CPU Scheduling

(Chapters 7-11)

Mechanism and Policy

- Mechanism
  - enables a functionality
- Policy
  - determines how that funtionality should be used

Mechanisms should not determine policies!

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
        - select a runnable process and switch to it
    otherwise
        - wait for device interrupt
}
```

CPU Scheduling

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 turnaround time?
  - Minimize maximum turnaround time?
- 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, eat, and (occasionally) sleep

Schedulers in the OS

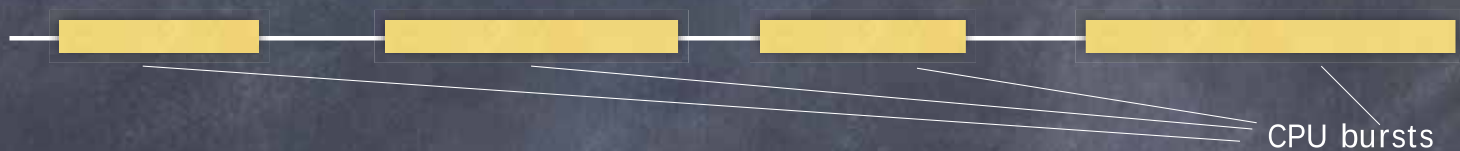
- CPU scheduler selects next process to run from the ready queue
- Disk scheduler selects next read/write operation
- Network scheduler selects next packet to send or process
- Page Replacement scheduler selects page to evict

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

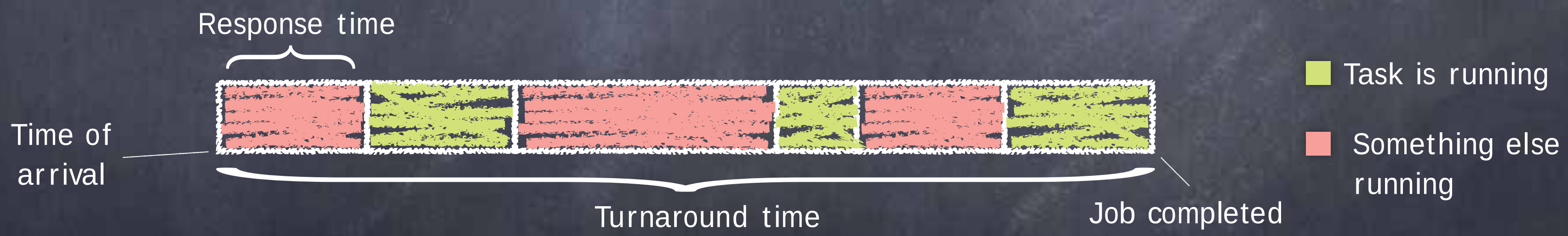
- Problem
  - don't know jobs type before running it
  - jobs behavior can change over time

Job Characteristics

- Job: A task that needs a period of CPU time
  - A user request: e.g., mouse click, web request, shell command...
- Defined by:
  - Arrival time
    - When the job was first submitted
  - Execution time
    - Time needed to run the task in isolation
  - Deadline
    - By when the task must have completed (e.g. for videos, car brakes...)

Metrics

- Response time
  - How long between job's arrival and first time job runs?
- Total waiting time
  - How much time on ready queue but not running?
    - sum of “red” intervals below
- Execution time: sum of “green” intervals



- Turnaround time: “red” + “green”
  - Time between a job's arrival and its completion
- Throughput: jobs completed/unit of time

Other Concerns

- Fairness: Who get the resources?
  - Equitable division of resources
- Starvation: How bad can it get?
  - Lack of progress by some job
- Overhead: How much useless work?
  - Time wasted switching between jobs
- Predictability: How consistent?
  - Low variance in response time for repeated requests

The Perfect Scheduler

- Minimizes response time and turnaround time for each job
- Maximizes overall throughput
- Maximizes resource utilization (“work conserving”)
- Meets all deadlines
- Is fair: everyone makes progress, no one starves
- Is Envy-Free: no job wants to switch its schedule with another
- Has zero overhead

Alas, no such scheduler exists...

When does the Scheduler Run?

