CPU Scheduling

Knut Omang
Ifi/Oracle
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(with slides from several people)

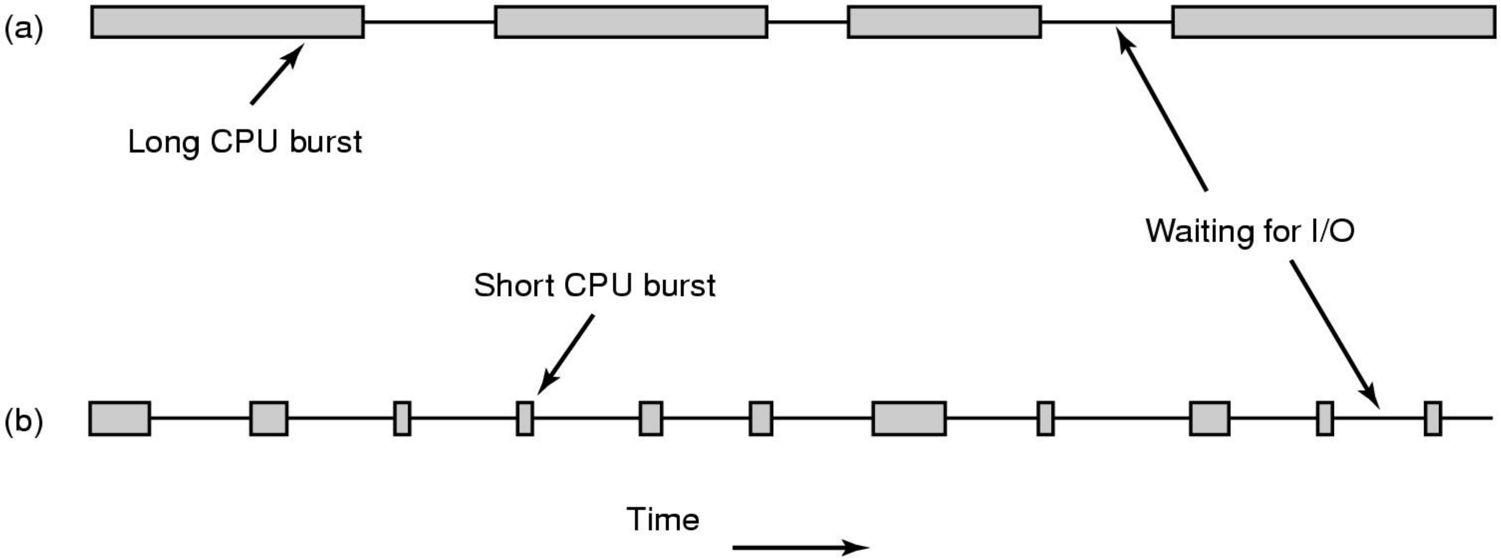
Today

- *Goals of scheduling*
- *Scheduling algorithms:*
  - FCFS/FIFO, RR, STCF/SRTCF
  - Priority (CTSS, UNIX, Windows, Linux)
  - Lottery
  - Fair share

  - Real-time: RM and EDF

Why Spend Time on Scheduling?

- Optimize the system to the given goals
- Example: CPU-Bound vs. I/O-Bound Processes:



- *Bursts of CPU usage alternate with periods of I/O wait*
  - a CPU-bound process
  - an I/O bound process

Scheduling Performance Criteria

- ***CPU (resource) utilization***
    - 100%, but 40-90% normal
- ***Throughput***
    - Number of “jobs” per time unit
    - Minimize overhead of context switches
    - Efficient utilization (CPU, memory, disk etc)
- ***Turnaround time***
    - = $\text{time}_{\text{process arrives}} - \text{time}_{\text{process exits}}$
    - = sum of all waiting times (memory, R_Q, execution, I/O, etc)
    - How fast a single job got through
- ***Response time***
    - = $\text{time}_{\text{request starts}} - \text{time}_{\text{response starts}}$
    - Having low variance in Response Time is good (predictability)
    - Short response time: type on a keyboard, click on GUI
- ***Waiting time***
    - in the Ready_Queue, for memory, for I/O, etc.
- ***Fairness***
    - no starvation

Scheduling Algorithm Goals

All systems

Fairness - giving each process a fair share of the CPU
Policy enforcement - seeing that stated policy is carried out
Balance - keeping all parts of the system busy

Batch systems

Throughput - maximize jobs per hour
Turnaround time - minimize time between submission and termination
CPU utilization - keep the CPU busy all the time

Interactive systems

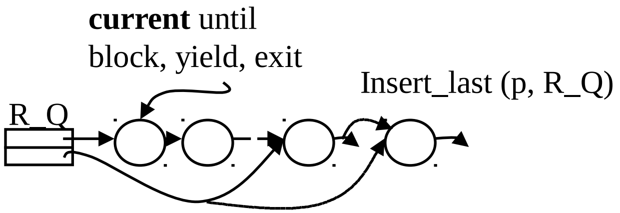
Response time - respond to requests quickly
Proportionality - meet users' expectations

Real-time systems

Meeting deadlines - avoid losing data
Predictability - avoid quality degradation in multimedia systems

Non-Preemptive: FIFO (FCFS) Policy

- *Run*
  - to completion (old days)
  - until blocked, yield, or exit



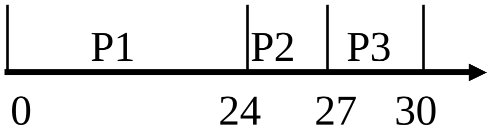
- *Advantages?*

- *Disadvantage*

Average Turnaround Time for CPU bursts:

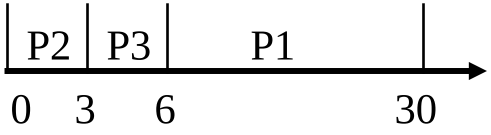
Process	Burst time
1	24
2	3
3	3

Arrival order: 1 - 2 - 3



$TT_{\text{average}} = (24+27+30)/3=\mathbf{27}$

Arrival order: 2 - 3 - 1

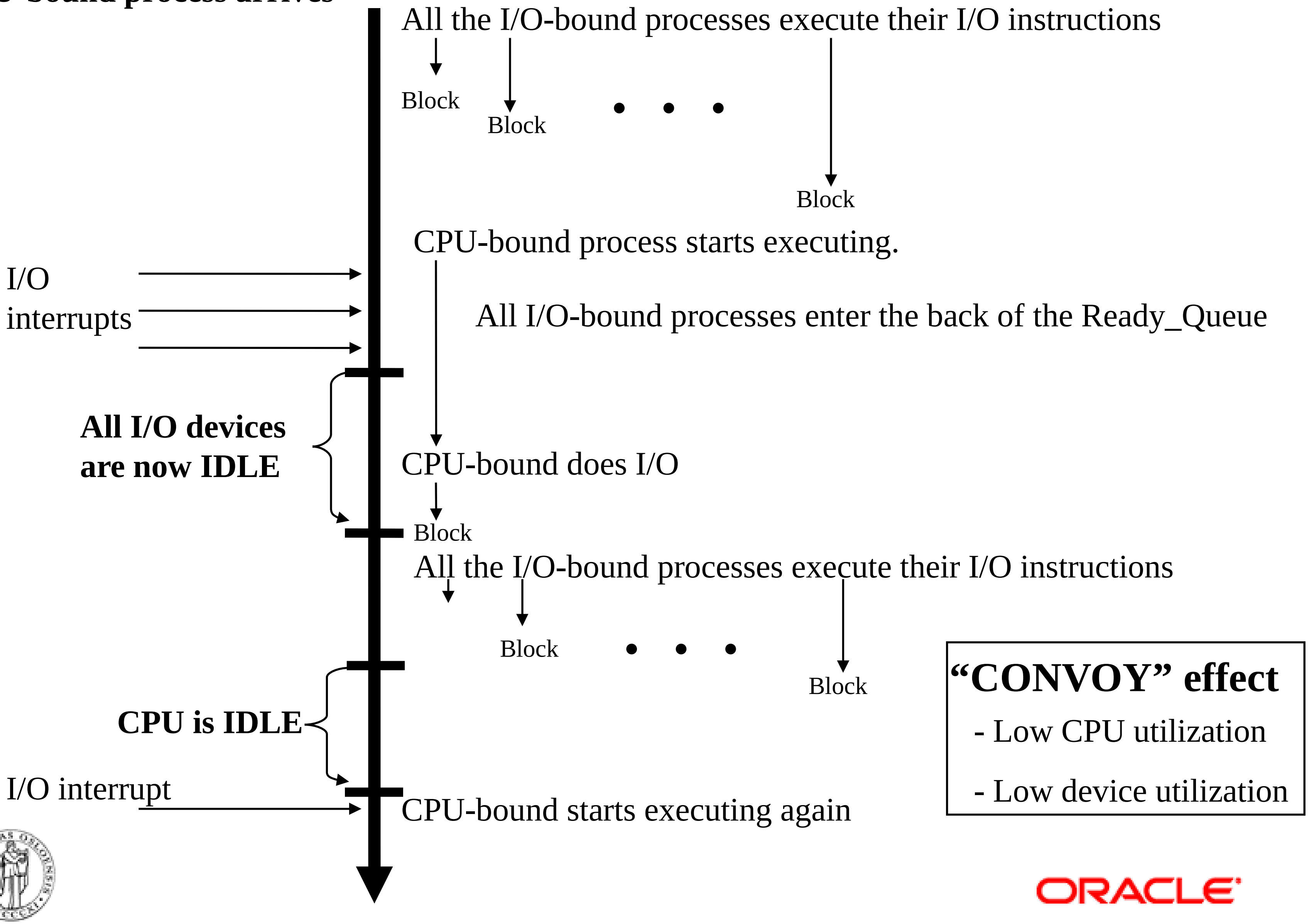


$TT_{\text{average}} = (3+6+30)/3=\mathbf{13}$

Discussion topic FCFS

How well will FCFS handle:

- **Many processes doing I/O arrives**
- **One CPU-bound process arrives**



All the I/O-bound processes execute their I/O instructions

Block

Block

• • •

Block

CPU-bound process starts executing.

I/O interrupts

All I/O-bound processes enter the back of the Ready_Queue

All I/O devices are now IDLE

CPU-bound does I/O

Block

All the I/O-bound processes execute their I/O instructions

Block

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Block

CPU is IDLE

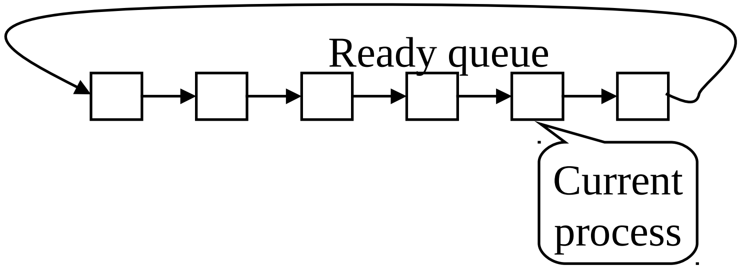
I/O interrupt

CPU-bound starts executing again

“CONVOY” effect

- Low CPU utilization
- Low device utilization

Round Robin



- *FIFO queue*
- *n processes, each runs a time slice or quantum, q*
  - each process gets 1/n of the CPU in max q time units at a time

- *Max waiting time in Ready_Queue per process: (n-1) * q*

- *How do you choose the time slice?*
  - Overhead vs. throughputs
  - Overhead is typically about 1% or less
    - interrupt handler + scheduler + dispatch
    - 2 context switches: going down, and up into new process
  - CPU vs. I/O bound processes

