CPU Scheduling

(Chapters 7-11)

The Problem

- You are the cook at the State Street Diner
  - Customers enter and place orders 24 hours a day
  - Dishes take varying amounts of time to prepare
- What are your goals?
  - Minimize average latency
  - Minimize maximum latency
  - Maximize throughput
- Which strategy achieves your goal?

Context matters!

- What if instead you are:
  - the owner of an expensive container ship, and have cargo across the world
  - the head nurse managing the waiting room of an emergency room
  - a student who has to do homework in various classes, hang out with other students and (occasionally) sleep

Kernel Operation (conceptual, simplified)

```
Initialize devices
Initialize "first process"
while (TRUE) {
    while device interrupts pending
      - handle device interrupts
    while system calls pending
      - handle system calls
    if run queue is non-empty          <-- CPU Scheduling
      - select a runnable process and switch to it
    otherwise
        - wait for device interrupt
}
```

Schedulers in the OS

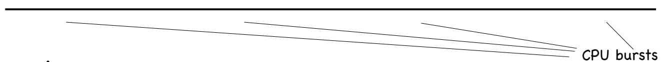
- CPU scheduler selects next process to run from the ready queue
- Disk scheduler selects next read/write operation
- Network scheduler selects next packet to send or process
- Page Replacement scheduler selects page to evict

Scheduling processes

- OS keeps PCBs on different queues
  - Ready processes are on ready queue - OS chooses one to dispatch
  - Processes waiting for I/O are on appropriate device queue
  - Processes waiting on a condition are on an appropriate condition variable queue
- OS regulates PCB migration during life cycle of corresponding process

Why scheduling is challenging

- Processes are not created equal!
  - CPU-bound process: long CPU bursts
    - mp3 encoding, compilation, scientific applications



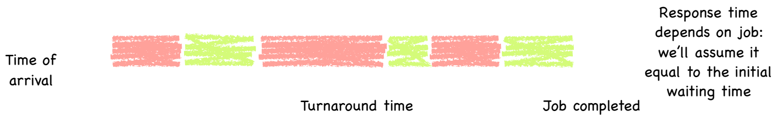
  - I/O-bound process: short CPU bursts
    - index a file system, browse small web pages
- Problem
  - don't know jobs type before running it
  - jobs behavior can change over time

Terminology and Metrics

- Job/Task
  - A user request: e.g., mouse click, web request, shell command...
- Turnaround time
  - Time elapsed between a job's arrival and its completion
- Throughput
  - Number of tasks completed per unit of time

More Metrics

- Response time
  - Time between job's arrival and first response produced
- Initial waiting time
  - Time between job's arrival and first time job runs
- Total waiting time
  - Time on the ready queue but not running
    - sum of "red" intervals below
- Execution time: sum of "green" intervals



Other Concerns

- Fairness
  - Equitable division of resources
- Starvation
  - Lack of progress by some job
- Overhead
  - Time wasted switching between jobs
- Predictability
  - Low variance in response time for repeated requests

The Perfect Scheduler

- Minimizes response and turnaround time
- Maximizes throughput
- Maximizes resource utilization ("work conserving")
- Meets deadlines
  - think watching a video, operating car brakes, etc
- Guarantees fairness
- Is envy-free
  - no job wants to switch its schedule with another

Alas, no such scheduler exists...

When Does the Scheduler Run?

- Non-preemptive
  - job runs until its actions cause it to yield CPU
    - job blocks on an event (e.g., I/O or P(sem))
    - job explicitly yields
    - job terminates
- Preemptive
  - all of the above, plus timer and other interrupts
  - incurs some context switching overhead

Workload assumptions

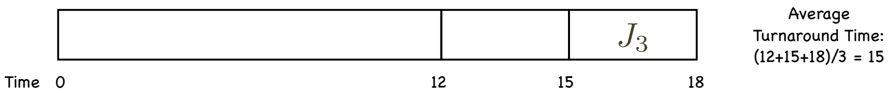
- Jobs arrive at the same time
  - but can still be ordered w.r.t. one another
- Once started, jobs run to completion
  - unless preempted
- Run-time of each job is known

Basic Scheduling Algorithms

- FIFO (First In First Out)
- SJF (Shortest Job First)
- STCF (Shortest Time-to-Completion First)
  - preemptive
- Round Robin
  - preemptive

FIFO

- Jobs with compute time 12, 3, 3
  - Job arrival



FIFO

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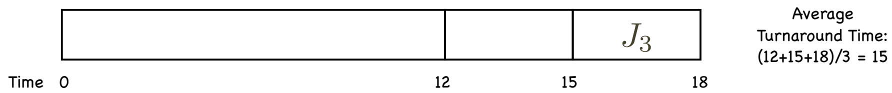
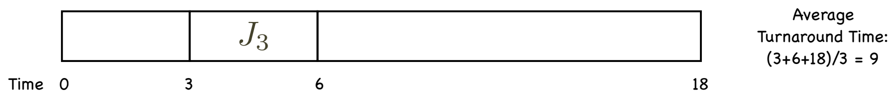


  - Job arrival



Average turnaround time very sensitive to arrival time!