- Non-preemptive
  - job runs until it voluntarily yields the CPU
    - process blocks on an event (e.g., I/O or P(sem))
    - process explicitly yields
    - process terminates
- Preemptive
  - all of the above, plus timer and other interrupts
    - when processes can't be trusted
  - incurs some context switching overhead

Context switch overhead

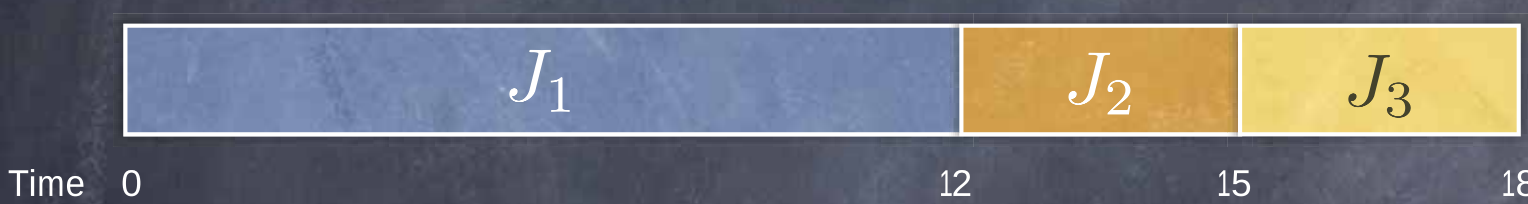
- Cost of saving registers
- Cost of scheduler determining which process to run next
- Cost of restoring register
- Cost of flushing caches
  - L1, L2, L3, TLB

Basic Scheduling Algorithms

- FIFO (First In First Out)
- SJF (Shortest Job First)
- EDF (Earliest Deadline First)
  - preemptive
- Round Robin
  - preemptive
- Shortest Remaining Time First (SRTF)
  - preemptive

FIFO

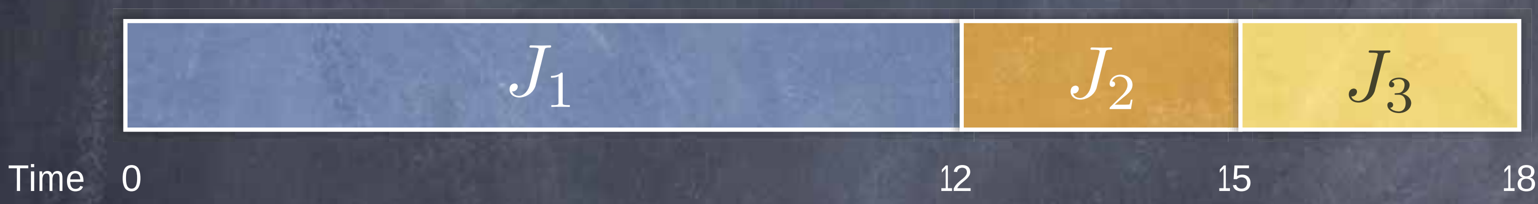
- Jobs J_1, J_2, J_3 with compute time 12, 3, 3
  - Job arrival J_1, J_2, J_3



Average
Turnaround Time:
(12+15+18)/3 = 15

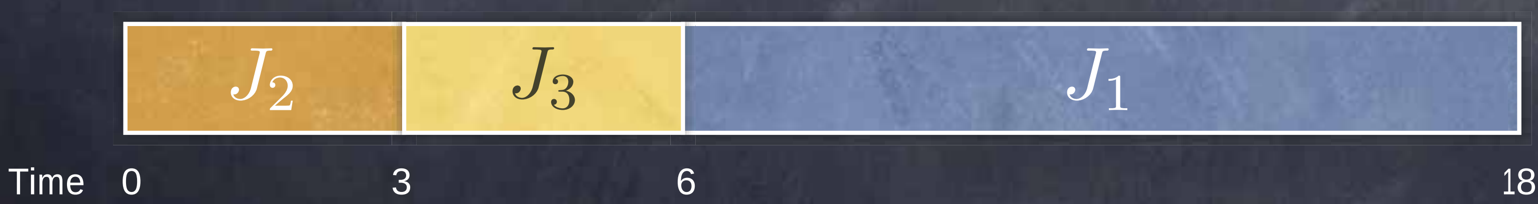
FIFO

- Jobs J_1, J_2, J_3 with compute time 12, 3, 3
  - Job arrival J_1, J_2, J_3



Average Turnaround Time: (12+15+18)/3 = 15

  - Job arrival J_2, J_3, J_1



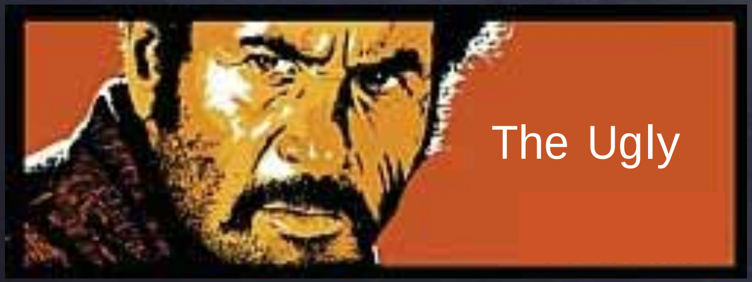
Average Turnaround Time: (3+6+18)/3 = 9

Average turnaround time very sensitive to arrival time!

FIFO Roundup

Simple
Low overhead
No starvation

Average turnaround time very sensitive to arrival time

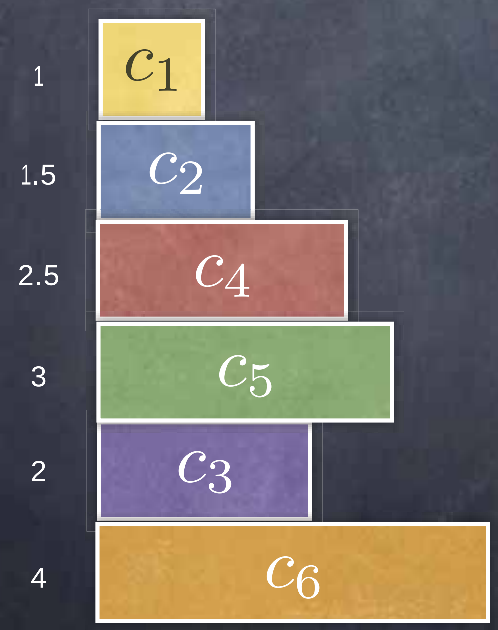


Not responsive to interactive tasks

How to minimize average turnaround time?

