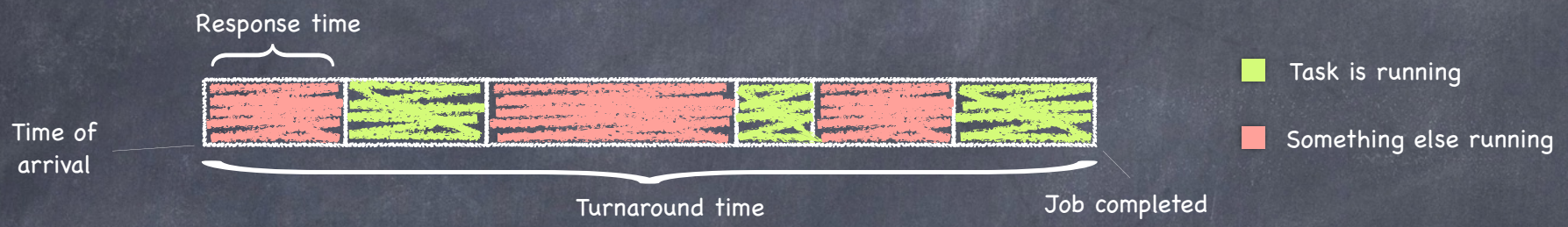
Metrics



- 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 above
- 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 (e.g. 10 jobs/sec)

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

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 (including, if appropriate, page table register)
- Cost of scheduler determining which process/thread to run next
- Cost of restoring registers (including, if appropriate, page table register)
- Cost of flushing caches
  - L1, L2, L3, TLB

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 core envies the schedule assigned to another core
- Has zero overhead

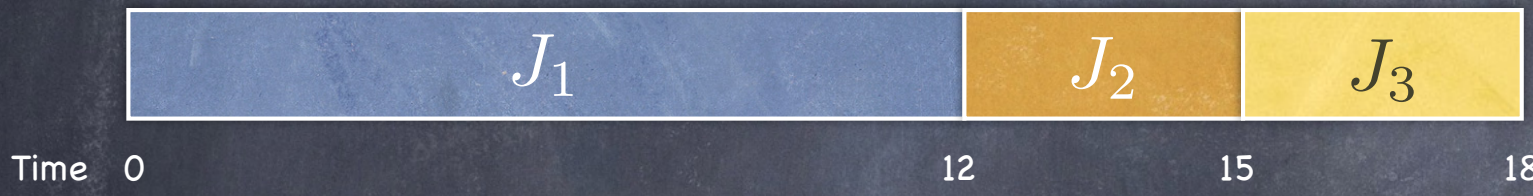
Alas, no such scheduler exists...

Basic Scheduling Algorithms

- FIFO (First In First Out) a.k.a. FCFS
- 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. Same arrival time (so can be scheduled in any order)
  - Scenario 1: Schedule order J_1, J_2, J_3



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

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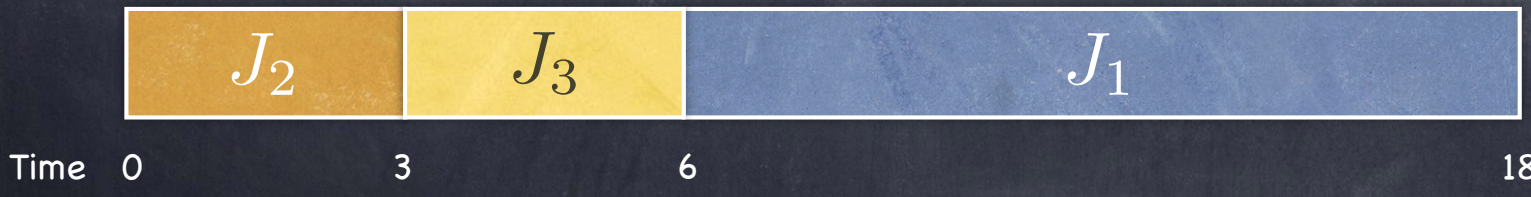
Average Turnaround Time: (12+15+18)/3 = 15

  - Scenario 2: Schedule order J_2, J_3, J_1



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

Average turnaround time very sensitive to schedule order!