FIFO vs. Round Robin

- *10 jobs and each takes 100 seconds*
  - 10 seconds of this is I/O wait

- *FIFO*

- *Round Robin*
  - time slice 1s and no overhead

- *Comparisons*

Case: Time Slice Size

- *Resource utilization example*
  - **A** and **B** each uses 100% CPU
  - **C** loops forever (1ms CPU and 10ms disk)

- *Large or small time slices?*
  - nearly 100% of CPU utilization regardless of size
  - Time slice 100ms: nearly 5% of disk utilization with Round Robin
  - Time slice 1ms: nearly 85% of disk utilization with Round Robin

- *What do we learn from this example?*
  - The right (shorter) time slice can improve overall utilization
  - CPU bound: benefits from having longer time slices (>100 ms)
  - I/O bound: benefits from having shorter time slices ($\leq$ 10ms)

- *[But what about memory bound?]*

Shortest Time to Completion First (STCF) (a.k.a. Shortest Job First)

- *Non-preemptive*
- *Run the process having smallest service time*
- *Random, FCFS, … for "equal" processes*
- *Problems*
  - establish what the running time of a job is
- *Suggestions on how to do this?*
  - Length of next CPU-burst
    - Assuming next burst = previous burst
    - Can integrate over time using a formula taking into account old and new history of CPU burst lengths
  - But mix of CPU and I/O, so be careful

Shortest Remaining Time to Completion First (SRTCF) (a.k.a. Shortest Remaining Time First)

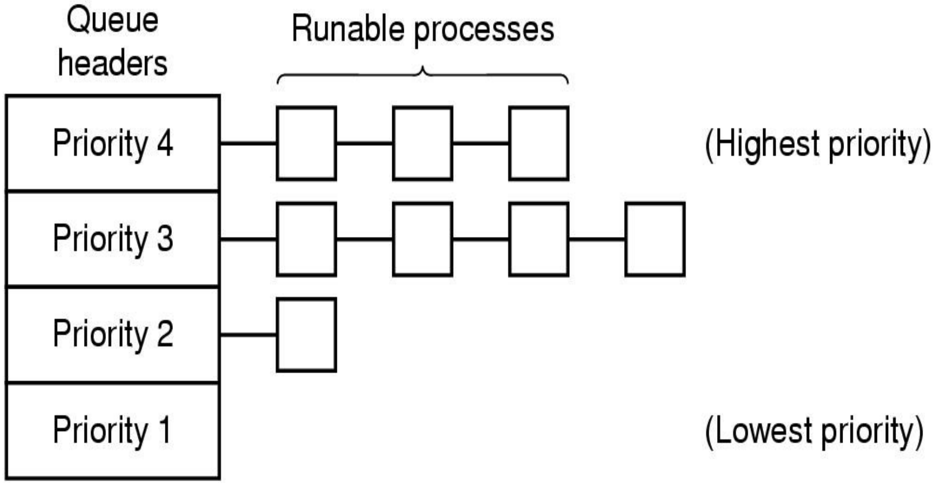
- *Preemptive, dynamic version of STCF*
- *If a shorter job arrives, PREEMPT current, and do STCF again*

- *Advantage:*
  - high throughput, low average turnaround

    (Running a short job before a long decreases the waiting time MORE for the short than it increases for the long!)
  - Memory/cache benefits
- *Disadvantage:*
  - starvation possible, must know execution time

Priority Scheduling

- *Assign each process a priority*
- *Run the process with highest priority in the ready queue first*



- *Multiple queues*
- *Advantage*
  - Different priorities according to importance
- *Disadvantage*
  - Users can hit keyboard frequently
  - Starvation (should use dynamic priorities)
- *Special cases (RR in each queue)*
  - FCFS (all equal priorities, non-preemptive)
  - STCF/SRTCF (the shortest jobs are assigned the highest priority)

Interactivity

- Dynamically scale a tasks priority based on it‘s 'interactivity'
- Interactive tasks receive a prio bonus [-5]
  - Hence a larger timeslice
- CPU bound tasks receive a prio penalty [+5]
- Interactivity estimated using a running sleep average.
  - Interactive tasks are I/O bound. They wait for events to occur.
  - Sleeping tasks are I/O bound or interactive
  - Actual bonus/penalty is determined by comparing the sleep average against a constant maximum sleep average.
- But problem: this is heuristics – can be fooled can make mistakes..

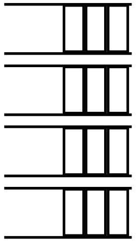
Multiple Queues

- *Good for classes of jobs*
  - real-time vs. system jobs vs. user jobs vs. batch jobs

- *Multi level feedback queues*
  - Adjust priority dynamically
    - Aging
    - I/O wait raises the priority
    - Memory demands,
      #open files, CPU:I/O bursts
  - Scheduling **between** the queues
    - Time slice (and cycle through the queues)
    - Priority typical:
      - Jobs start at highest priority queue
      - If timeout expires (used current time slices), drop one level
      - If timeout doesn’t expires, stay or pushup one level
  - Can use different scheduling per queue
  - A job doing much I/O is moved to an “I/O bound queue”

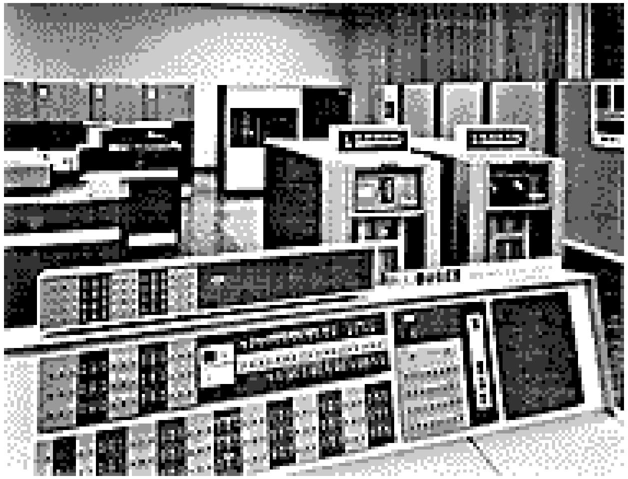
Compatible Time-Sharing System (CTSS)