SJF: Shortest Job First

- Schedule jobs in order of estimated completion time



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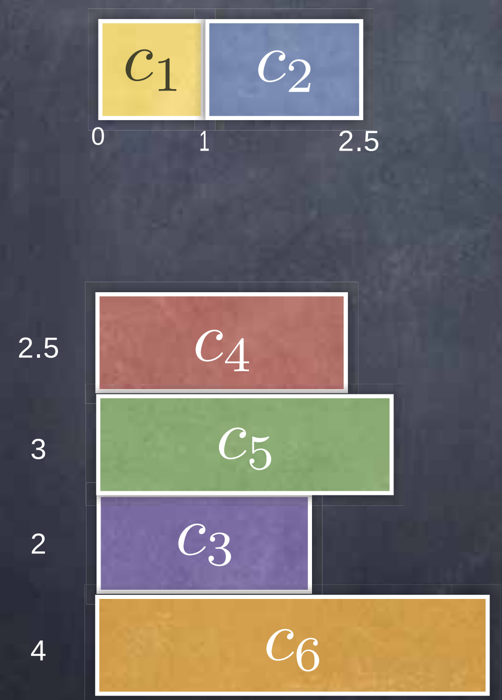

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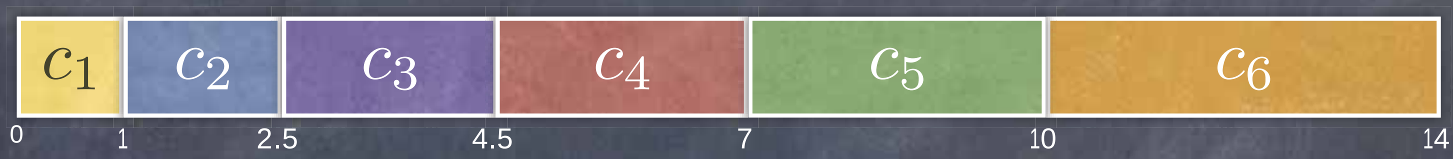
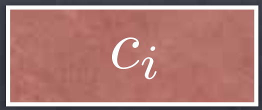


- Average Turnaround time (att): 39/6 = 6.5
- Would a different schedule produce a lower turnaround time?



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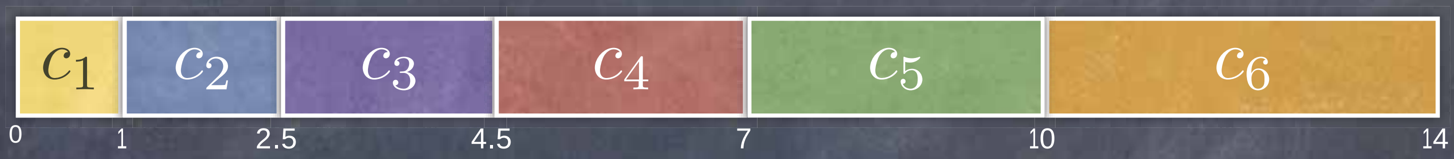

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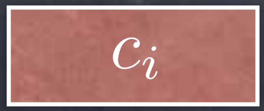


Graduate School?

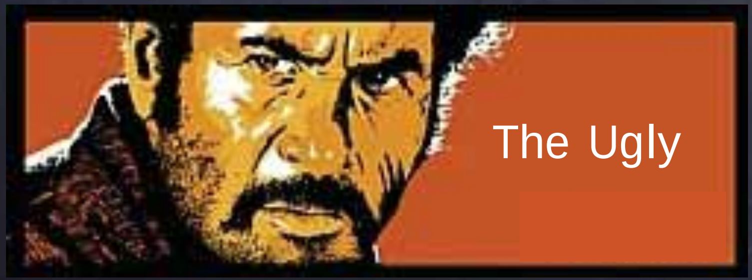
- Resume building
  - March 3rd, 7:00 pm
  - Register at: https://tinyurl.com/GSW1Register
- Perspectives on Graduate School
  - interaction with current graduate students
  - March 11, 6:00 pm
  - Register at: https://tinyurl.com/gradschoolperspectives
- CMMRS
  - More info: https://www.cs.cornell.edu/information/news/newsitem11391/learning-about-cornell-maryland-and-max-planck-pre-doctoral-research
  - Apply at: https://cmmrs.mpi-sws.org/how-to-apply/

SJF Roundup

Optimal average turnaround time

Pessimal variance in turnaround time

Need to estimate execution time



Can starve long jobs

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 n^{th} CPU burst
  estimated duration of n^{th} CPU burst
  estimated duration of next CPU burst

$0 \leq \alpha \leq 1$ determines weight placed on past behavior

Earliest Deadline First (EDF)

- Schedule in order of earliest deadline
- If a schedule exists that meets all deadlines, then EDF will generate that schedule!
  - does not even need to know the execution times of the jobs

Informal Proof

- Let S be a schedule of a set of jobs that meets all deadlines
- Let j_1 and be two neighboring jobs in S so that .deadline > .deadline
- Let S’ be S with and switched
  - S’ also meets all deadlines!
- Repeat until sorted (i.e., bubblesort)
  - Resulting schedule is EDF

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..but only if tasks only need the processor!