FIFO Roundup

Simple
Low overhead
No starvation

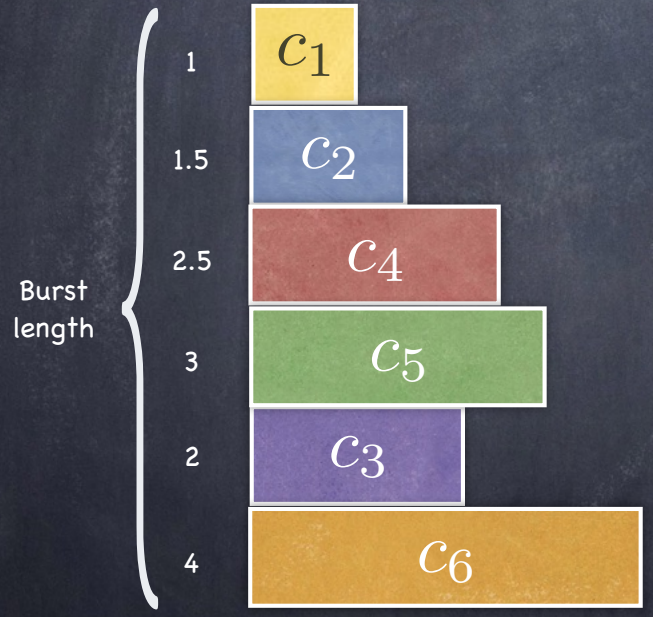
Average turnaround time very sensitive to order/ arrival time

Not responsive to interactive tasks

How to minimize average turnaround time?

SJF: Shortest Job First

- Schedule jobs in order of estimated completion time
  (or, better, shortest length of next CPU burst!)



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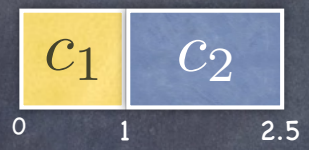

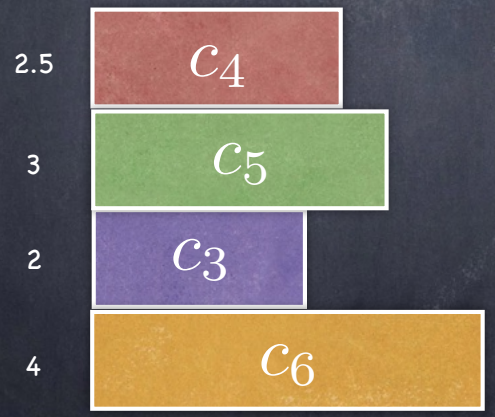

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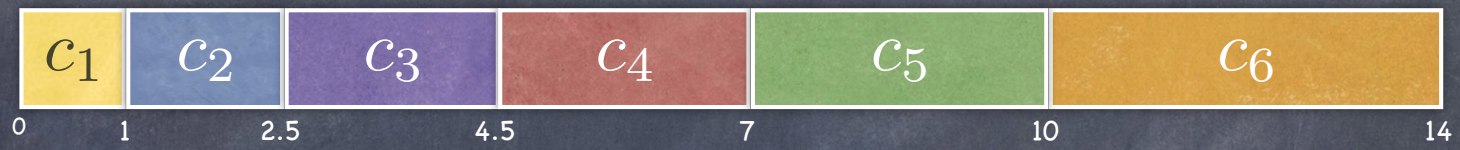
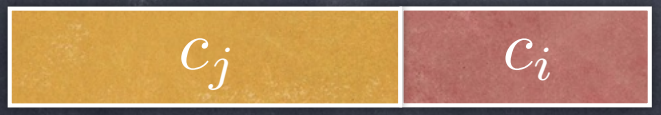


- Average Turnaround time (att): 39/6 = 6.5
- Would a different schedule produce a lower turnaround time?

