- next week: 2 teaching units (DS)

Real-Time Systems

Event-Driven Systems
Scheduling Basics

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Outline

- mostly following Jane Liu, Real-Time Systems
- Principles
- Scheduling
- EDF and LST as dynamic scheduling methods
- Fixed Priority schedulers
- Admission based on Utilization
- Few multi-processor insights (more later)
- Anomalies

Principles

Important properties:

- scheduling decisions are triggered by events (not time instants)
- events are release, completion, blocking, unblocking of jobs
- scheduler calls, interrupts, timers, … may trigger events
- scheduling decisions are on-line
  - scheduling must be simple
- admission is on-line or off-line
- *work-conserving* schedulers never leave a resource idle intentionally

Relaxing Restrictions of Time-Driven Systems

some restrictive assumptions of time-driven systems are relaxed:

- fixed inter-release times
  → minimum inter-release times
- fixed number of real-time tasks
  → number of real-time and non real-time tasks can vary
- a priori fairly well known parameters
  → overload, schedule non-RT in the background, …

Principles

At Admission Time:

- select scheduler (may depend on the OS)
- check if feasible schedule exists for the selected scheduler
- assign to jobs a value of a simple selection criteria:
  some form of priority

Scheduling / Dispatching:

- at event, select highest prioritized job

Principles

How good are schedulers?

- shorter response times
- more task sets possible
- higher utilization of resources

Optimality of schedulers (!):

- A scheduling method X is called *optimal in a class of scheduling methods,* if X produces a feasible schedule whenever there exists a scheduling method Y in this class that produces a feasible schedule.
- X is called *optimal,* if X produces a feasible schedule whenever there exists such a schedule (no matter which method produced it).

Earliest Deadline First

Assign priorities at time when jobs are released:
"the earlier the deadline the higher the priority"

Theorem:

- one processor,
- jobs are preemptable,
- jobs do not contend for passive resources,
- jobs have arbitrary release times, deadlines,
- then: EDF is optimal
  (i.e. if there is a feasible schedule, there is also one with EDF)

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

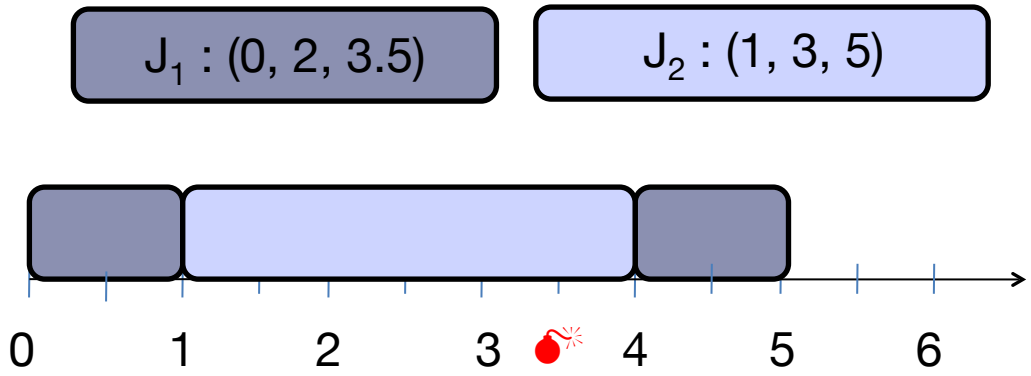
- Slack Time = Laxity:
  - (time to deadline -
    remaining execution time required to reach deadline)
- slack time: D - x - t
  - x remaining execution time of a job
  - D absolute deadline
  - t current time
- priority dynamic per job (see example)
- strict version is optimal

Least Slack Time First

- scheduler checks slacks of all ready jobs and runs the job with the least slack
- two versions:
  - Strict: slacks are computed at all times
    - Each instruction (prohibitively slow)
    - Each timer “tick”
  - Non-strict: slacks are computed only at events (release, completion)