- One of the first (1962) priority schedulers using multiple queues
- One process in memory at a time (high switch costs)
  - Memory sz: Users: 27K of total 32K, 5K reserved for monitor
- Large slices vs. response time → priority classes
- Each time the quantum was used, the process dropped one priority class (larger slice, less frequent)



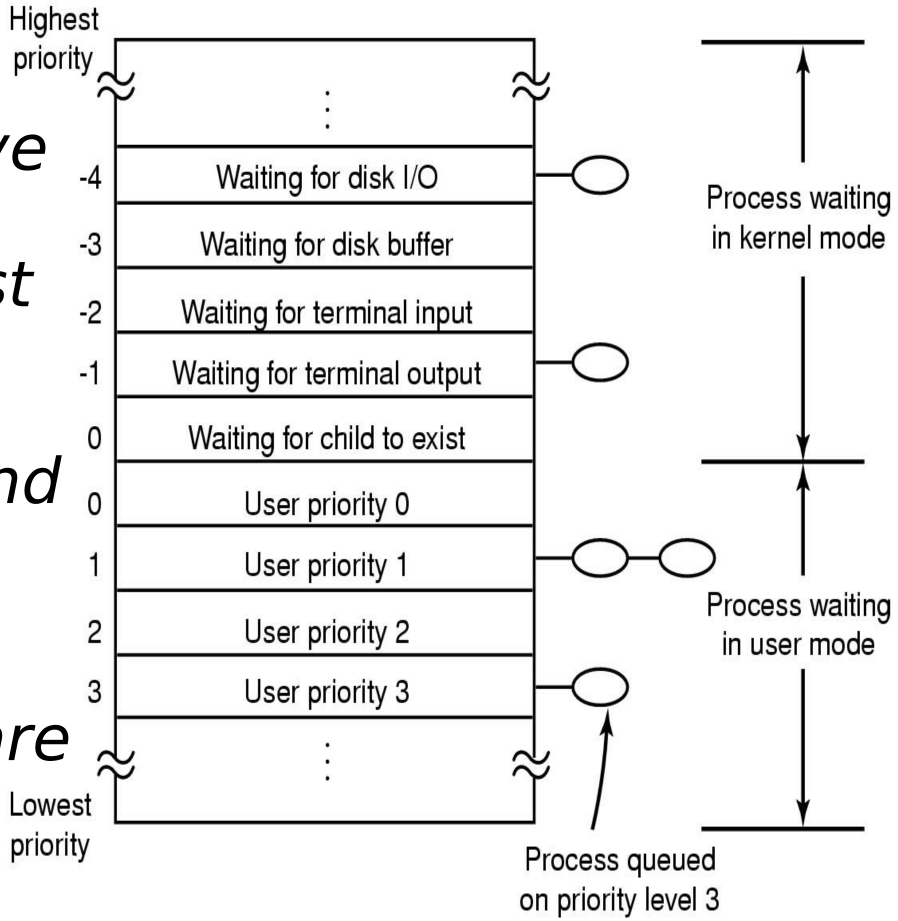
"Priority"	Time slices
0	1
1	2
2	4
3	8

- Interaction → back to highest priority class
- Short, interactive should run more often
- Proved viability of time sharing



Scheduling in UNIX

- *Many versions*
- *User processes have positive priorities, kernel negative*
- *Schedule lowest priority first*
- *If a process uses the whole time slice, it is put back at the end of the queue (RR [round robin])*
- *Each second the priorities are recalculated:*
  priority =
  CPU_usage (average #ticks)
  - \+ nice (+- 20)
  - \+ base (priority of last corresponding kernel process)



Scheduling in UNIX (4.4BSD)

- *Similar to last slide*

- *Time slices of 100 ms*

- *Priorities is updated every 4th tick (40 ms)*

$$p\_usrpri = PUSER + [p\_estcpu \times \tfrac{1}{4}] + 2 \times p\_nice$$

  - PUSER defaults to 50 (min), may be changed but here one uses only values between 50 and 127

  - $p\_estcpu =$
    - running process: $[(2 \times load)/(2 \times load + 1)] \times p\_estcpu + p\_nice$
    - blocked process: $[(2 \times load)/(2 \times load + 1)]^{p\_sleeptime} \times p\_estcpu$

  - p_nice defaults to 0

Scheduling in Windows 2000

- *Preemptive kernel*
- *32 priority levels - Round Robin (RR) in each*
- *Schedules threads individually*

- *Processor affinity*

- *Default time slices (3 quantums = 10 ms) of*
  - 120 ms – Win2000 server
  - 20 ms – Win2000 professional/workstation
  - may vary between threads

- *Interactive and throughput-oriented:*
  - “Real time” – 16 system levels
    - fixed priority
    - may run forever
  - Variable – 15 user levels
    - priority may change – *thread priority* = process priority ± 2
    - uses much CPU cycles → drops
    - user interactions, I/O completions → increase
  - Idle/zero-page thread – 1 system level
    - runs whenever there are no other processes to run
    - clears memory pages for memory manager

Real Time (system thread)

31

30

...

17

16

Variable (user thread)

15

14

...

