Real-Time Systems

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Scheduling

An Introduction

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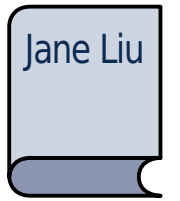
TECHNISCHE UNIVERSITÄT DRESDEN

Event-Driven / Priority-Based Scheduling

Outline:

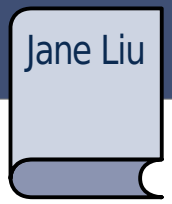
- Principles
- Preemption and Scheduling
- EDF and LST as “dynamic” scheduling methods
  - **Few SMP insights**
  - **Anomalies**
- Fixed Priority schedulers
- Admission based on Utilization
- mostly following Jane Liu, Real-Time Systems



Principles

- Admission:
  - **check if feasible schedule exists**
  - **decide how “priorities” are assigned to Jobs**
- Scheduling / Dispatching:
  At events, jobs are selected according to their priorities

Principles



Important properties:

- **decisions, which job to execute next at EVENTS (not time instants)**
  Events are modeled as releases and completions of jobs
- **a (timer) interrupt is an (implementation of a) special event**
- **never leaves a resource idle intentionally (“greedy”)**
- **scheduling on line,**
  admission on line or off line
- **scheduling must be simple**
  (otherwise difficult/not possible on line)

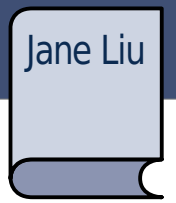
Principles

Optimality of Schedulers:

A scheduling method X is called “optimal” in a class of scheduling problems, if the following property holds:

> If there exists a scheduling method Y that produces a feasible schedule
> then X produces a feasible schedule as well

Restrictions Given Up



- some “restrictive” assumptions of time-driven systems are given up:
  - **fixed inter-release times**
    → minimum inter-release times
  - **fixed number of rt tasks in systems**
    real-time and non real-time, number can vary
  - **a priori fairly well known parameters**
    tasks come and go, overloading, ...

Priority Assignment Following "Criticality"

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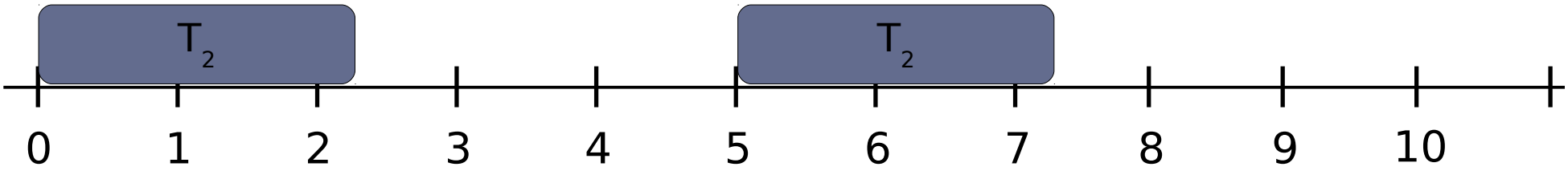
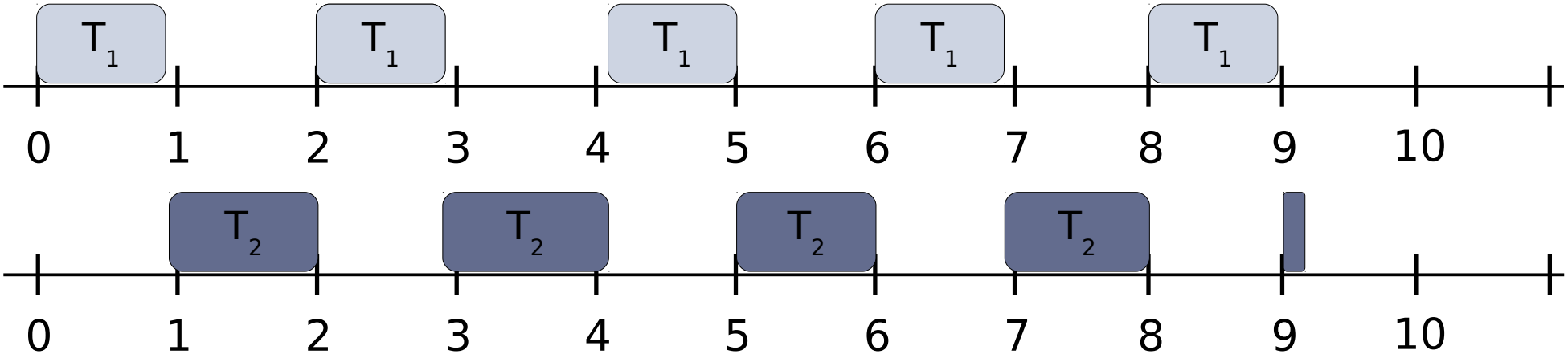
- The more critical a task, the higher its priority

T_1: (2 , 0.9) T_2: (5 , 2.3) → T2 more critical than T1



- T_1 misses deadline in Job 1 and 2/3, unnecessarily ...



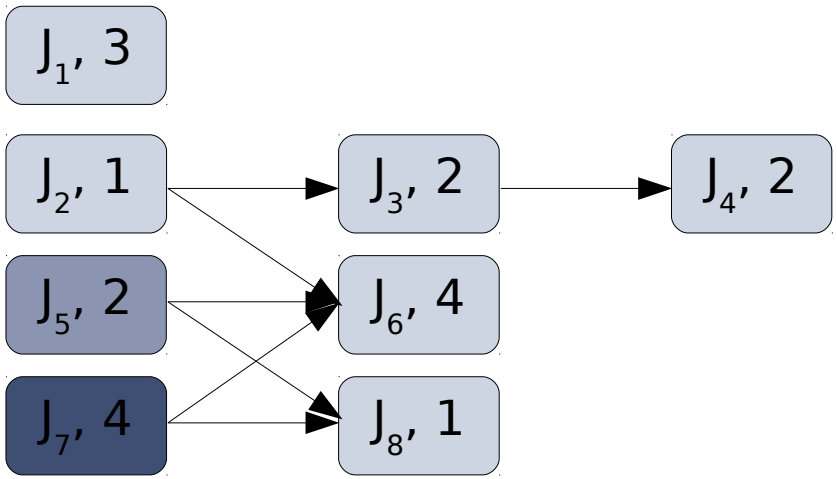
Important Variants

- Static vs dynamic allocation to processors
  - **Partitioned tasks are assigned to processors**
  - **Static: jobs are assigned to processors once and stay**
  - **Dynamic: jobs “migrate”**
    - **example: one run queue served by all processors**
- preemptive or non preemptive
  - **some tasks**
  - **all tasks**

Preemptive vs. Non-Preemptive Scheduling

Jane Liu

- 2 processors,
- Tasks: Notation used below: J_i ,e_i
  - **release time of J_5 is 4, all others 0; (!)**
- static priorities, assigned such that:
  $i < k \Rightarrow$ Prio(J_i) higher than Prio(J_k)
- Tasks can “migrate”
- precedence graph:



Example, executions

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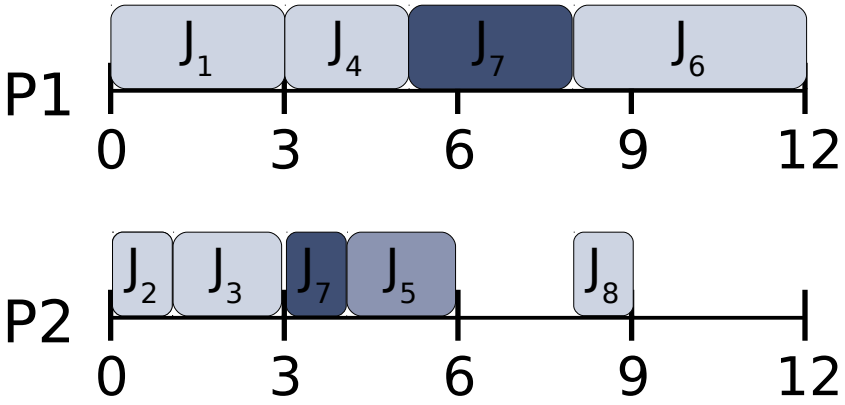
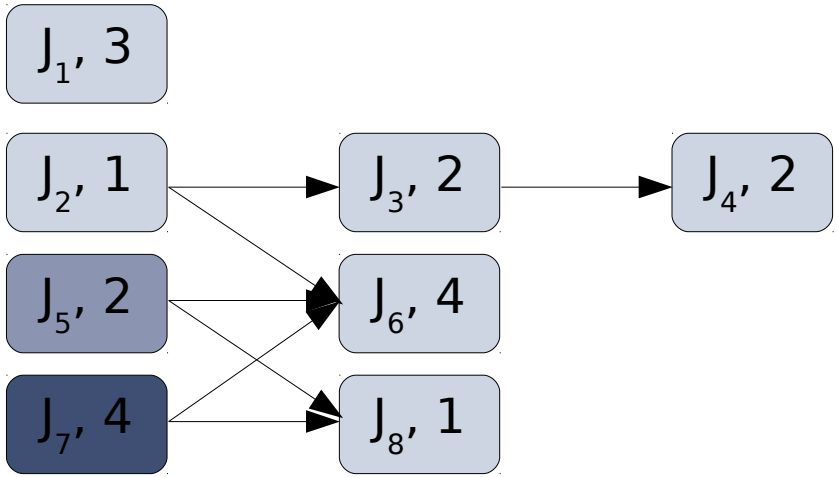
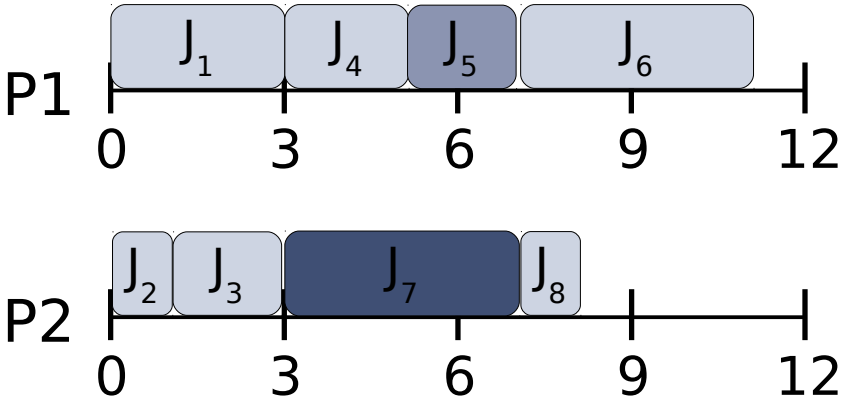


preemptiv





non-preemptiv

Modified Example: release time of $J_5 = 0$

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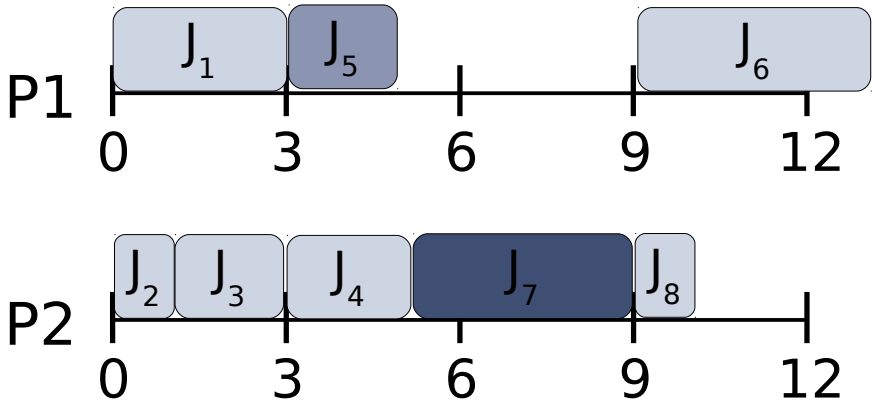

non-
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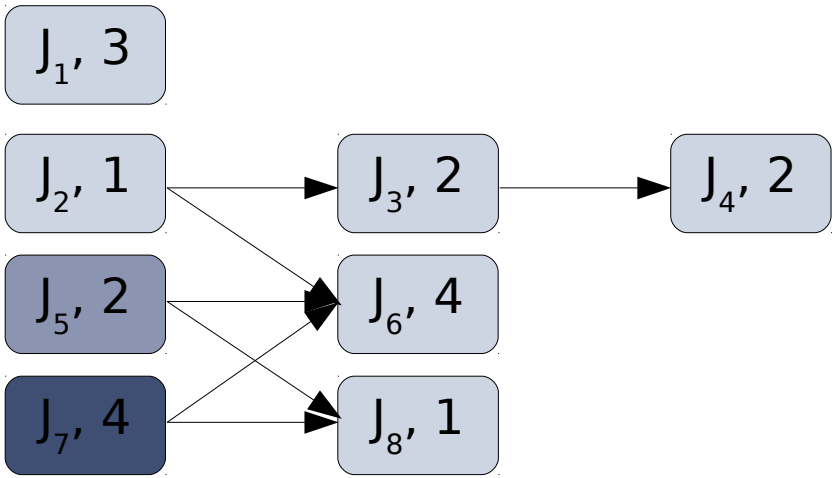

Which is better?

- No *general* answer known!
- If jobs have same release time:

  preemptive is better (or equal) in a multiprocessor system if cost for preemption is ignored
- more precise: “makespan” is better

  (makespan = response time of job that completes last)
- how much better? Coffman and Garey:
  - **2 processors: makespan(non-preemptive) <= 4/3 * makespan(preemptive)**

Earliest Deadline First

- Assign priorities at run time …

  “the earlier the deadline the higher the priority”

- Theorem:
  - **One processor.**
  - **Jobs preemptable.**
  - **Jobs do not contend for passive resources.**
  - **Jobs have arbitrary deadlines, release times.**
  - **Then: EDF is “optimal”, i.e.**
    if there is a feasible schedule,
    there is also one with EDF