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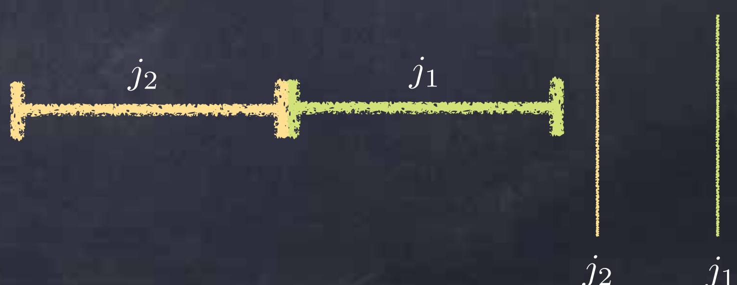


When EDF fails

- Two jobs:
  - : deadline at 12; 1 unit of computation, 10 of I/O
  - j_2: deadline at 10; 5 units of computation

EDF:

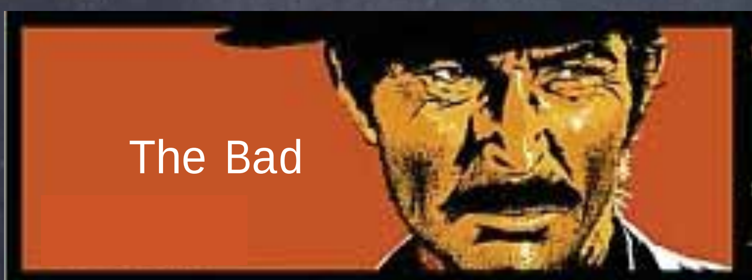
When EDF fails

- Two jobs:
  - : deadline at 12; 1 unit of computation, 10 of I/O
  - j_2: deadline at 10; 5 units of computation

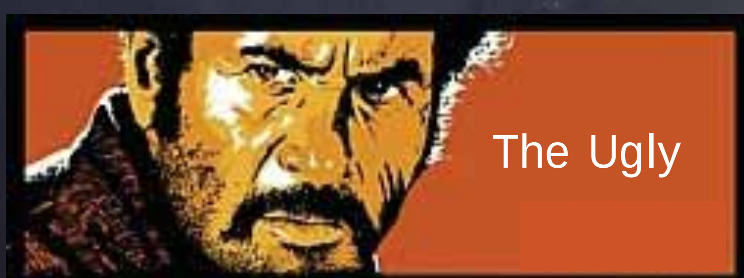
EDF Roundup

Meets deadlines if possible (but...)

Free of starvation



Does not optimize other metrics



Cannot decide when to run jobs without deadlines

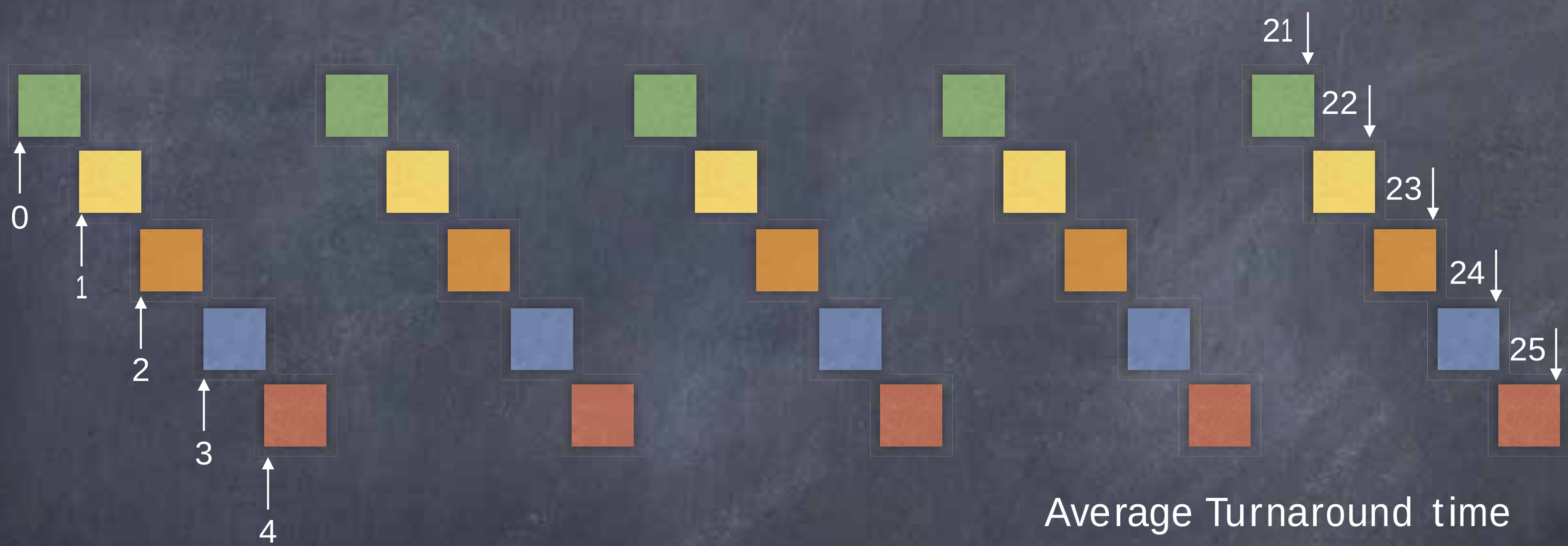
Round Robin

- Each process is allowed to run for a quantum
- Context is switched (at the latest) at the end of the quantum – preemption!