Example: Non-strict LST

Job: (release time, execution time, deadline)



t = 0: J_1 released and scheduled

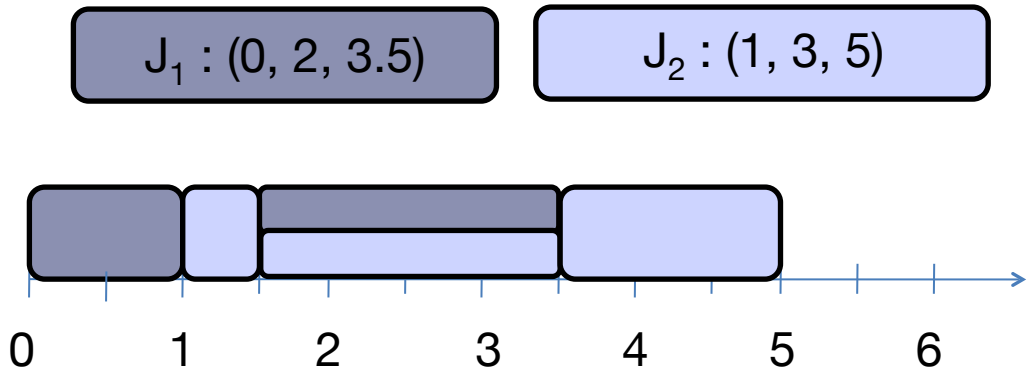
t = 1: J_2 released;
$L(J_1) = 3.5 - 1 - 1 = 1.5$; $L(J_2) = 5 - 3 - 1 = 1 \rightarrow J_2$ scheduled

t = 3.5: J_1 deadline miss

EDF schedules both jobs successfully!

Example: Strict LST

Job: (release time, execution time, deadline)



t = 0: J_1 released and scheduled

t = 1: J_2 released;
$L(J_1) = 3.5 - 1 - 1 = 1.5$; $L(J_2) = 5 - 3 - 1 = 1 \rightarrow J_2$ scheduled

t = 1.5: $L(J_1) = 3.5 - 1 - 1.5 = 1$; $L(J_2) = 5 - 2.5 - 1.5 = 1 \rightarrow$
J_1, J_2 are scheduled and executed in parallel (at half speed)

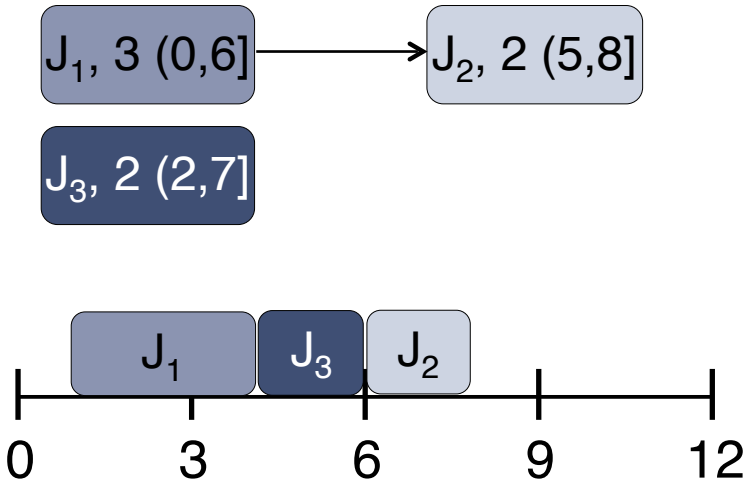
t = 3.5: J_1 completes → J_2 continued at full speed

t = 5: J_2 completes

Latest Release Time (LRT)