EDF Optimality

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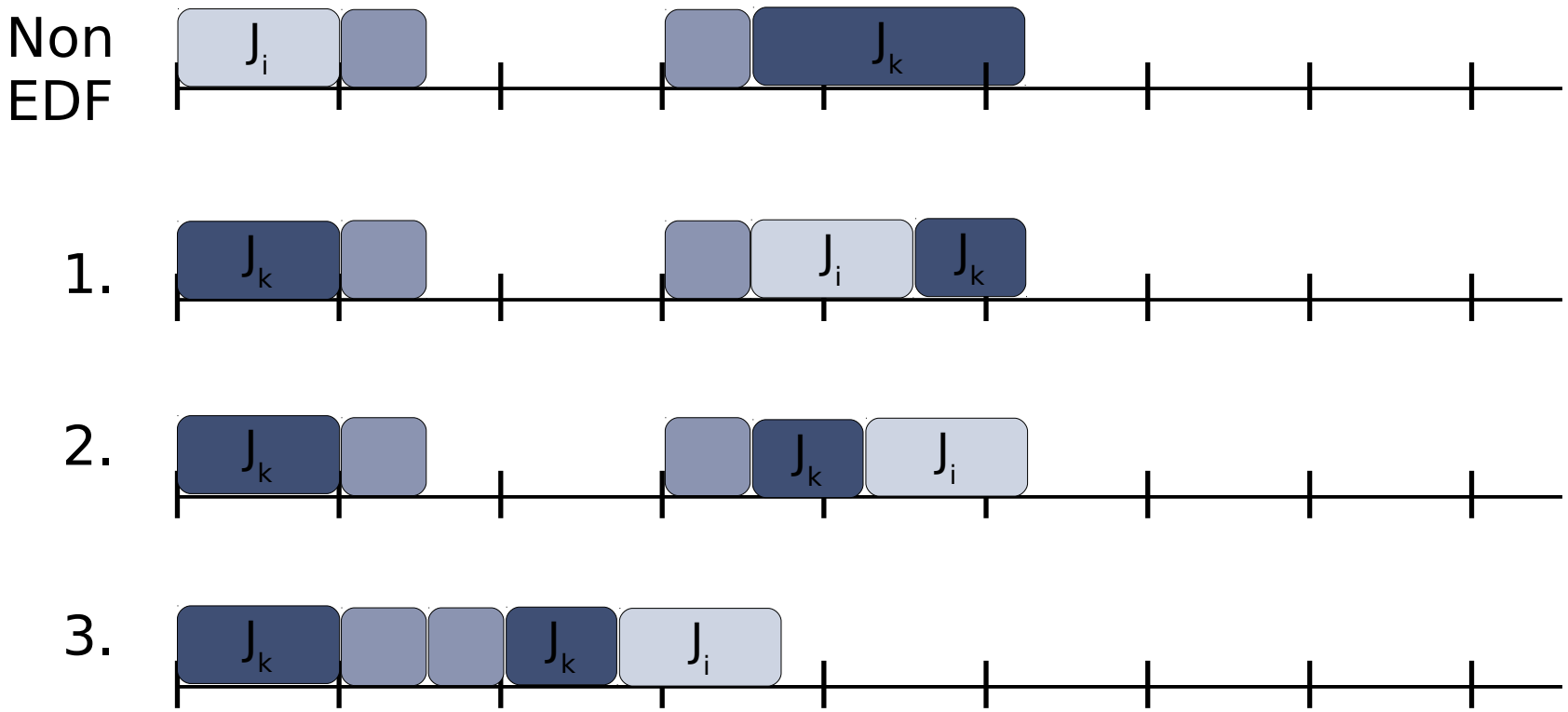
- Proof: (informal)
  - **assume a feasible, non EDF schedule**
  - **systematically transform it to an EDF schedule (3 steps)**



Latest Release Time (LRT)

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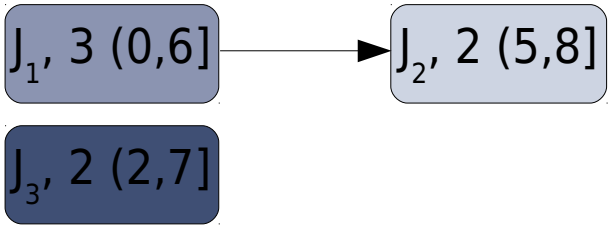
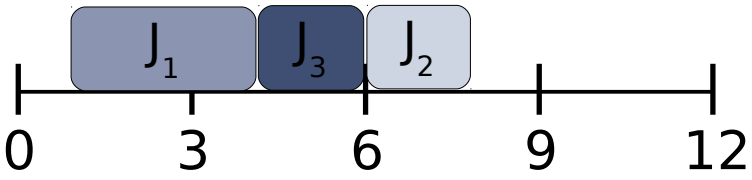
- Rationale:
  - **no need to complete rt-jobs before deadline**
  - **use time for other activities**
- Idea:
  - **Backwards Scheduling**

  - **Run as late as possible**
  - **Use latest possible release times as „priority“**
  - **optimal (analog EDF-Definiton of Optimality)**
- Example (Precedence Graph):





[Least/Minimum] [Slack Time/Laxity] First

- Slack Time = Laxity:
  - **(time to deadline - remaining execution time required to reach deadline)**
- slack time: d - x - t
  - **x remaining execution time of a job**
  - **d absolute deadline**
  - **t current time**
  - **dynamic per job, dynamic at task level (see example)**
- also optimal (analog EDF definition)

Least Slack Time First

- two versions:
  - **Strict: slacks are computed at all times**
    - ***Each instruction (prohibitively slow)***
    - ***Each timer "tick"***
  - **Non-strict: slacks computed only at events (release and completion)**
- scheduler checks slacks of all ready jobs and reorders queue

Non-Strict LST Example

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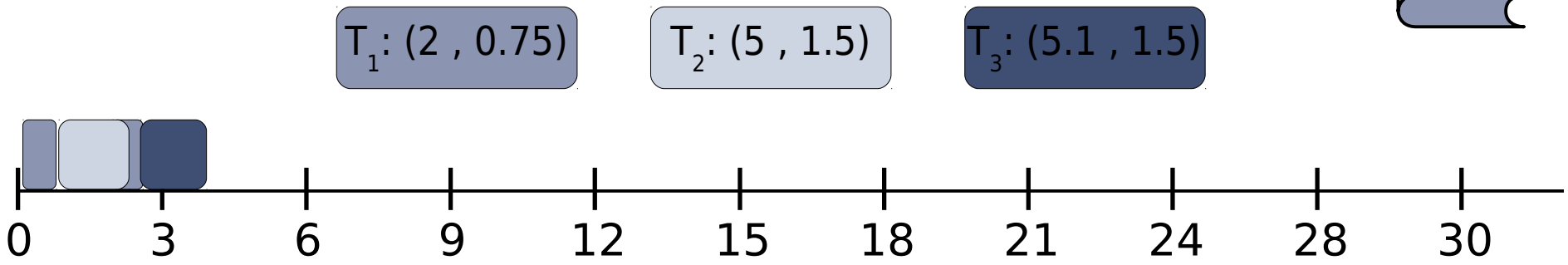

- **t=0 all Jobs are released**
  - **T_1,J_1: 1.25 T_2,J_1: 3.5 T_3,J_1: 3.6**
  - **d.h. T_2,J_1 higher priority than T_3,J_1**

- **t=2 T_1,J_2 released**
  - **T_1,J_2: 1.25 T_2,J_1: 2.75 T_3,J_1: 1.6**
  - **d.h. T_2,J_1 lower priority than T_3,J_1**

- **t=2.75 T_1,J_2 completed**
  - **T_1,J_2: T_2,J_1: 2 T_3,J_1: 0.85**

Static. Static and Dynamic (priority)

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If no new tasks arrive:

static vs. dynamic priorities

- Task static: Task T, i.e. jobs of T do not change their priorities
- Job static: Jobs do not change their priorities
- Job dynamic: Jobs change their priorities

Careful:

Job static is often called dynamic as well

Earliest Deadline First, priority assignment:

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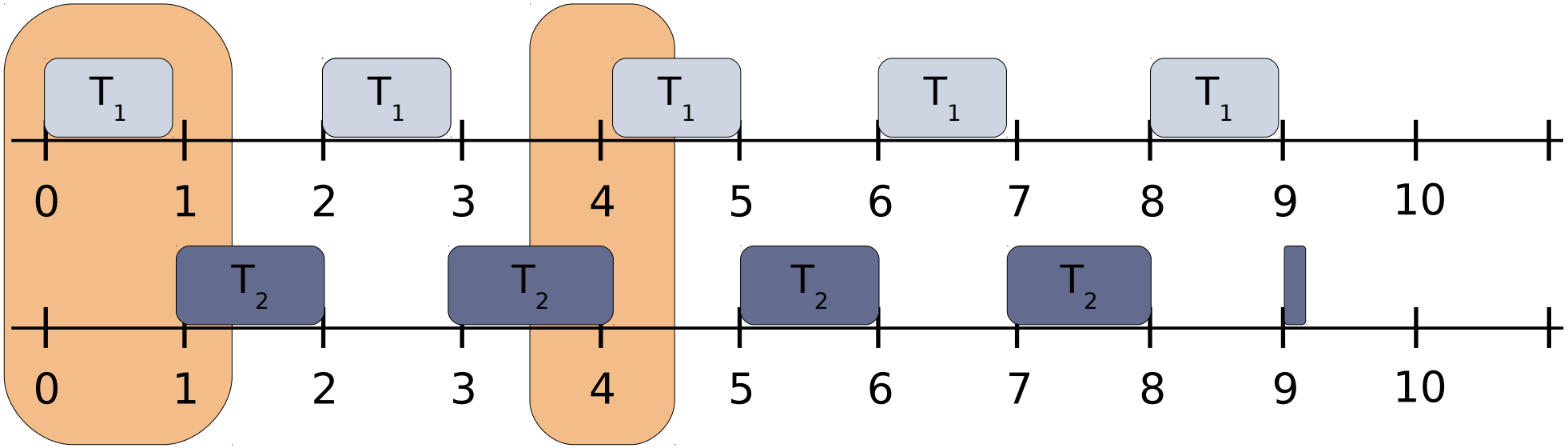
- fixed per job, dynamic at task level:
  - **the nearer the absolute deadline of a job at release time**
  - **the higher the priority**