Consider 

where $c_i < c_j$

att = $(c_j + (c_i + c_j))/2$

SJF: Shortest Job First

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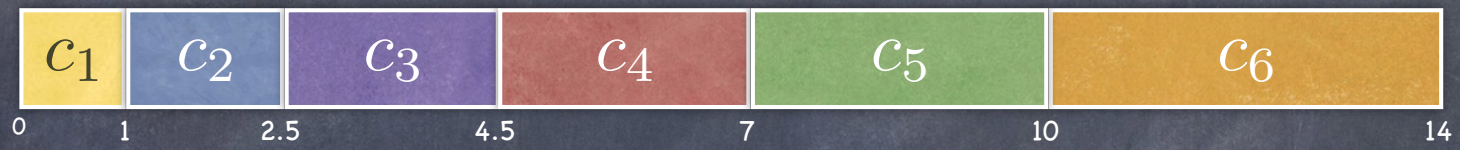

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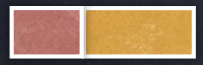

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$<$

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SJF Roundup

Optimal average turnaround time

Job's turnaround time depends on length of other jobs

Pessimal variance in turnaround time for a given task

Need to estimate execution time

Can starve long jobs

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Shortest Process Next (SJF for interactive jobs)

- Enqueue in order of estimated completion time
  - Exponential moving average (EMA): Use recent history as indicator of near future
- Let $t_n =$ duration of n^{th} CPU burst
  $\tau_n =$ estimated duration of n^{th} CPU burst
  $\tau_{n+1} =$ estimated duration of next CPU burst

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

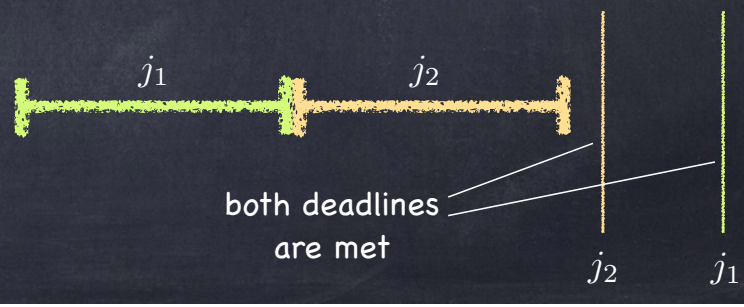
$0 \leq \alpha \leq 1$ determines weight placed on past behavior

Earliest Deadline First (EDF)

- Schedule in order of earliest deadline; preemptive
- 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 j_2 be two neighboring jobs in S so that j_1.deadline > j_2.deadline
- Let S' be S with j_1 and j_2 switched
  - S' also meets all deadlines!
- Repeat until sorted (i.e., bubblesort)
  - Resulting schedule is EDF



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..but only if tasks need only the processor!

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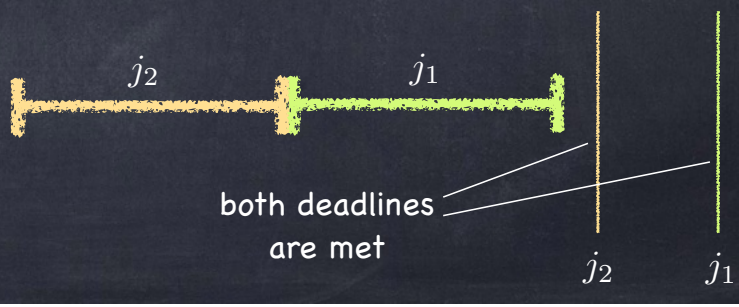
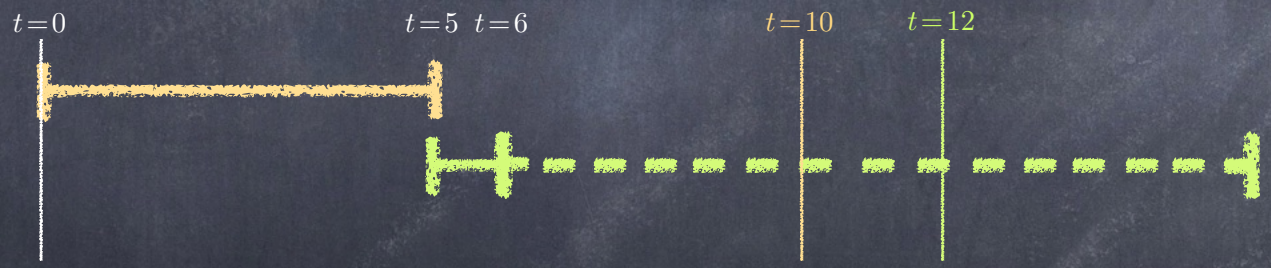