2

1

Idle (system thread)

0

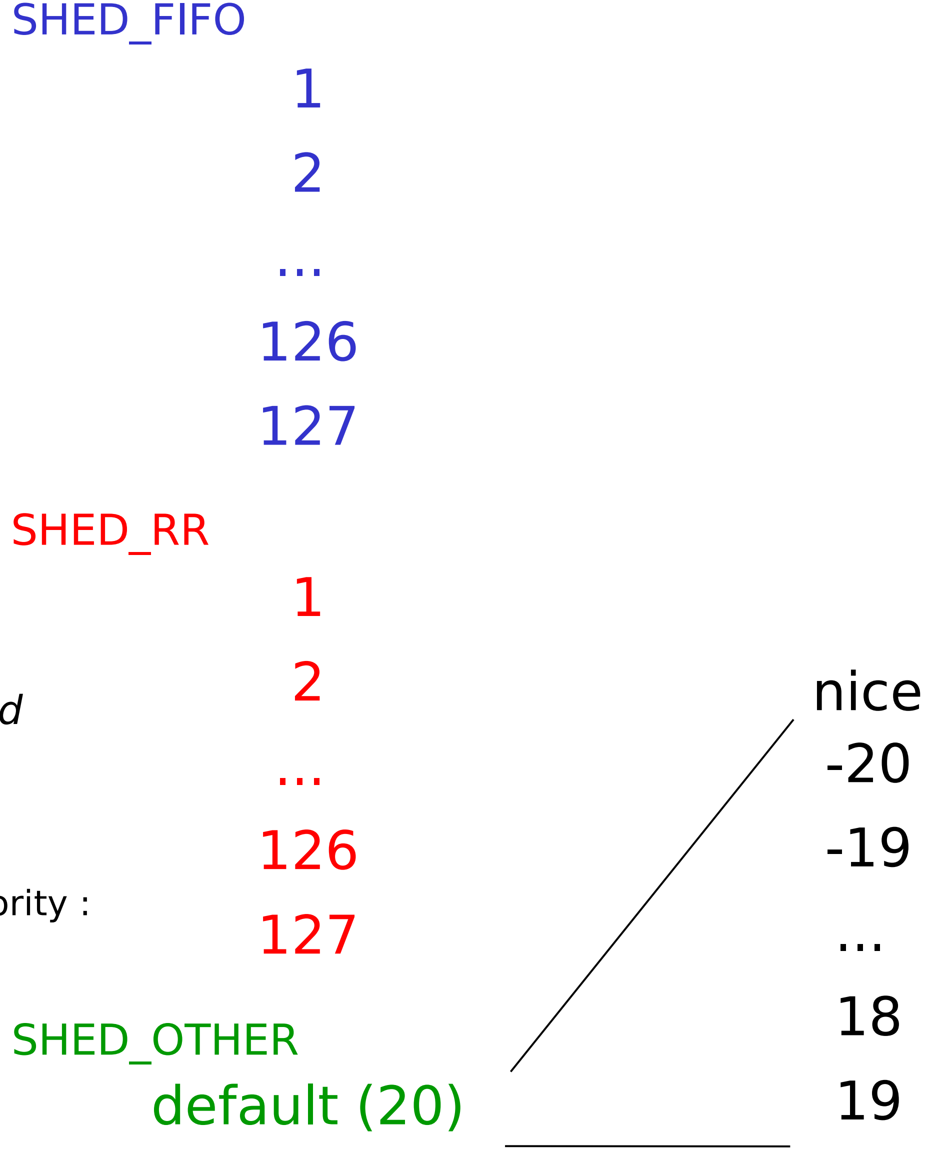
Scheduling in Linux <= 2.6.23

- ***Linux <= 2.4.x: Threads ~ processes***
- ***Linux 2.6.x: thread scheduling***

- *SHED_FIFO*
  - may run forever, no timeslices
  - may use it’s own scheduling algorithm
- *SHED_RR*
  - each priority in RR
  - timeslices of 10 ms (quantums)
- *SHED_OTHER*
  - ordinary user processes
  - uses “nice”-values: 1≤ priority≤40
  - timeslices of 10 ms (quantums)

- *Threads with highest goodness are selected first:*
  - realtime (FIFO and RR):
    goodness = 1000 + priority
  - timesharing (OTHER):
    goodness = (quantum > 0 ? quantum + priority : 0)

- *Quantums are reset when no ready process has quantums left:*
  quantum = (quantum/2) + priority
- *O(1) from 2.6.1*



SHED_FIFO

1
2
...
126
127

SHED_RR

1
2
...
126
127

SHED_OTHER

default (20)

nice
-20
-19
...
18
19

Linux CFS Scheduler (kernel >= 2.6.23)

- Used for SCHED_OTHER
- Waiting processes added to time ordered tree of all waiters
  - red/black binary search tree
- Remove 'smallest' = O(1), insert is O(log n) for n waiters
- Tasks can be scheduled at fine granularity
  - 'liberated' from timer interrupt frequency
- Simplifies logic
  - no need to 'switch between queues'
  - no interactivity heuristics
- Tuned with single parameter:

  /proc/sys/kernel/sched_min_granularity_ns

Lottery Scheduling

- *Motivations*
  - SRTCF does well with average response time, but unfair
  - Guaranteed scheduling may be hard to implement
  - Adjust priority is a bit ad hoc. For example, at what rate?

- *Lottery method*
  - Give each job a number of tickets
  - Randomly pick a winning tickets
  - To approximate SRTCF, short jobs gets more tickets
  - To avoid starvation, give each job at least one ticket
  - Allows ticket exchange