T_1: (2 , 0.9) T_2: (5 , 2.3)



EDF and Non - Preemptivity

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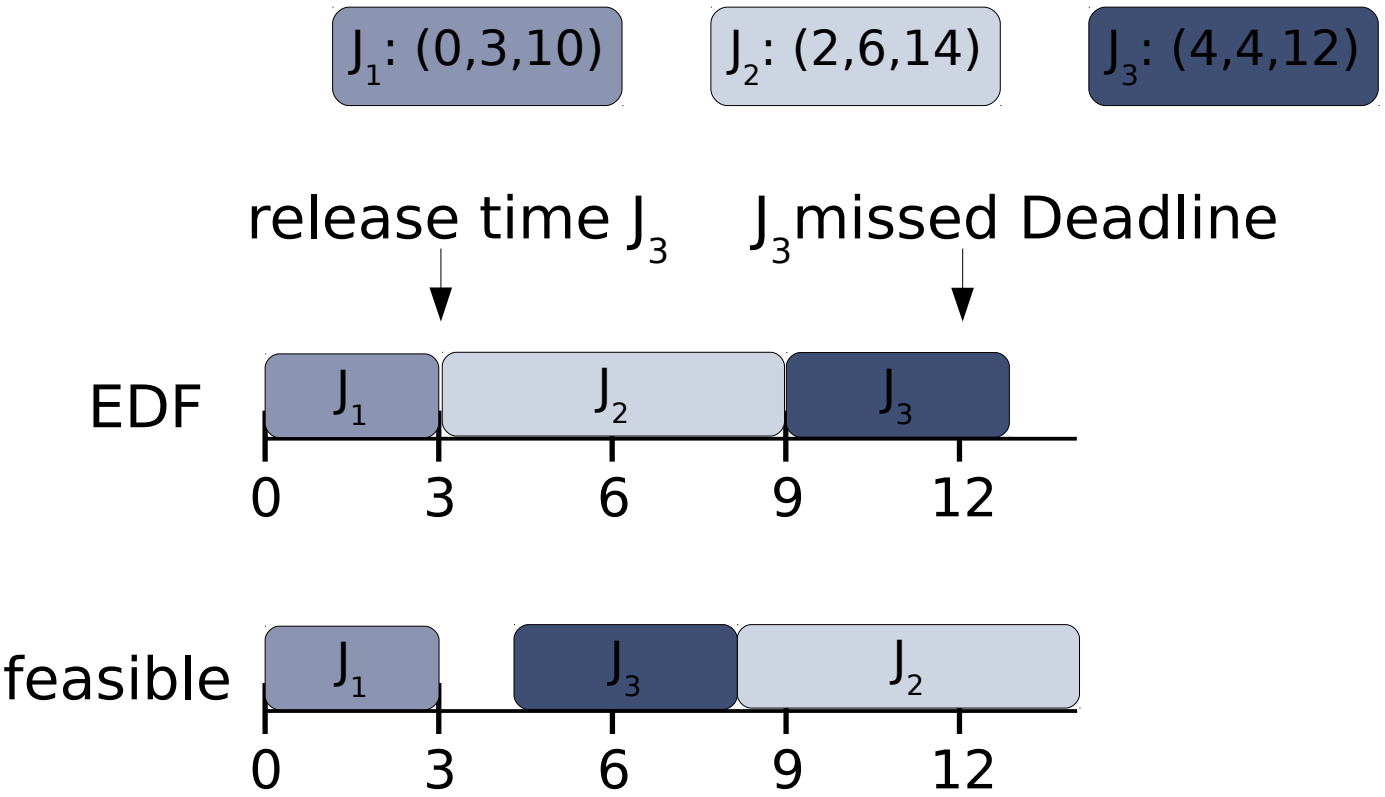
- Job: (release time, execution time, deadline)



- EDF is not optimal if jobs are not preemptable

EDF and Multiple Processors

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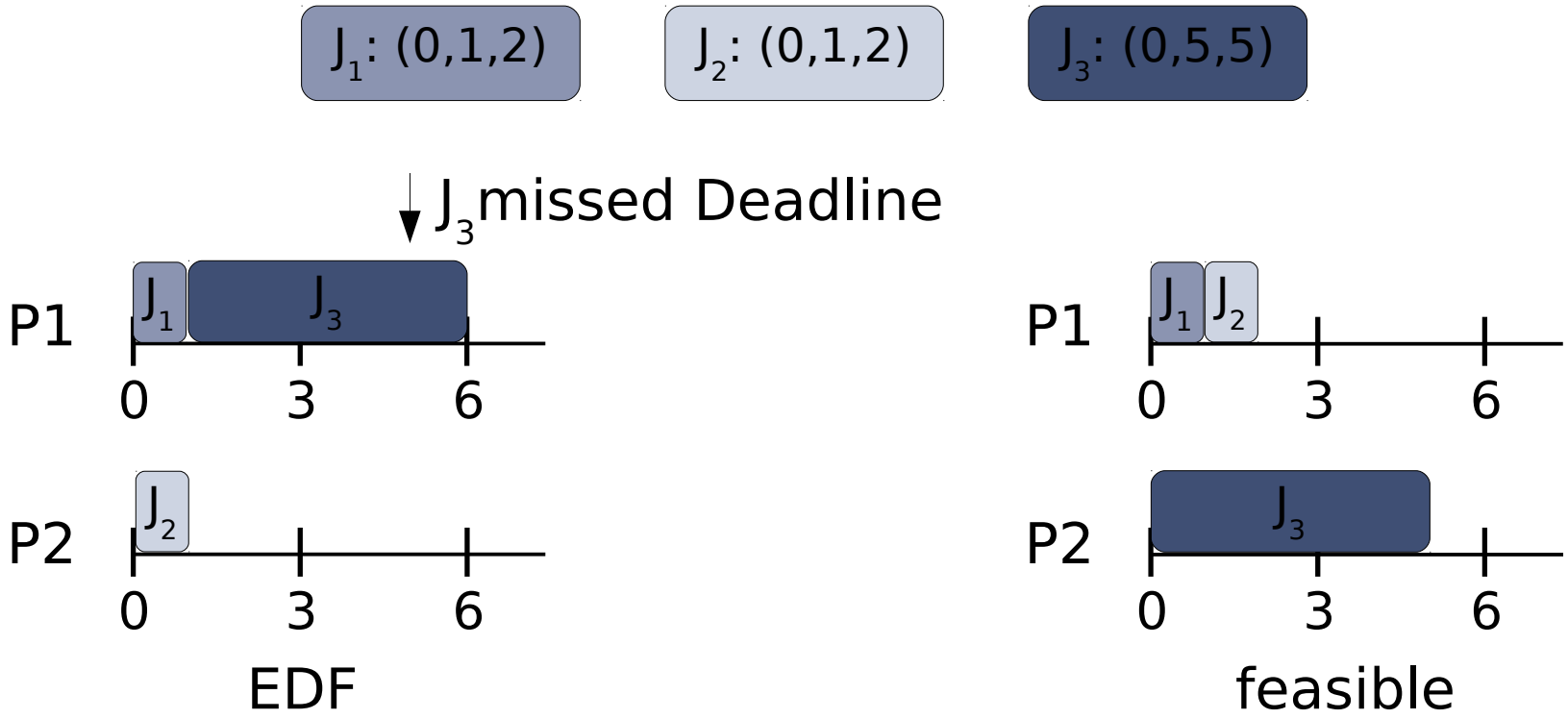
- Job: (release time, execution time, deadline)