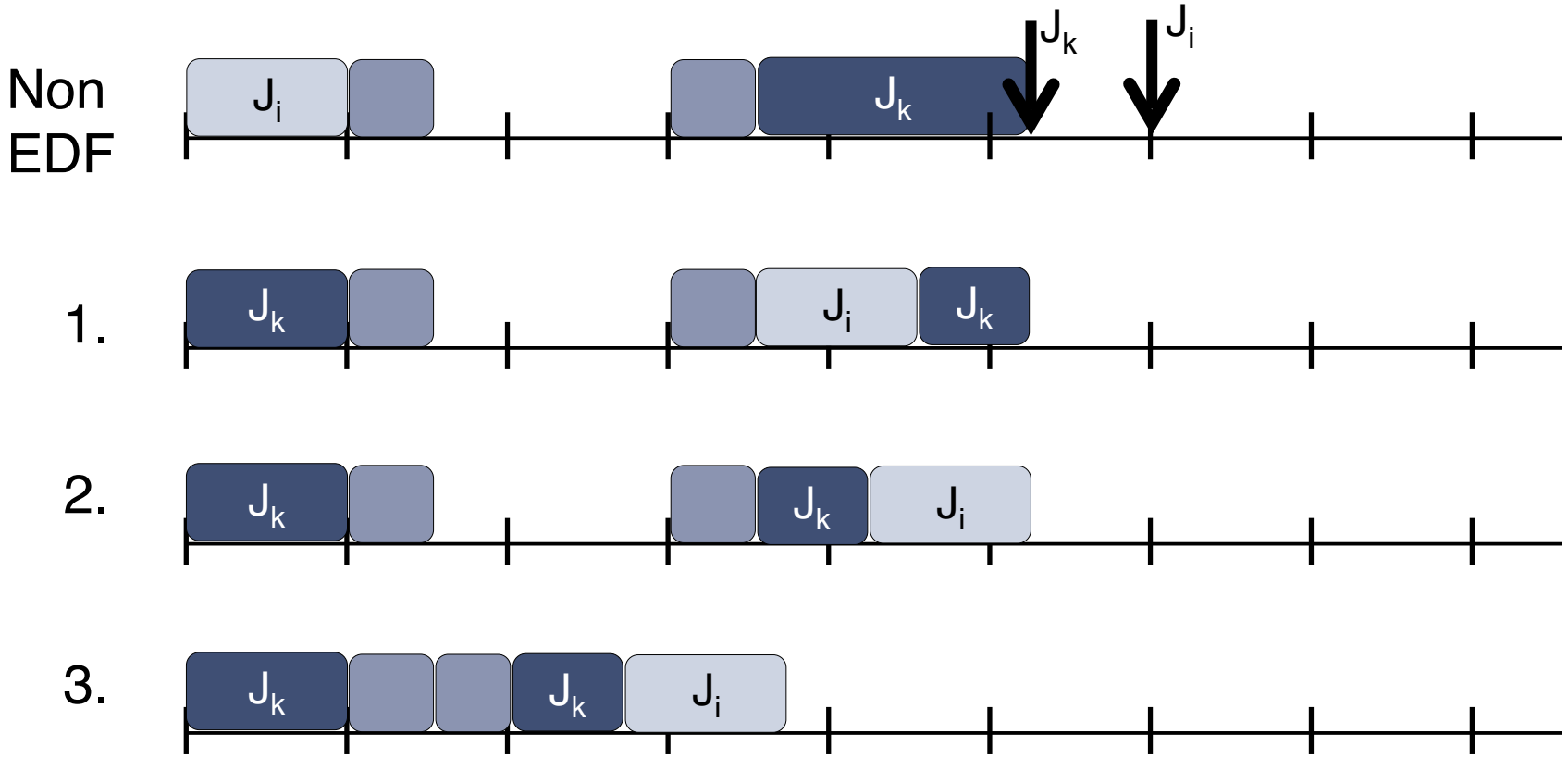
- Rationale:
  - no need to complete real-time jobs before deadline
  - use time for other activities
- Idea:
  - backwards scheduling
    (Deadline <-> Release, turn around

    precedence graph, EDF)
  - run as late as possible
  - use latest possible release times
  - optimal (analog EDF and strict LST)