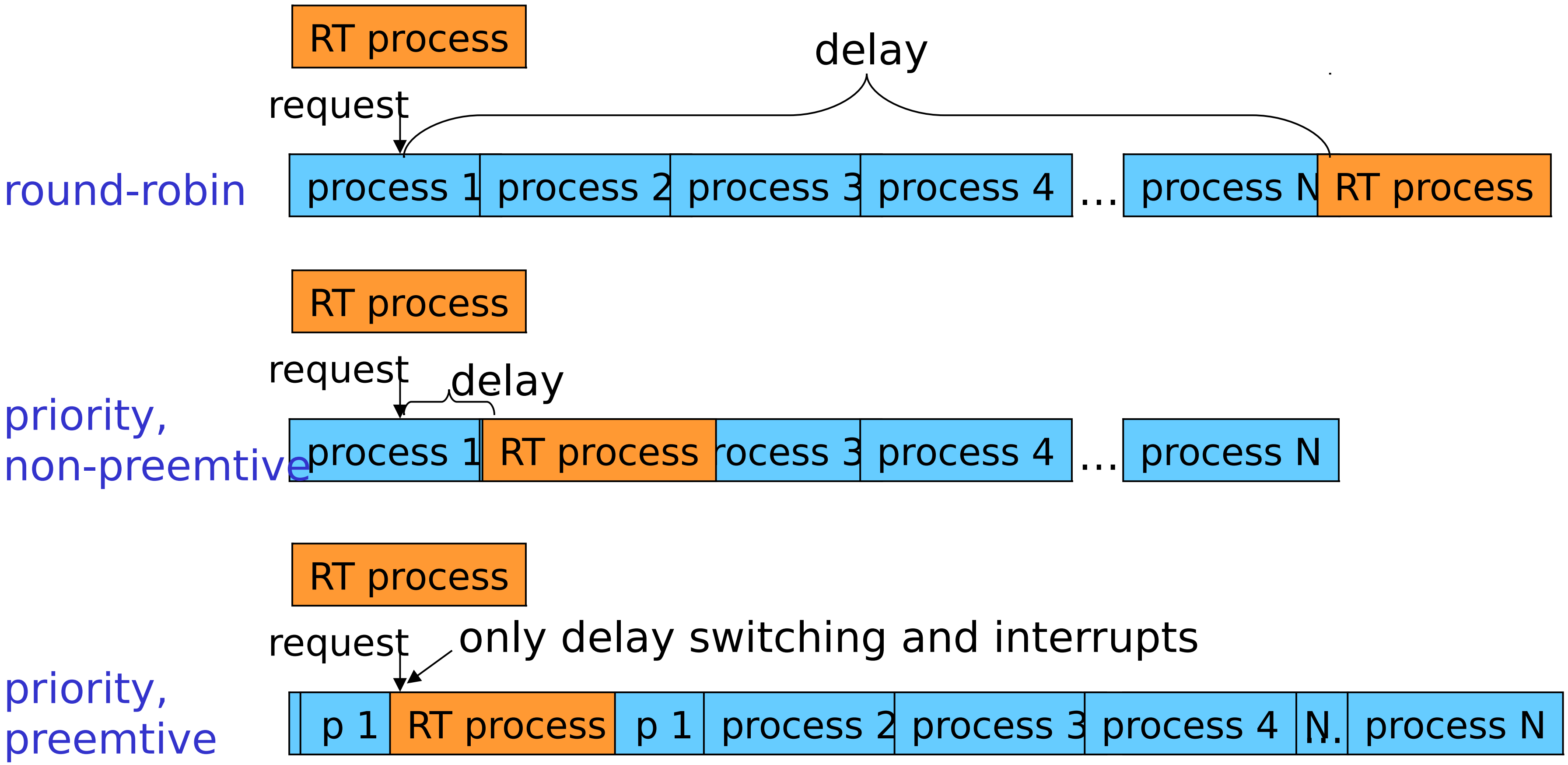
C.A. Waldspurger and W.E. Weihl, “Lottery Scheduling: Flexible Proportional-Share Resource Management.”
Proc. of the 1st USENIX Symp. on Operating System Design and Implementation (OSDI). Nov 1994.

Fair Share

- *Each PROCESS should have an equal share of the CPU*
- *History of recent CPU usage for each process*
- *Process with least recently used CPU time := highest priority*
  - ➔ an editor gets a high priority
  - ➔ a compiler gets a low priority

- *Each USER should have an equal share of the CPU*
- *Take into account the owner of a process*
- *History of recent CPU usage for each user*

Real-Time Scheduling



RT process

request

delay

round-robin

process 1 | process 2 | process 3 | process 4 | … | process N | RT process

RT process

request

delay

priority, non-preemtive

process 1 | RT process | rocess 3 | process 4 | … | process N

RT process

request

only delay switching and interrupts

priority, preemtive

p 1 | RT process | p 1 | process 2 | process 3 | process 4 | N. | process N

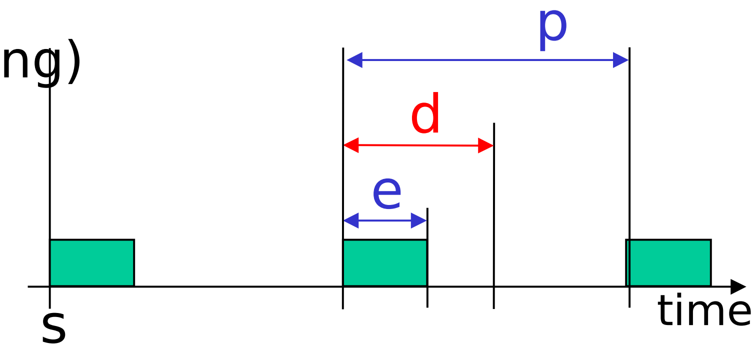
NOTE: preemption may also be limited to preemption points (fixed points where the scheduler is allowed to interrupt a running process) → giving larger delays

Real-Time Scheduling

- *Real-time tasks are often periodic (e.g., fixed frame rates and audio sample frequencies)*

- *Time constraints for a periodic task:*
  - s – starting point (first time the task require processing)
  - e – processing time
  - d – deadline
  - p – period
  - r – rate ($r = 1/p$)

  - $0 \le e \le d$ (often $d \le p$: we'll use $d = p$ – end of period, but $\boldsymbol{\Sigma} d \le \boldsymbol{\Sigma} p$ is enough)
  - the **k**th processing of the task
    - is ready at time $s + (k - 1) p$
    - must be finished at time $s + (k - 1) p + d$
  - the scheduling algorithm must account for these properties



Schedulable Real-Time Systems

- *Given*
  - *m* periodic events
  - event *i* occurs within period P_i and requires C_i seconds

