLFQ rules:
  • **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:** When a job enters the system, it is placed at the highest priority
  • **Rule 4:** Once a job uses up its time allotment at a given level (regardless of how many times it has given up the CPU), its priority is reduced (i.e., it moves down on queue)
  • **Rule 5:** After some time period S, move all the jobs in the system to the topmost queue