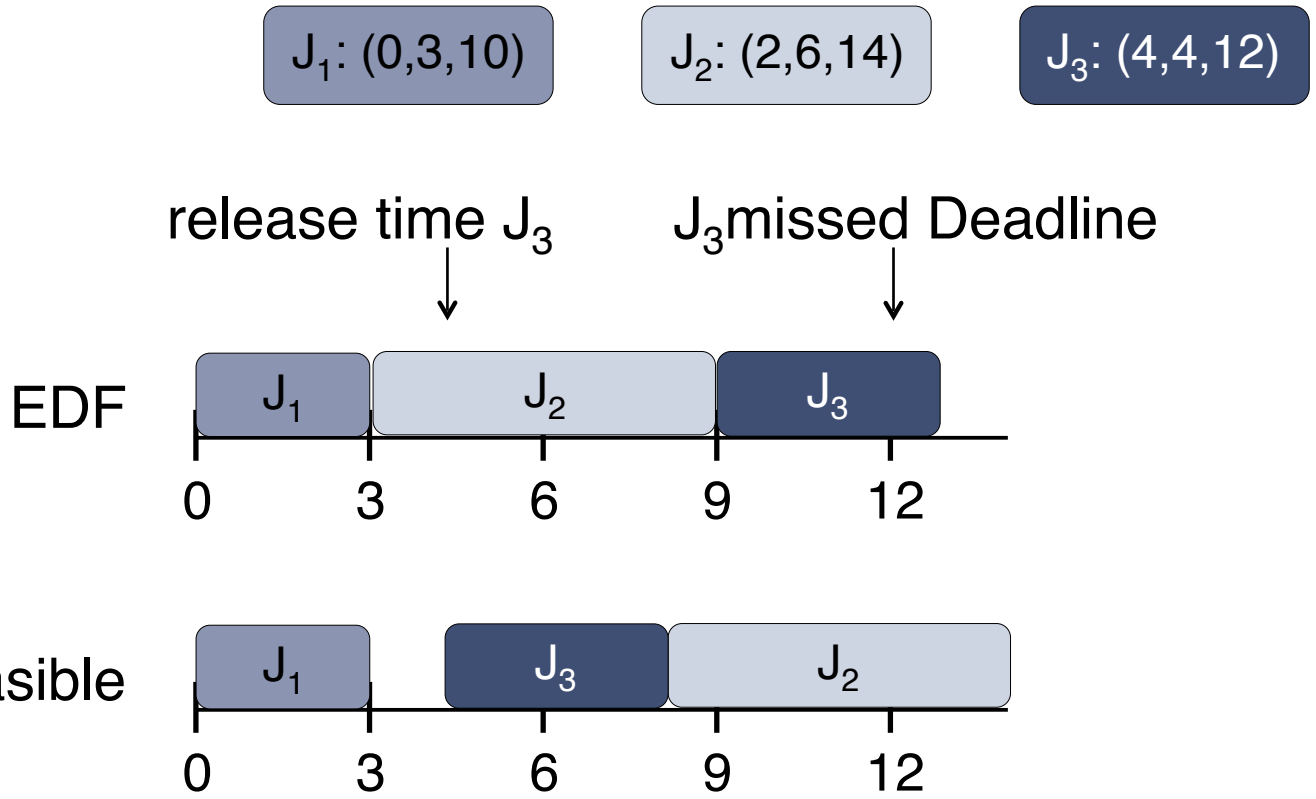
EDF Optimality

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



EDF and Non - Preemptivity

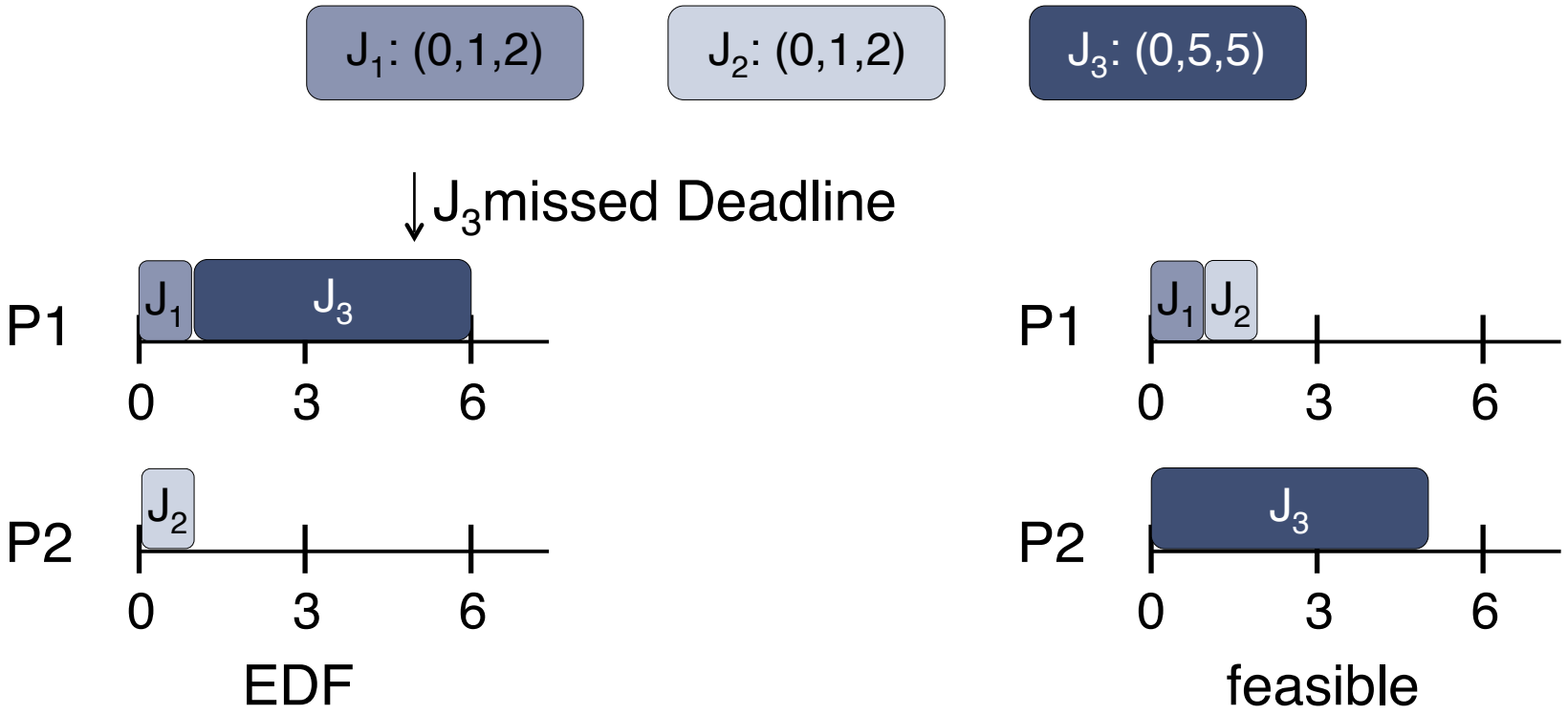
- Job: (release time, execution time, deadline)



- EDF is not optimal if jobs are not preemptable

EDF and Multiple Processors

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



- easy for time driven schedulers
- EDF is not optimal for multiprocessor systems