- *Then the load can only be handled if*

$$\sum_{i=1}^{m} \frac{C_i}{P_i} \leq 1$$

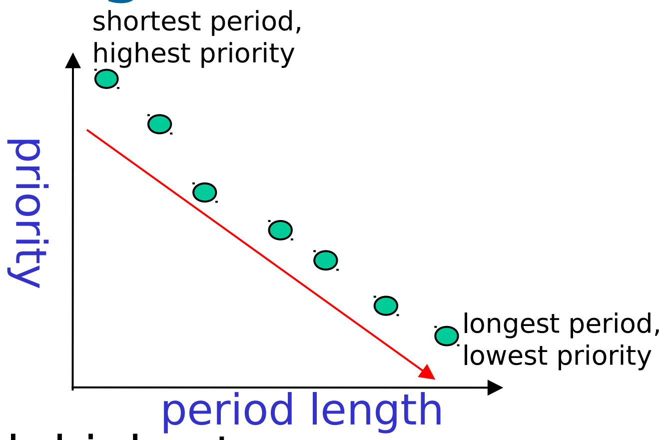
- *Can we process 3 video streams, 25 fps, each frame require 10 ms CPU time?*
  - $3 * (10\text{ms}/40\text{ms}) = 3 * 25 * 0.010 = 0.75 < 1$ → YES

Rate Monotonic (RM) Scheduling

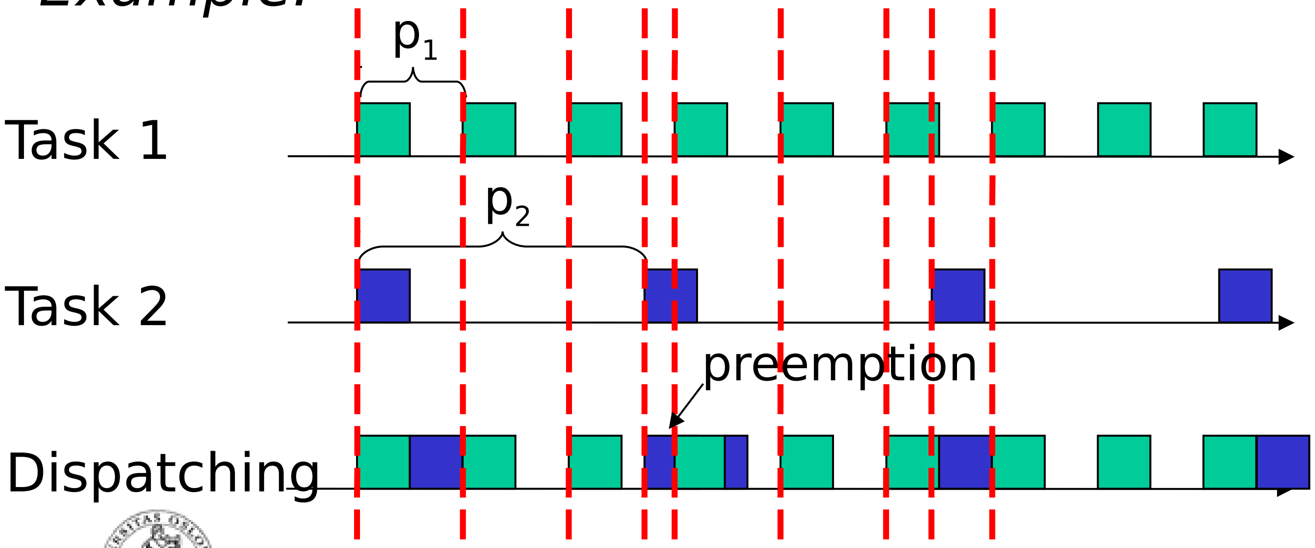
- *Classic algorithm for hard real-time systems with one CPU*
  [Liu & Layland ‘73]
- *Pre-emptive scheduling based on static task priorities*
- *Optimal: no other algorithms with static task priorities can schedule tasks that cannot be scheduled by RM*
- *Assumptions:*
  - requests for all tasks with deadlines are periodic
  - the deadline of a task is equal to the end on its period (starting of next)
  - independent tasks (no precedence)
  - run-time for each task is known and constant
  - context switches can be ignored
  - any non-periodic task has no deadline

Rate Monotonic (RM) Scheduling

- *Process priority based on task periods*
  - task with shortest period gets highest *static* priority
  - task with longest period gets lowest *static* priority
  - dispatcher always selects task requests with highest priority