- easy for time driven schedulers
- EDF is not optimal for Multiprocessors

Multiple Processors

- EDF not optimal

  general: “static-job” scheduling not optimal

- There are optimal “dynamic-job” schedulers

More later in this course (including references)

Scheduled for 13.1.2010 (Marcus Völp)

Scheduling Anomaly

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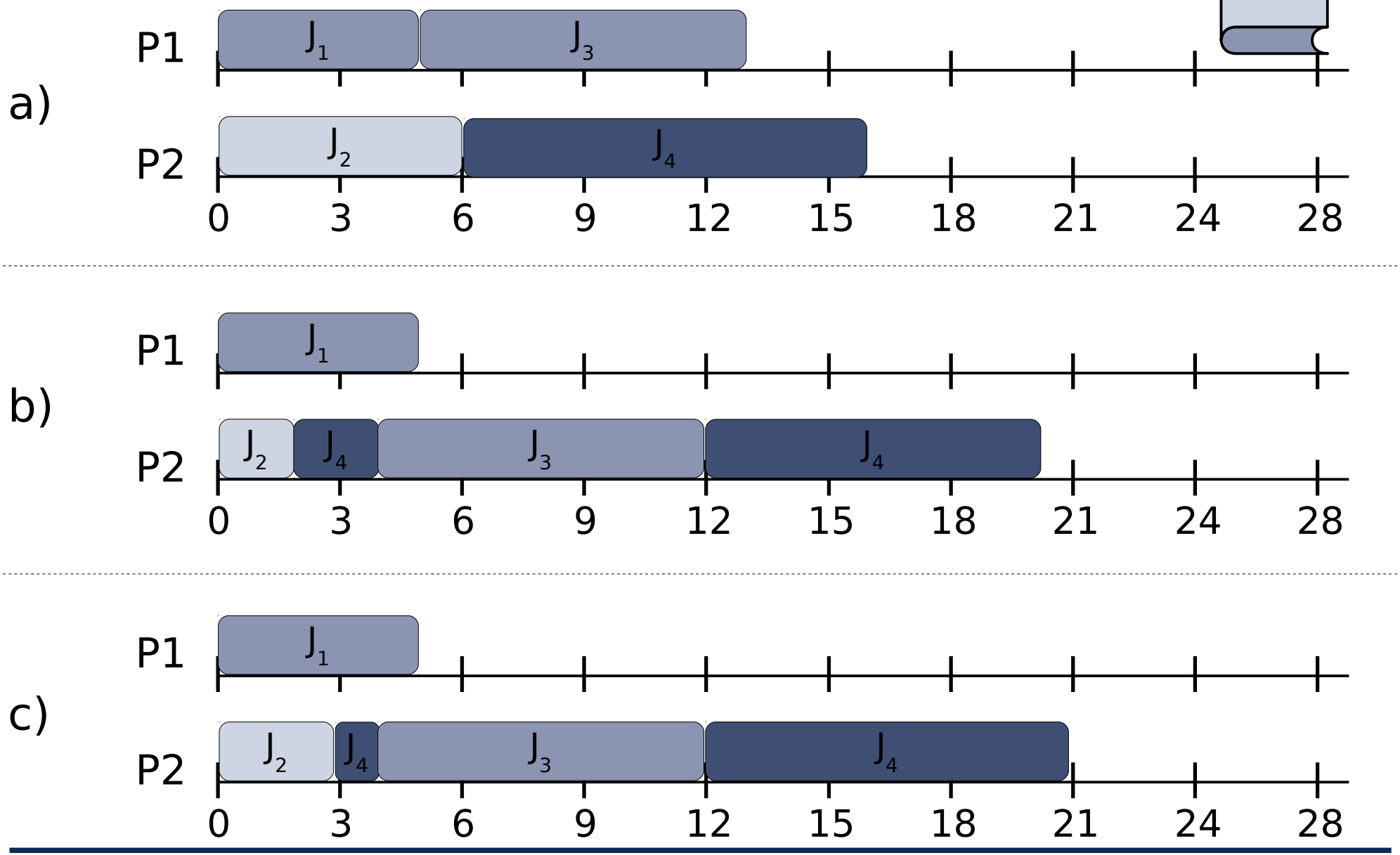
	release	deadline	execution
J_1	0	10	5
J_2	0	10	[2,6] varies
J_3	4	15	8
J_4	0	20	10

- increasing priorities:
  - **i < k => Prio(J_i) higher than Prio(J_k)**
- 2 processors, preemptable but not migratable
- intuitive approach:
  - **check for worst case(a) and best case(b) execution times and be confident ...**

Scheduling Anomaly, cont



Scheduling Anomaly on One Processor

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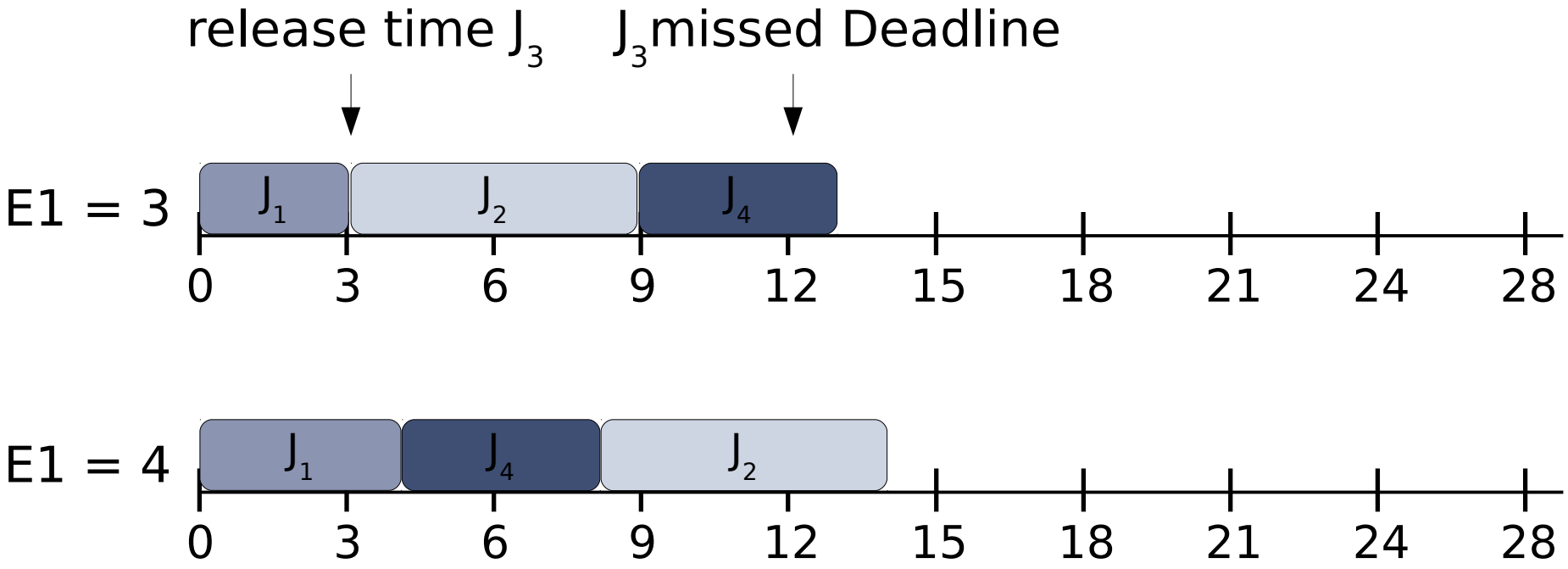
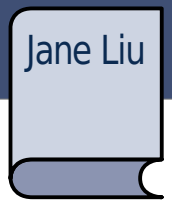
- Job: (release time, execution time, deadline)

J_1: (0,3-4,10) J_2: (2,6,14) J_3: (4,4,12)

- Not preemptable



Predictable/Sustainable Execution



- Informal definition:

  Given a set of periodic tasks with known minimal and maximal execution times and a scheduling algorithm.