Assumptions for Next Algorithms

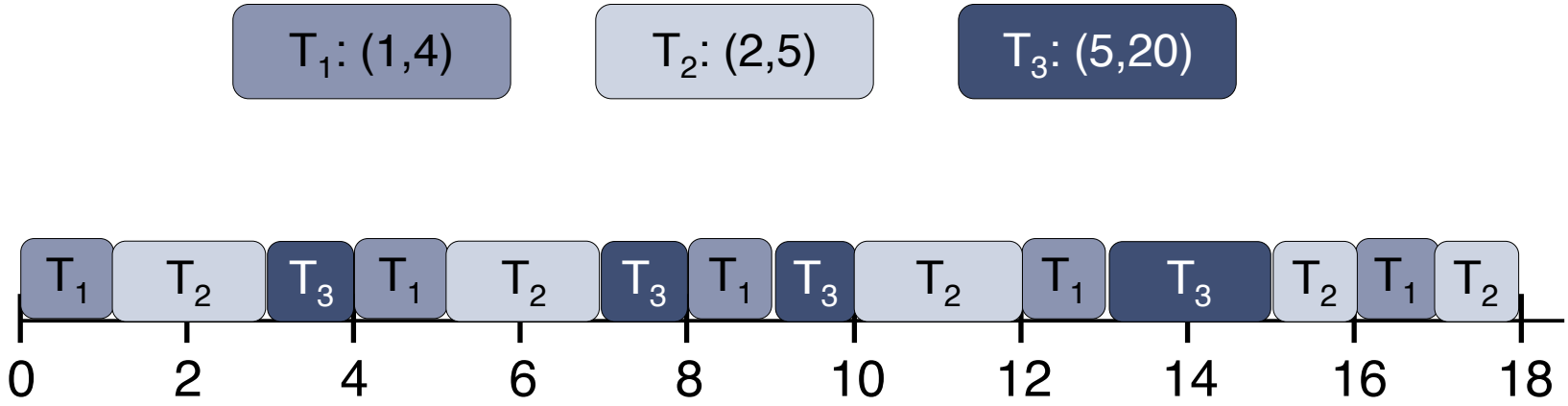
- Set of **periodic tasks** with these properties:
  - tasks are independent
  - one processor
  - no aperiodic tasks
  - preemptable, context switch overhead is negligibly small
  - period = minimum inter-release time
    (release times are not fixed but at least period apart)
- Since tasks are independent, tasks can be added (if admitted) and deleted at any time without causing deadline misses.