- Next job to run is the one that hasn't run for the longest amount of time
- 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

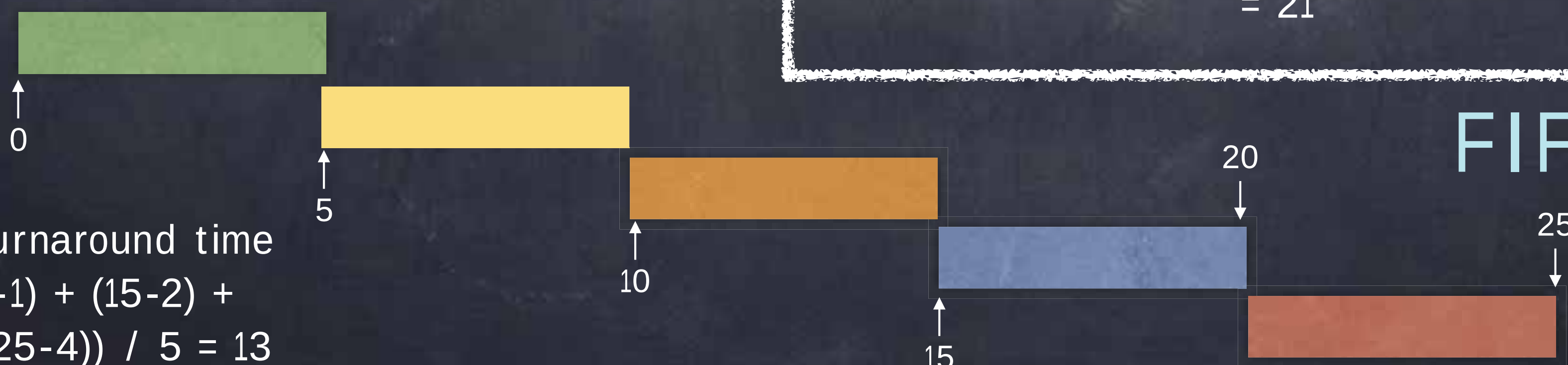
Jobs of about equal length (5 TU) start at about the same time

RR



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

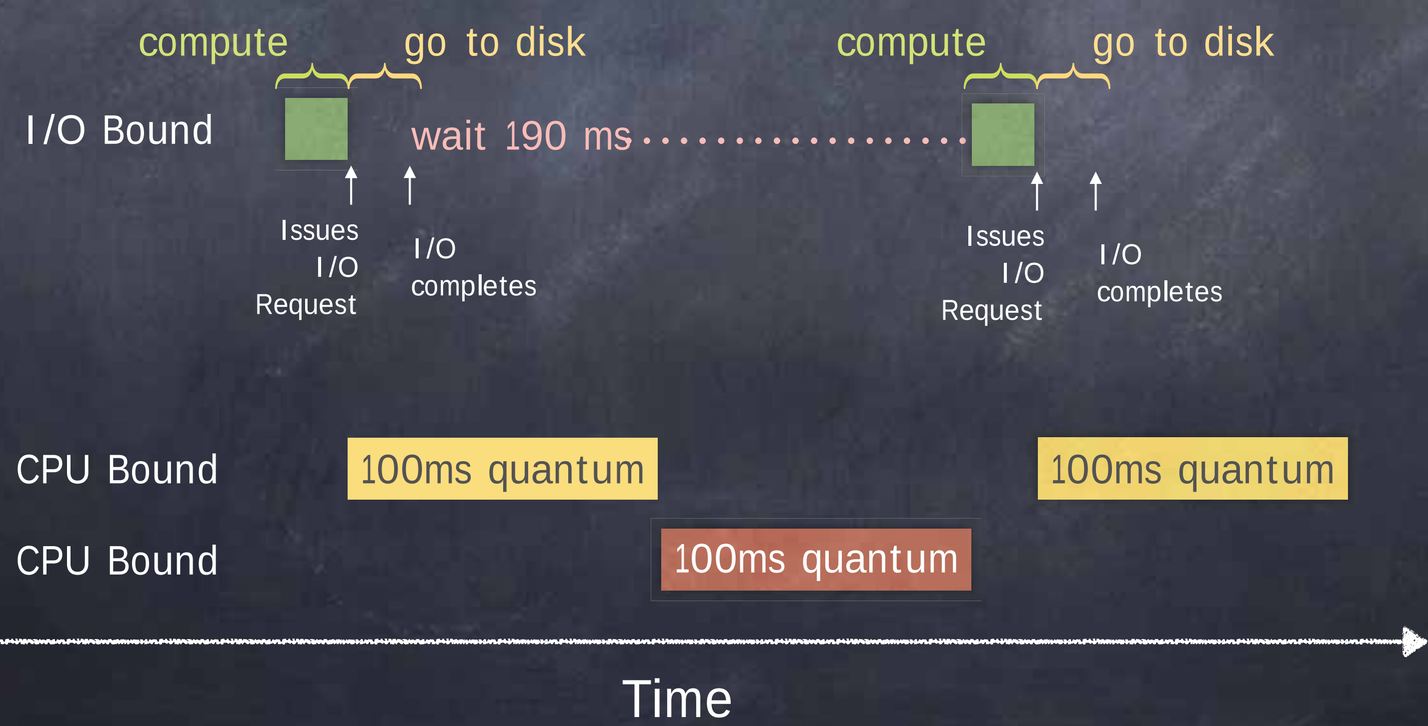
FIFO/SJF



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

At least it is fair...?

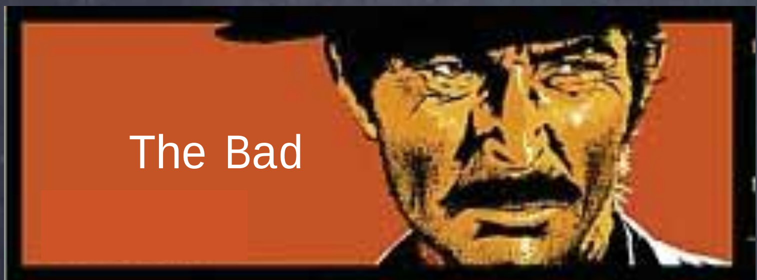
- Mix of one I/O-bound and two CPU-bound jobs
  - I/O-bound: compute; go to disk; repeat



Round Robin Roundup

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

SJF

- J_1 arrives at time 0; J_2, J_3 arrive at time 10

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

SJF + Preemption

- J_1 arrives at time 0; J_2, J_3 arrive at time 10

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

- With a preemptive scheduler — SRTF

Shortest Remaining Time First

At end of each quantum, scheduler selects job with the least remaining time to run next

- Often same job is selected, avoiding a context switch...