  A schedule produced by the scheduler when the execution time of each job has ist maximum (minimum) value is called a *maximum (minimum) schedule*.

  An execution is called *predictable*, if for each actual schedule the start and completion times for each job are bound be those of the *minimum and maximal schedules*.

The execution of every job in a set of independent, preemptable jobs with fixed release times is predictable when scheduled in a priority driven manner on one processor.

Assumptions for Next Set of Algorithms

- Periodic set of tasks with these properties:
  - **Tasks are independent**
  - **one processor**
  - **no aperiodic tasks**
  - **preemptable, context switch is negligibly small**
  - **(period = minimum inter-release times (not fixed))**

- Since tasks are independent, tasks can be added (if admitted) and deleted at any time without causing deadline misses.

Rate Monotonic Scheduling

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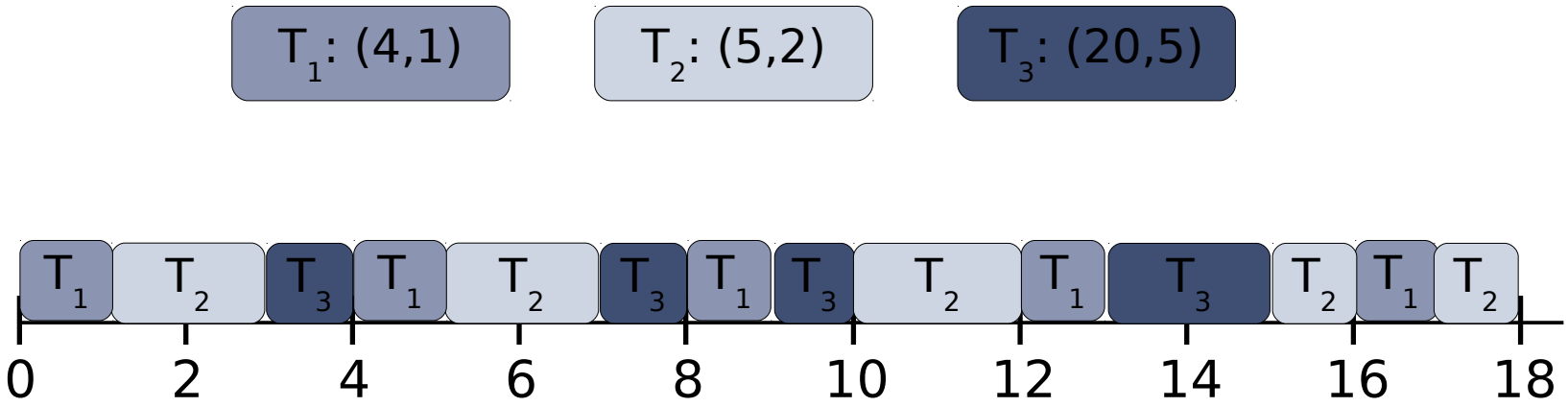
- fixed priority:
  - **the shorter the period the higher the priority (rate: inverse of period)**



Deadline Monotonic Scheduling

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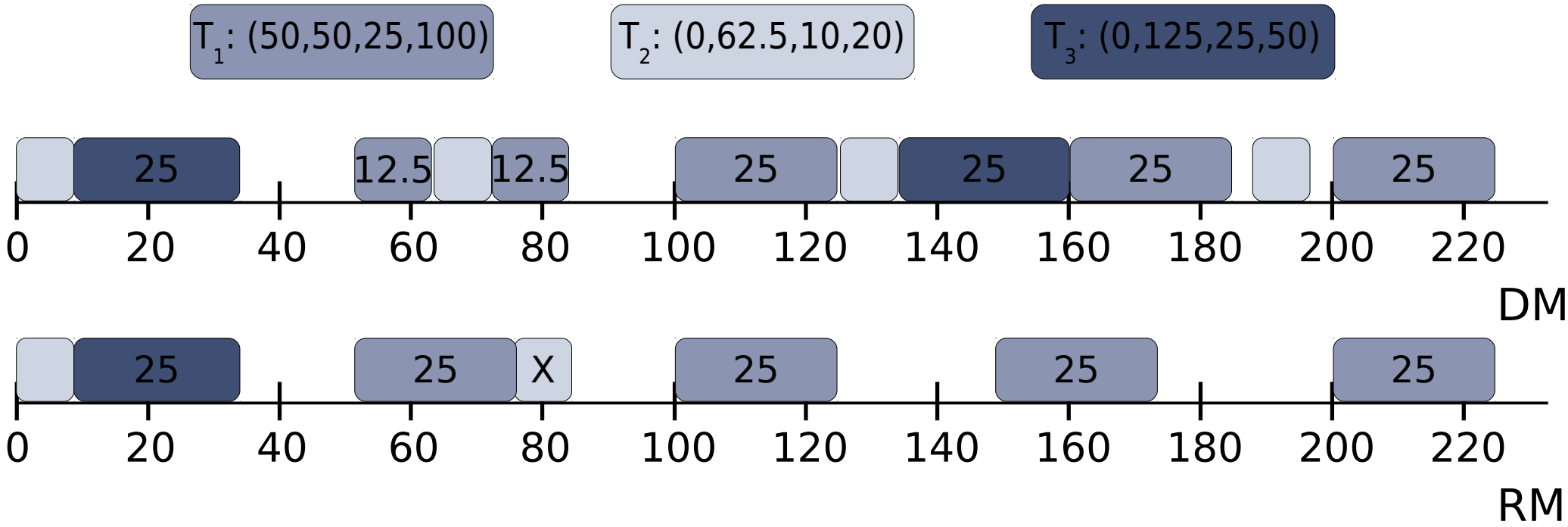
- fixed priority:
  - **the shorter the relative deadline the higher the priority**
- example: (,P,e,D)



- Conclusion (no proof): DM is better than RM if D arbitrary

Priority-Driven Scheduling of Periodic Tasks

- To do:
  - **admission (required before new tasks are admitted)**
  - **priority assignment (off line / on line)**
  - **selection of next task (on line)**
- restrictions (whether they apply or not)
  - **dependencies (precedence, sharing)**
  - **multiple processors**
  - **aperiodic, sporadic**
- achievable resource utilization: U= e/p