When EDF fails

- Two jobs:
  - j_1 : deadline at $t=12$; 1 unit of computation, 10 of I/O
  - j_2: deadline at $t=10$; 5 units of computation

EDF:



but...

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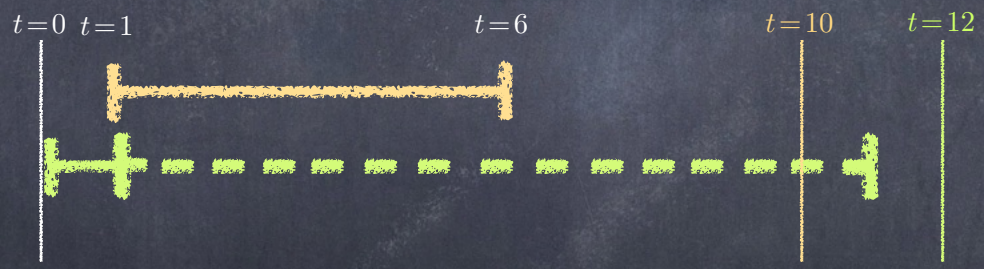


- Need to think of jobs at a finer granularity:
  - Real deadline for the computing portion of j_1 is 2!

EDF Roundup

Meets deadlines if possible (but beware...)

Free of starvation

CPU-bound jobs will make
I/O-bound jobs wait

Cannot decide when to
run jobs without deadlines

Round Robin

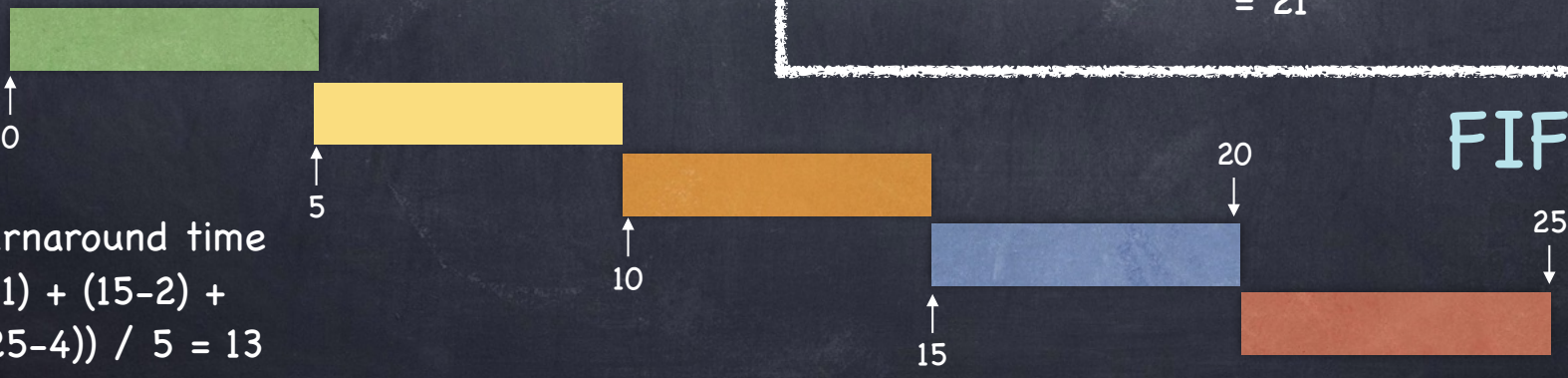
- Each process is allowed to run for a quantum
- Context is switched (at the latest) at the end of the quantum — preemption!
- Next job to run is the one that hasn't run for the longest amount of time
- What is a good quantum size?
  - Too long, and it morphs into FIFO
  - Too short, and too much time lost context switching
  - Typical quantum: about 100X cost of context switch (~100ms vs. << 1ms)