FIFO

Simple
Low overhead
No starvation
Optimal average turnaround time (with same-sized jobs)

Poor average turnaround time when jobs have variable size

Average turnaround time very sensitive to arrival time

Not responsive to interactive tasks

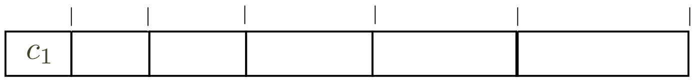
SJF: Shortest Job First

- Schedule jobs in order of estimated completion time
- Optimal* average turnaround time ( )

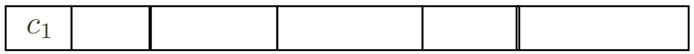
*when jobs are available simultaneously

SJF: Shortest Job First

- Schedule jobs in order of estimated completion time
- Optimal* average turnaround time ( )
- Intuition



- Can switching execution order reduce response time?



$(c_4+c_5-2c_3)$

*when jobs are available simultaneously

SJF

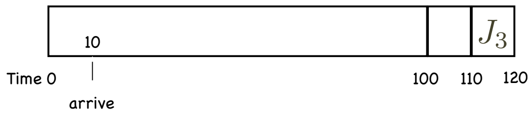
Optimal average turnaround time (when jobs are available simultaneously)

Pessimal in how turnaround times can get far apart (see under "starvation")

Needs estimate of execution times
Can starve long jobs

Relaxing "Same Arrival Time"

arrives at time 0; arrive at time 10

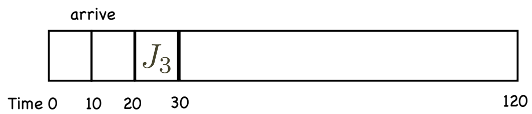


Average Turnaround Time:
100+(110-10)+(120 -10)/3
= 103.33

- To retain benefits of SJF, we relax "Jobs run to completion"
  - use a preemptive scheduler

STCF: Shortest Time-to-Completion First

- On job arrival, scheduler schedules job with shortest remaining time



Average Turnaround Time:
((120-0) + (20-10) + (30 -10))/3 = 50

But what if the completion time is unknown?

Shortest Process Next (SJF for interactive jobs)

- Enqueue in order of estimated completion time
  - Use recent history as indicator of near future
- Let duration of CPU burst
  estimated duration of CPU burst
  estimated duration of next CPU burst

$$\tau_{n+1} = \alpha\tau_n + (1-\alpha)t_n$$

determines weight placed on past behavior

Round Robin

- Each process is allowed to run for a quantum
- Context is switched (at the latest) at the end of the quantum
- What is a good quantum size?
  - Too long, and it morphs into FIFO
  - Too short, and much time lost context switching
  - Typical quantum: about 100X cost of context switch (~100ms vs. << 1ms)

Round Robin vs FIFO

- Assuming no overhead to time slice, is Round Robin always better than FIFO?

- What is the least efficient way you could get work done this semester using RR?

Round Robin vs FIFO

Jobs of about equal length start at about the same time

RR

0 1 2 3 4 ... 21 22 23 24 25

Average Turnaround time
(21 + (22-1) + (23-2) + (24-3) + (25-4)) / 5
= 21

FIFO/SJF

0 5 10 15 20 25

Average Turnaround time
(5 + (10-1) + (15-2) +
(20-3) + (25-4)) / 5 = 13

At least it is fair...?

- Mix of one I/O-bound and two CPU-bound jobs
  - I/O-bound: compute; go to disk; repeat

compute go to disk compute go to disk

I/O Bound wait 190 ms..................

Issues I/O Request | I/O completes | Issues I/O Request | I/O completes

CPU Bound 100ms quantum 100ms quantum

CPU Bound 100ms quantum

Time

Round Robin

No starvation
Can reduce response time

Overhead of context switching
Mix of I/O and CPU bound

Particularly bad average turnaround for simultaneous, equal length jobs

Taking stock

- STCF has great average turnaround time, but very uneven response time
- Round Robin can reduce response time, but can have terrible att
- FIFO works well if jobs are short, but otherwise is problematic for both turnaround (unless jobs have equal size) and response time...

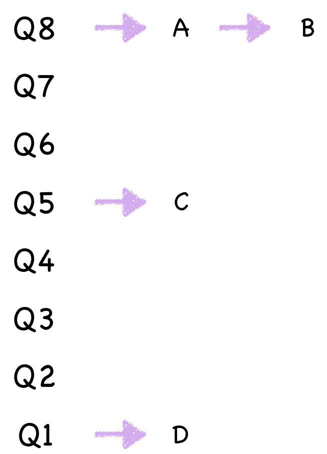
Priority Scheduling

- Assign a number (priority) to each job and schedule jobs in priority order
- Reduces to STCF if is used as priority
- To avoid starvation, change job's priority with time (aging)

Multi-level Feedback Queue (MFQ)

- Scheduler learns characteristics of the jobs it is managing
    - Uses the past to predict the future
- Favors jobs that used little CPU...
    - ...but can adapt when the job changes its pattern of CPU usage

The Basic Structure



- Queues correspond to different priority levels
    - higher is better
- Scheduler runs job in queue i if no other job in higher queues
- Each queue runs RR

Problem?