- ...but new short jobs see improved response time

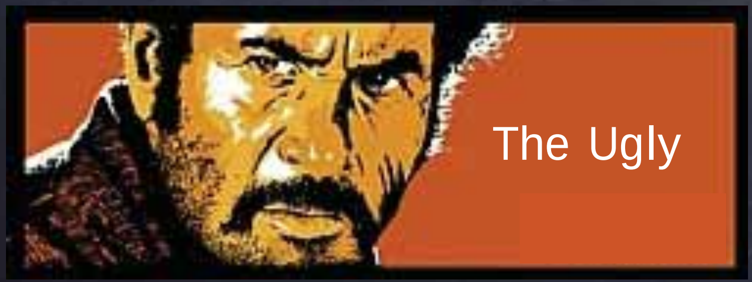
Average Turnaround Time:
(120-0)+(20-10)+(30-10)/3
= 50

SRTF Roundup

Good response time and turnaround time of I/O bound processes

Bad turnaround time and response time for CPU bound processes

Need estimate of execution for each job



Starvation

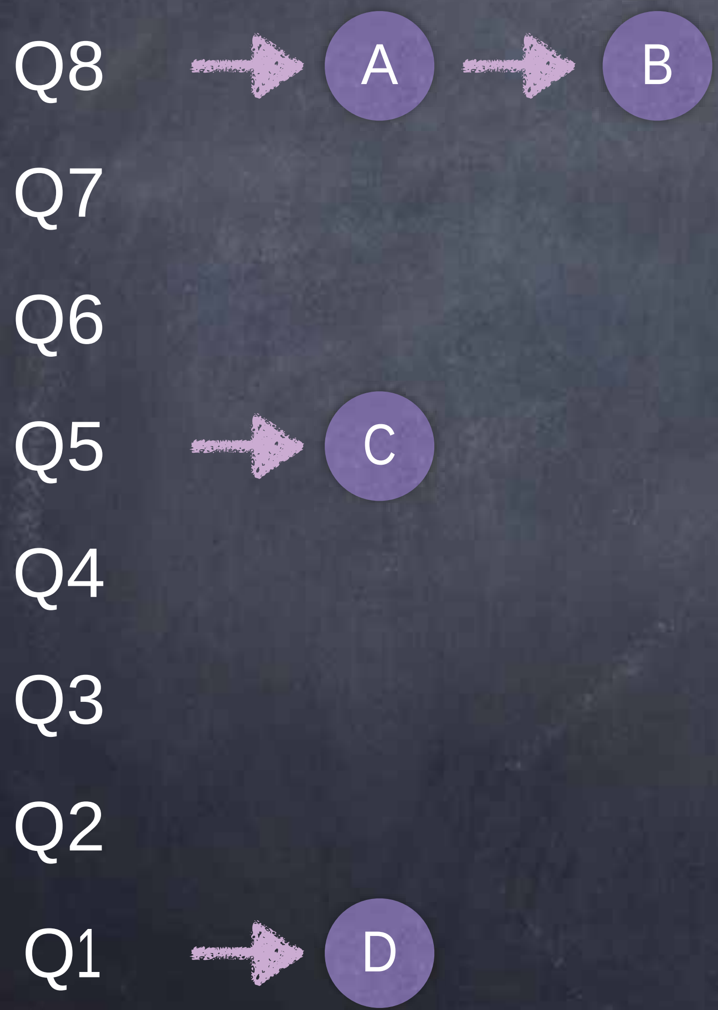
Priority Scheduling

- Assign a number (priority) to each job and schedule jobs in priority order
- Reduces to SRTF when using as priority the estimate of the execution time
- To avoid starvation
  - change job's priority with time (aging)
  - select jobs randomly, weighted by priority

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

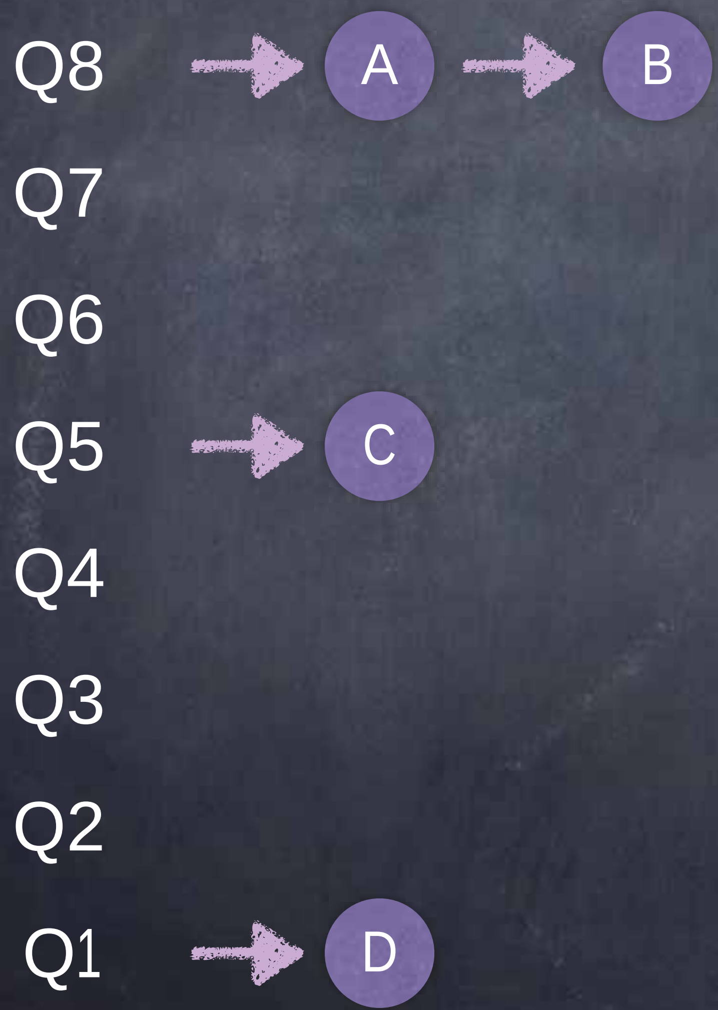
The Basic Structure



- 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
- Parameter:
  - how many queues?