Round Robin vs FIFO

5 jobs of about equal length (5 units of time)

RR

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

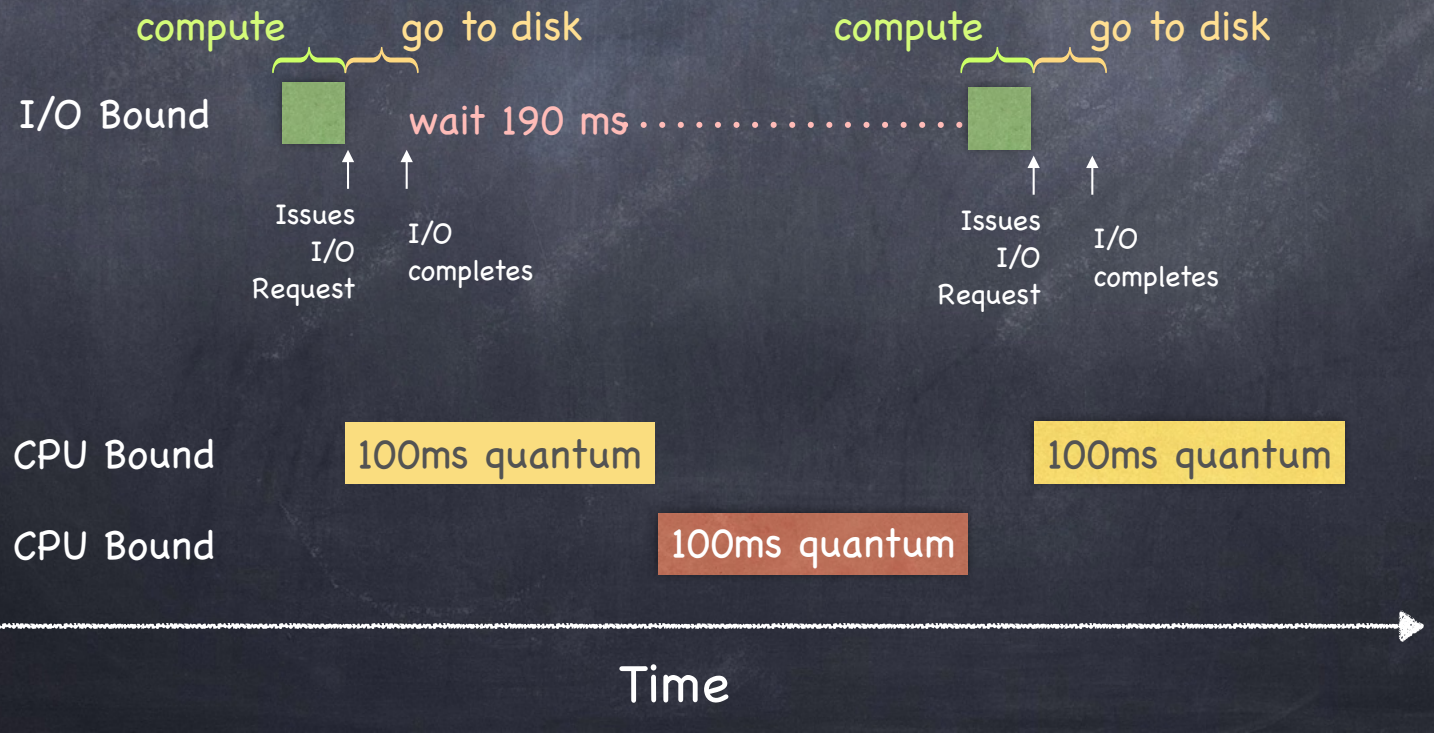


FIFO/SJF

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 close-in arrival-time, 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