Mobility

Q8 → A → B
Q7
Q6
Q5 → C
Q4
Q3
Q2
Q1 → D

- Job starts at the top level
- If it uses full quantum before giving up CPU, moves down
- Otherwise, stays were it is
- What about I/O?
  - Job with frequent I/O will not finish its quantum and stay at the same level

Problem?

Movin'On Up

Q8 → A
Q7
Q6
Q5 → C
Q4
Q3
Q2
Q1 → D → B

- A job's behavior can change
  - After a CPU-bound interval, process may become I/O bound
- Must allow jobs to climb up the priority ladder...
  - As simple as periodically placing all jobs in the top queue, until they percolate down again

Problem?

Sneeeeakyyy...

Q8 → A → B
Q7
Q6
Q5 → C
Q4
Q3
Q2
Q1 → D

- Say that I have a job that requires a lot of CPU
  - Start at the top queue
  - If I finish my quantum, I'll be demoted...

  - ...just give up the CPU before my quantum expires!
- Better accounting
  - fix a job's time budget at each level, no matter how it is used

Proportional Share Scheduling

- Each job receives a set fraction of CPU time
- Several approaches (see your readings)
  - Lottery scheduling
    - give jobs a number of lottery tickets in proportion to the target share
    - leverages randomness

  - Stride scheduling (deterministic)
    - stride ∝ 1/tickets
    - when scheduled, the job "takes a stride"; strides add up to constitute the job's pass
    - scheduler chooses job with lowest pass

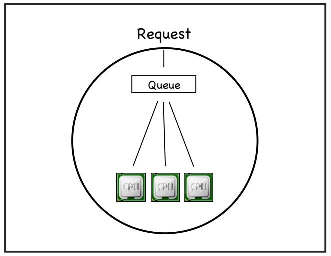
Linux's CFS
(Completely Fair Scheduler)

More in the readings! (and you are responsible for them…)

- Tracks processes' v(irtual)runtime
  - Picks next process with lowest
- All processes are equal when accounting for
  - but some processes are more equal than others!
- When translating runtime to , receives a "discount" proportional to its weight

Multiprocessor Scheduling: Sequential Applications

- A web server
  - A thread per user connection
  - Threads are I/O bound (access disk/network)
    - favor short jobs!



An MFQ, right?

- Idle processors take task off MFQ
- Only one processor at a time gets access to MFQ
- If thread blocks, back on the MFQ

Single MFQ Considered Harmful

Multiprocessor Scheduling: Sequential Applications

- Contention on MFQ lock
- Limited cache reuse
  - since threads hop from processor to processor
- Cache coherence overhead
  - processor need to fetch current MFQ state
  - on a uniprocessor, likely to be in the cache
  - on a multiprocessor, likely to be in the cache of another processor
    - 2-3 orders of magnitude more expensive to fetch

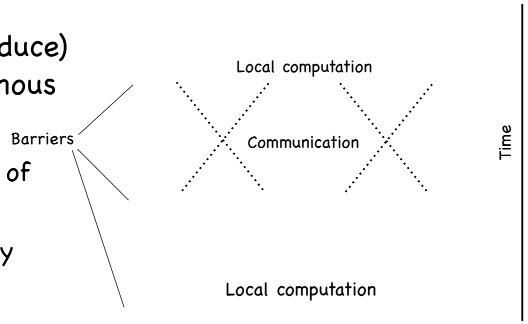
To Each (Process), its Own (MFQ)

Multiprocessor Scheduling: Sequential Applications

- Processors use affinity scheduling
  - each thread is run repeatedly on the same processors
    - maximizes cache reuse
  - more complex to achieve on a single MFQ
- Idle processors can steal work from other processors
  - only if it is worth the time of rewarming the cache!

Multiprocessor Scheduling: Parallel Applications

- Application is decomposed in parallel tasks
  - granularity roughly equal to available processors
    - or poor cache reuse
  - Often (e.g., MapReduce) using bulk synchronous parallelism (BSP)
    - tasks are roughly of equal length
    - progress limited by slowest processor

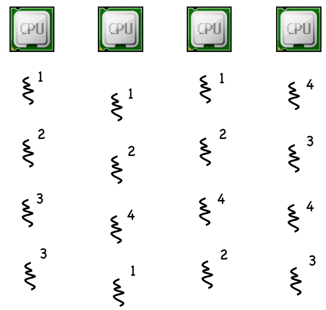


Scheduling Bulk Synchronous Applications

Oblivious Scheduling

Each process time-slices its ready list independently

Four applications, , each with four threads



Length of BSP step determined by last scheduled thread

Gang Scheduling

Schedule all tasks from the same program together

Four applications, , each with four threads