EDF and Multiple Processors

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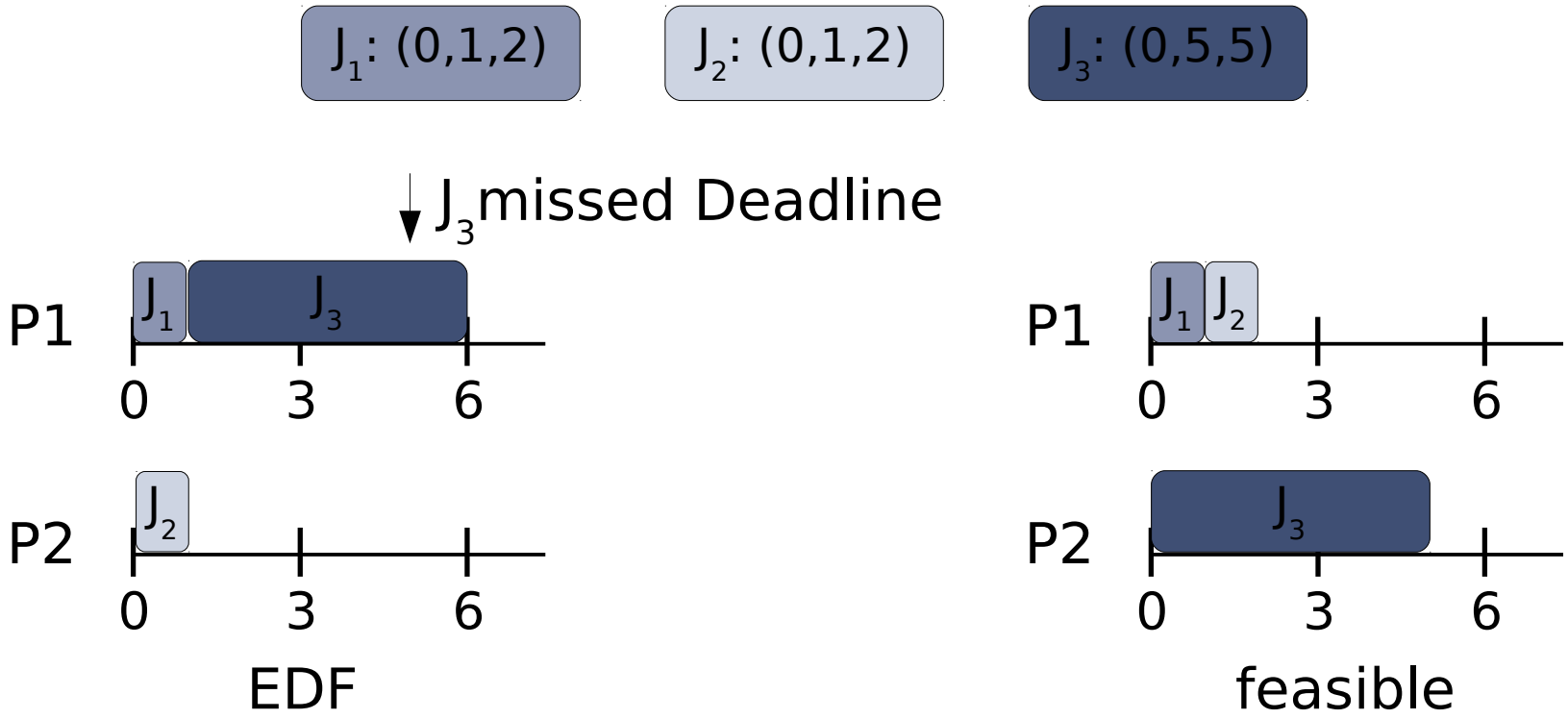
- Job: (release time, execution time, deadline)



- easy for time driven schedulers
- EDF is not optimal for Multiprocessors

Another Multiprocessor Example(Dhall 78)

m processors, m+1 tasks

> 0, m*2 < 1, small

- **T_i, i=1..m: Period 1, execution time: 2**
- **T_{m+1}: Period 1+ , execution time: 1**

- scheduler: priority (edf)
- allocation: dynamic
- *discuss !*

Pathological case.

EDF and Overload, examples

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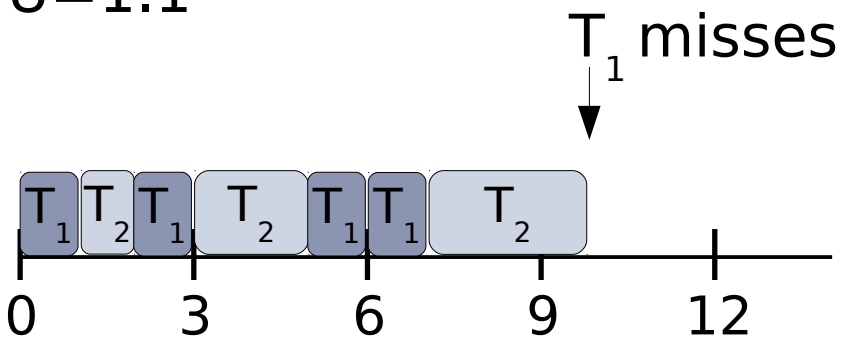
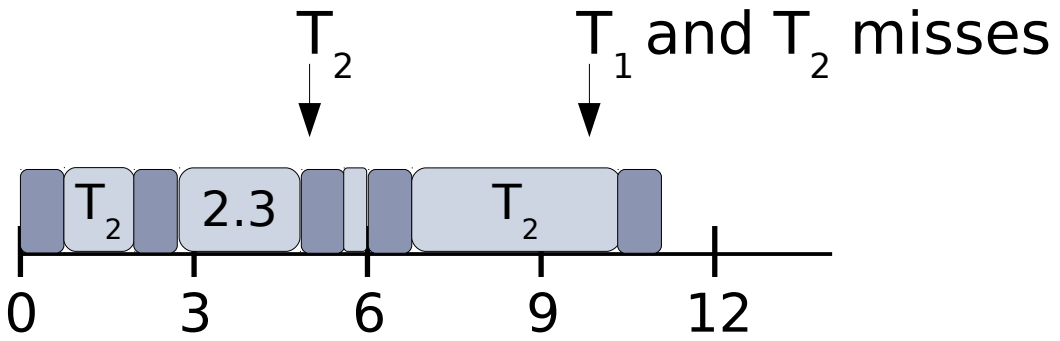
T_1: (2 , 1) T_2: (5 , 3) U=1.1



T_1: (2 , 0.8) T_2: (5 , 3.5) U=1.1



- No easy way to determine which jobs miss deadline ...

EDF and Overload, one more example

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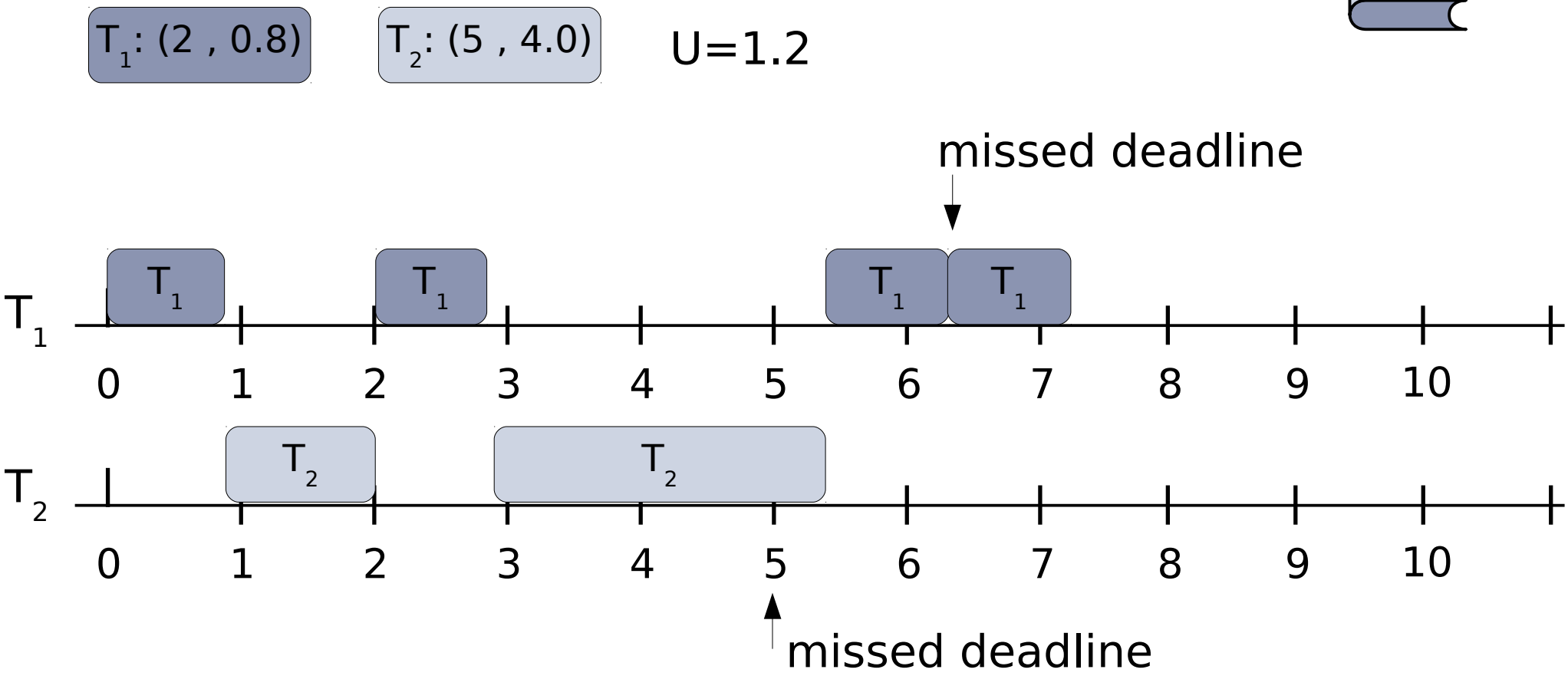


- J2,1 continues to execute after deadline and ...