- *Example:*



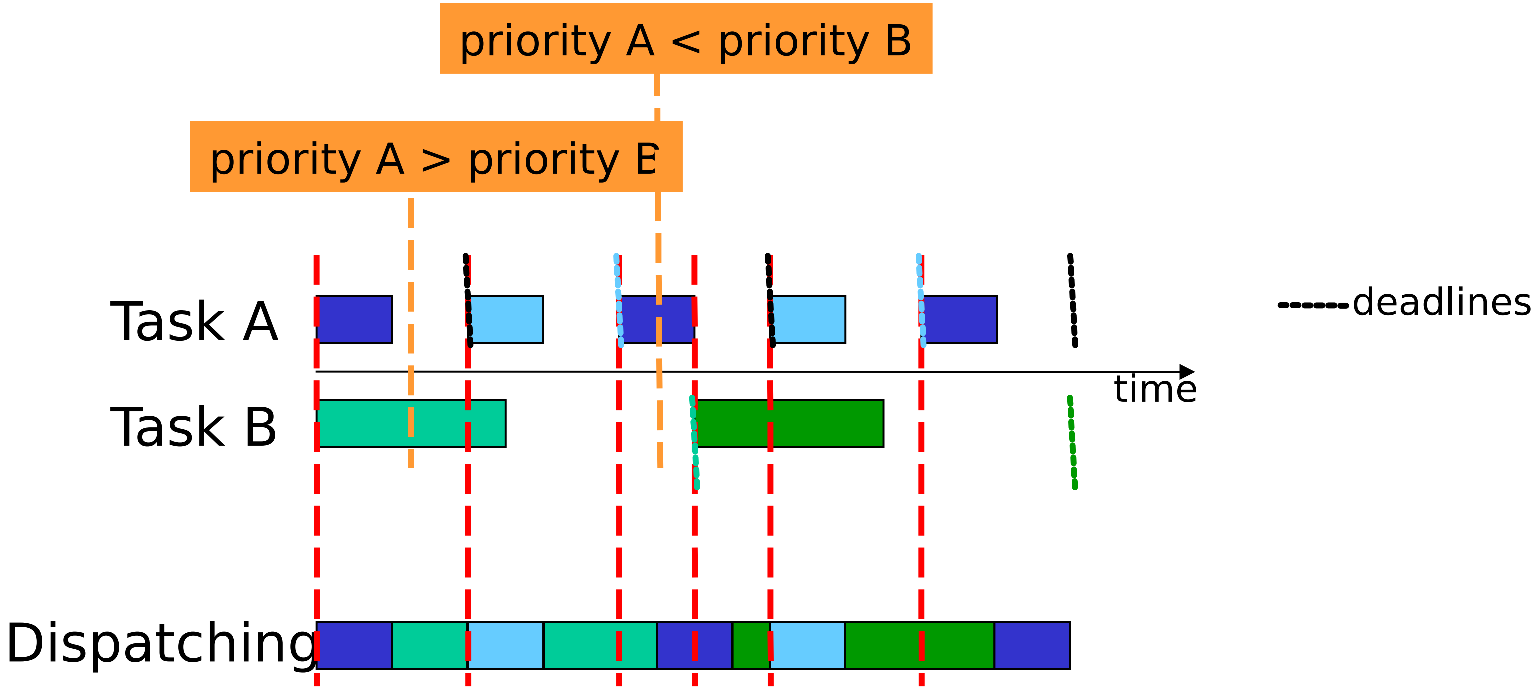
$P_1 < P_2$
→ P_1 highest priority

Earliest Deadline First (EDF)

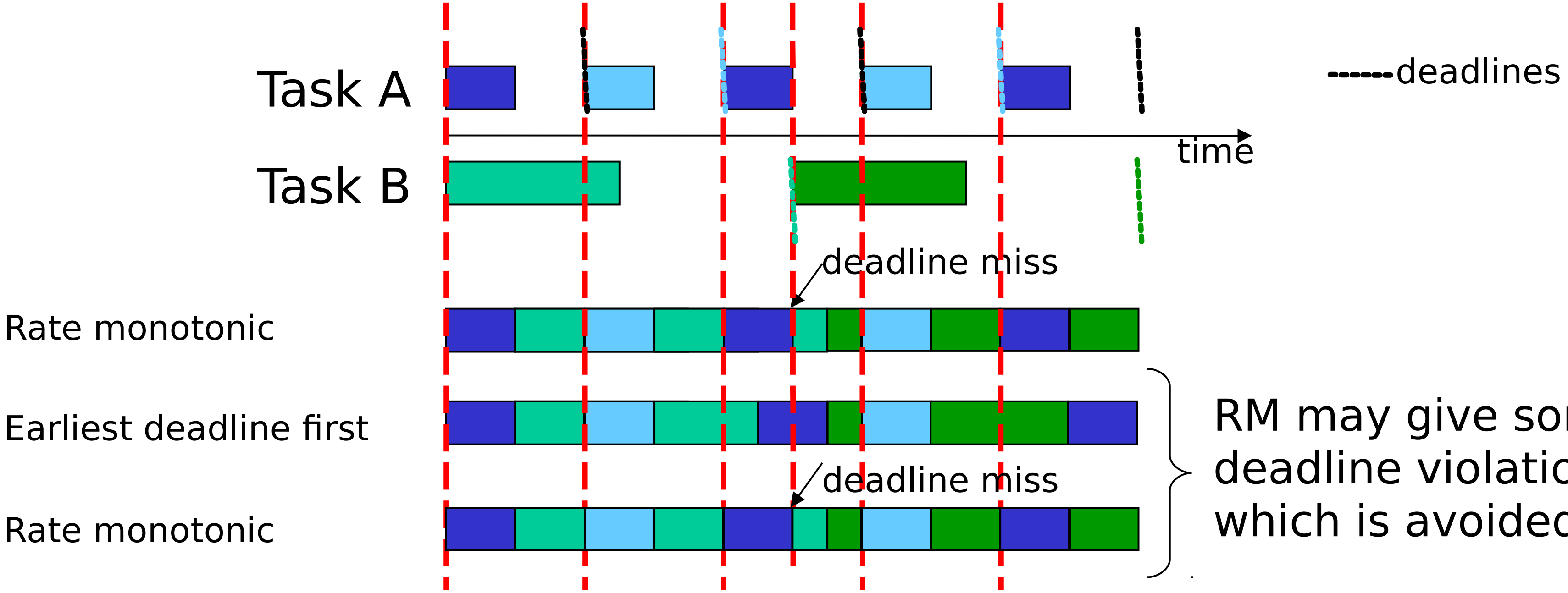
- *Preemptive scheduling based on dynamic task priorities*
- *Task with closest deadline has highest priority → priorities vary with time*
- *Dispatcher selects the highest priority task*
- *Assumptions:*
  - requests for all tasks with deadlines are periodic
  - the deadline of a task is equal to the end on its period (starting of next)
  - independent tasks (no precedence)
  - run-time for each task is known and constant
  - context switches can be ignored

Earliest Deadline First (EDF)

- *Example:*



EDF Versus RM – I



RM may give some deadline violations which is avoided by ED

EDF Versus RM – II

- *EDF*
  - dynamic priorities changing in time
  - overhead in priority switching
  - QoS calculation – maximal throughput:

$$\sum_{\text{all streams } i} R_i \text{ x } P_i \leq 1,$$ R – rate, P – processing time

- *RM*
  - static priorities based on periods
  - may map priority onto fixed OS priorities (like Linux)
  - QoS calculation:

$$\sum_{\text{all streams } i} R_i \text{ x } P_i \leq \ln(2),$$ R – rate, P – processing time

Summary

- *Scheduling performance criteria and goals are dependent on environment*
- *There exists several different algorithms targeted for various systems*
- *Traditional OSes like Windows, Unix, Linux, ... usually uses a priority-based algorithm*
- *The right time slice can improve overall utilization*