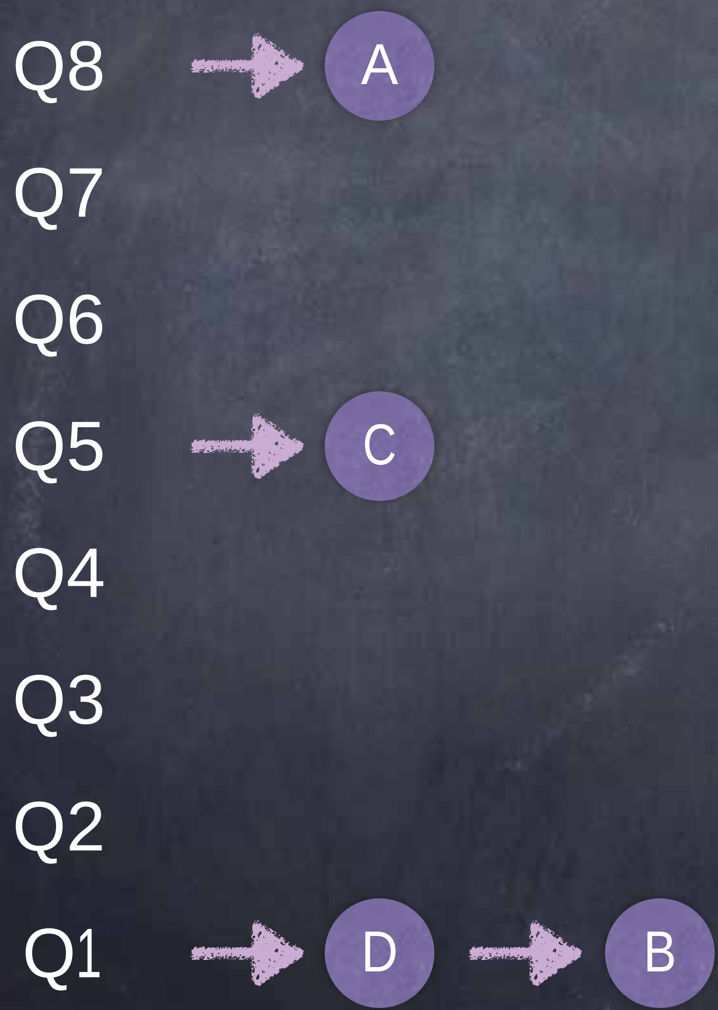
How are jobs assigned to a queue?

Moving down



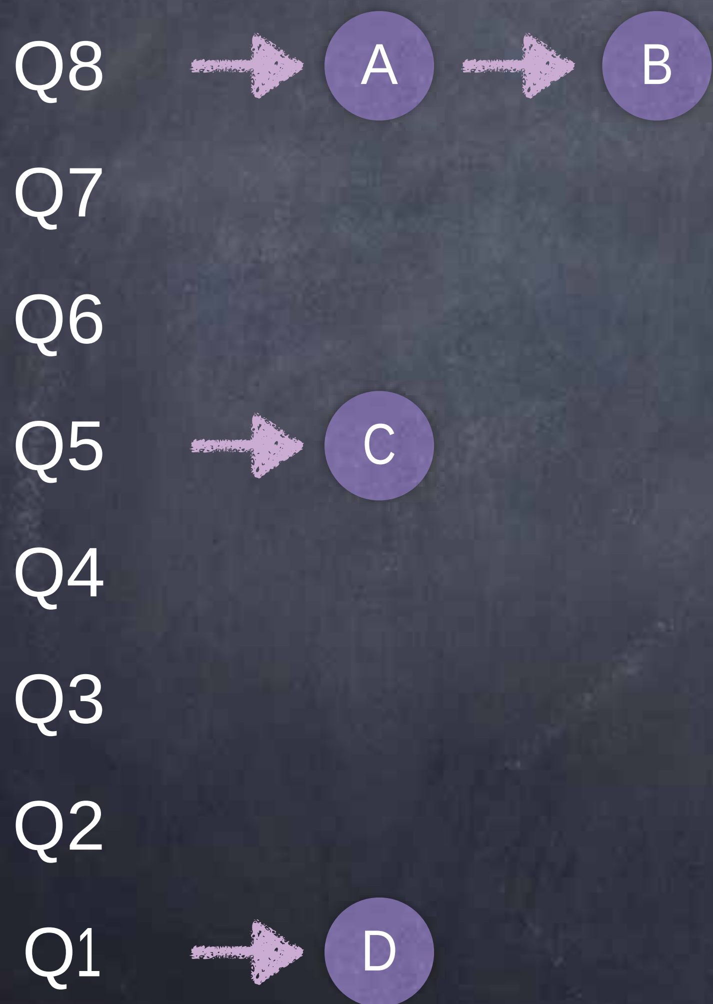
- Job starts at the top level
- If it uses full quantum before giving up CPU, moves down
- Otherwise, it stays were it is
- What about I/O?
  - Job with frequent I/O will not finish its quantum and stay at the same level
- Parameter
  - quantum size for each queue

Moving Up

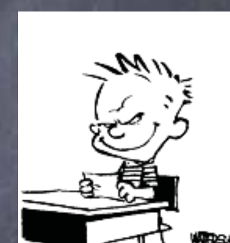


- A job's behavior can change
  - After a CPU-bound interval, process may become I/O bound
- Must allow jobs to climb up the priority ladder…
  - As simple as periodically placing all jobs in the top queue, until they percolate down again
- Parameter
  - time before jobs are moved up

Sneeeeakyyy...