  ... causes J1,3 to miss the deadline

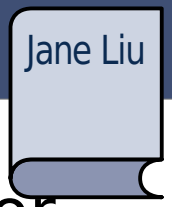
predictability in the presence of overload

-
  - **in fixed priority systems it is possible to predict which tasks are affected due to overruns**

Optimality of Fixed Priority Schedulers

- T: peridodic tasks, independent, preemptable, one proc.
- Deadline Monotonic:
  - **relative deadlines <= periods, in phase**
    if there is any feasible fixed priority schedule for T,
    then Deadline Monotonic is feasible as well
- Rate Monotonic (RMS):
  - **relative deadlines = periods**
    if there is any feasible fixed priority schedule for T,
    then Rate Monotonic is feasible as well
    simply periodic, i.e.
    for all pairs of tasks i,j: if $P_i <= P_j$ holds $P_j = n * P_i$

Admission based on Utilization



A task (P,e) requires e/P of the capacity of a processor

Any scheduler can admit at most up to full capacity:

- **For a task set $T_1 .. T_n$: $\sum e_i/p_i \leq 1$ is a necessary but not sufficient condition**

Can we establish a bound X such that

- $T_1 .. T_n$: $\sum e_i/p_i \leq X$

is sufficient?

Such bounds are called Schedulability Utilisation SU.

- SU depends on the Scheduling algorithm.
- SU: the higher the better.

Utilization: RMS ./. EDF

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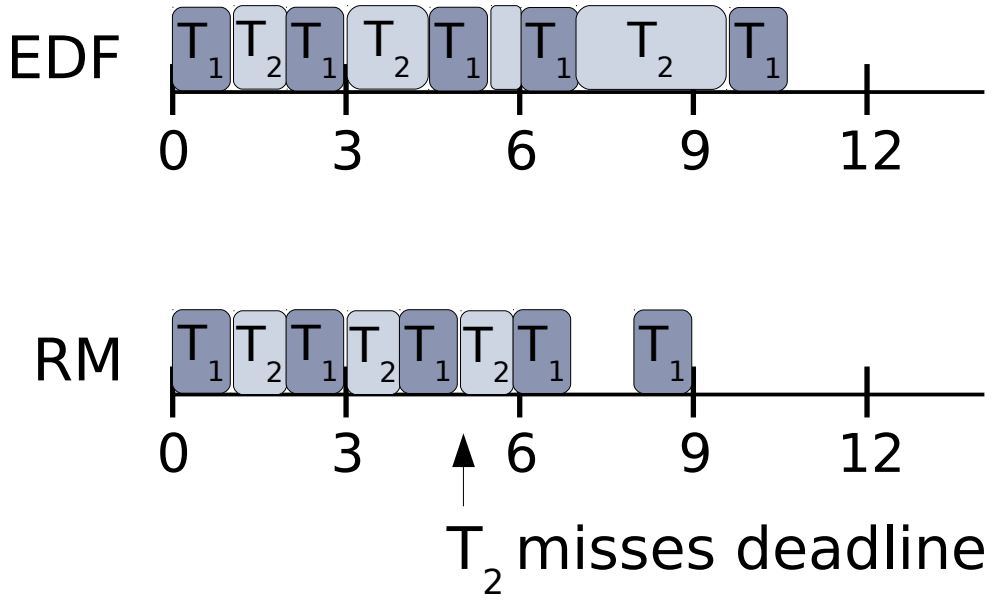
T_1: (2 , 1) T_2: (5 , 2.5) U=1



- RMS not optimal in general

Some Schedulable Utilization(SU) Results

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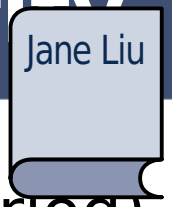
- indep. tasks, preemptable, relative deadline=period, 1 processor
- N ... Number of Tasks
- EDF: SU = 1
- RMS: SU = n ($2^{1/n}$ -1) n ln(2)
- RMS (simply periodical, D P): SU = 1

Schedulibility Test for Fixed(!) Priority



- (case where jobs must complete before end of period)
- Critical Instant Analysis / Time Demand Analysis
- critical instant for task T_i:
  - **one of the jobs of T_i is released at same time with a job in every higher priority task ...**
- It is sufficient to check a schedule for the critical instant for the longest envolved period

(Fixed Prio) Schedulibility and Blocking

- T_i may have to wait for non-preemptable, lower priority task
- b_i: longest non-preemptable portion of all lower prio. Jobs
- Schedulability for all tasks T_i with fixed priority scheduler x $SU_x(i)$:
  - **Schedulable Utilisation for scheduling method x with i tasks:**
    - **Ui = e1/p1 + e2/p2 ... ei/pi**
    - **Ui + bi/pi <= SU_x(i)**

Non Negligible Context Switch Time

Jane Liu

- For Job level fixed priority schedulers ... :
  - **i.e. each job preempts at most one other job**
- 2 context switches:
  - **release (when it preempts other)**
  - **completion**
- include CS overhead in wcet:
  - **$WCET_i := WCET_{i\_original} + 2CS$**

(Fixed Prio and) Limited Priority Levels

- Required: Mapping of
  - **Scheduling-Priorities: 1 ... n to**
  - **Operating System Priorities: Π_1, Π_2, ... Π_m**
- Jobs running with same OS-Prio but different Sched-Prio use:
  - **FIFO, Round Robin, ...**
- Schedulibility loss ?
  - **Notation: Π_i as grid on Scheduling Priorities**
  - **Example:**
    - **10 scheduling priorities, 3 OS priorities**
    - **possible mapping: Π_1=3, Π_2 = 8,Π_3 = 10**
    - **Interpretation: 0,1,2,3 mapped to Π_1, 4,5,6,7,8 to Π_2, 9,10 to Π_3**
- How is Schedulibility Test affected?

(Fixed Prio and) Limited Priority Levels

Jane Liu

- Mappings:
  - **<u>uniformly distributed</u>:**
    k=n/m
    Scheduling Priority X mapped to |X/m|*k
  - **<u>constant ratio</u>:**
    keep ($_{i-1}$ +1) $_{i}$ as equal as possible

Schedulilibility Loss

- Rate Monotonic, large n ...
  - **$g = \min(\Pi_{i-1} + 1) / \Pi_i$**
- $SU_{RM} = \ln(2g)+1-g$
- relative schedulibility(rs): relation to ln(2)
- Example:
  - **n = 100000, m = 256**
  - **rs= 0.9986**

=> 256 priorities is it !

Lessons Learned

- Schedulers: static, static and dynamic (RMS, EDF, LST)
- Schedulibility Analysis:
  Schedulibility Utilization and Critical Instant
- RMS and EDF are “optimal” under simplistic assumptions
- “Anomalies”
-