- 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...



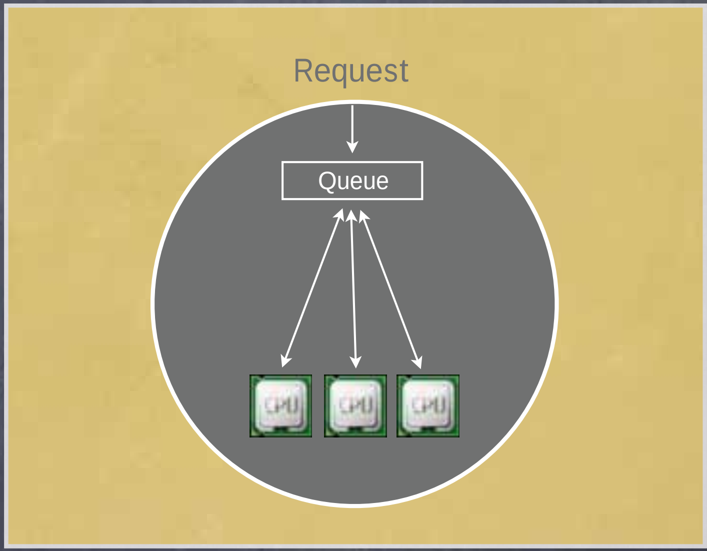
  - ...just give up the CPU before my quantum expires!
- Better accounting
  - fix a job's time budget at each level, no matter how it is used

Linux's "Completely Fair Scheduler" (CFS)

- Let "Spent Execution Time" (SET) to be the amount of time that a process has been executing
- Scheduler selects process with lowest SET
- Let △ be some time (typically, 50ms or so)
- Let N be the number of processes on the run queue
- Process runs for △/N time
  - there is a minimum value too
- If it uses up this quantum, reinsert into the queue
  - SET += △/N
- Computing of elapsed SET can be weighed by priority value
- Processes that move to a waiting queue, upon returning to the READY queue have SET initialized to the minimum SET of any process on the READY queue

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

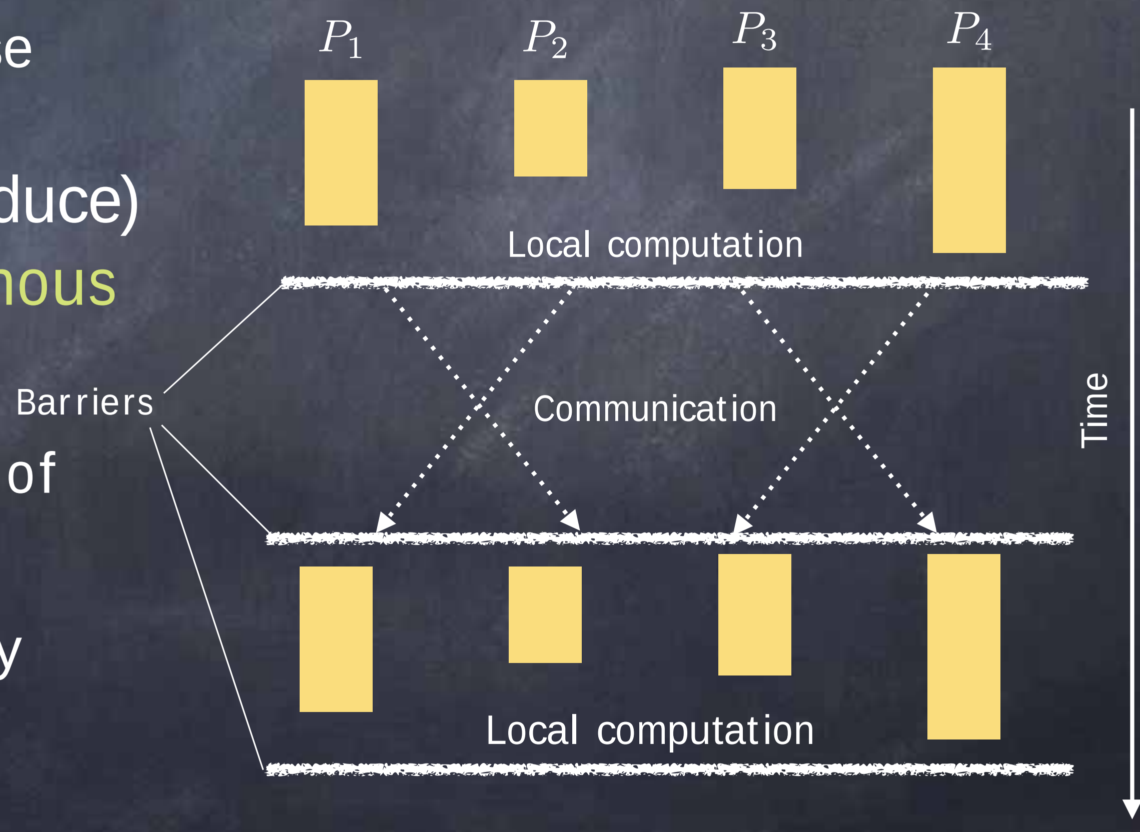
- Contention on MFQ lock
- Limited cache reuse
  - since threads hop from processor to processor
- Cache coherence overhead
  - processor need to fetch current MFQ state
  - on a uniprocessor, likely to be in the cache
  - on a multiprocessor, likely to be in the cache of another processor
    - 2-3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

To Each (Process), its Own (MFQ)

- 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
  - re-balance load at the cost of some loss of cache efficiency
  - 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