Priority-Driven Scheduling of Periodic Tasks

- To do:
  - priority assignment (off line / on line)
  - selection of next task (on line)
  - admission (required before new tasks are admitted)
- restrictions (whether they apply or not)
  - dependencies (precedence, sharing)
  - multiple processors
  - aperiodic, sporadic
- achievable resource utilization: $U = \sum_i \frac{e_i}{P_i}$

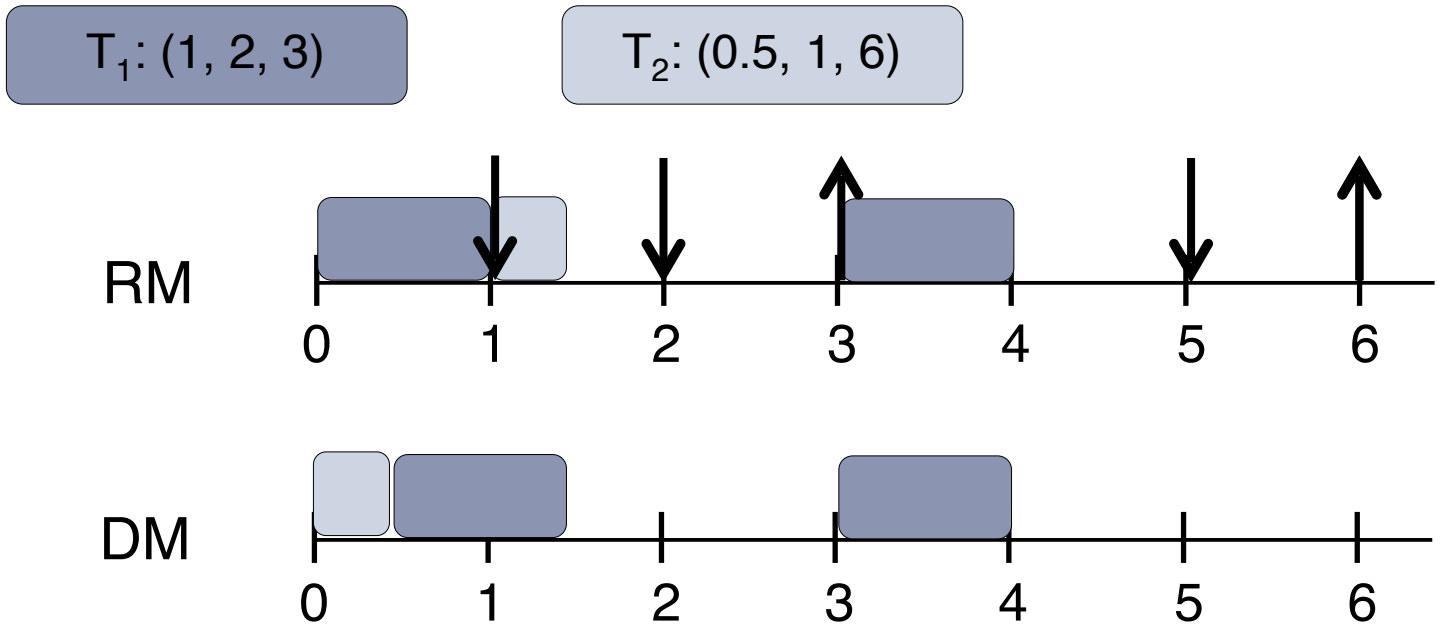
Rate Monotonic Scheduling

- fixed priority:
  - the shorter the period the higher the priority
    (rate: inverse of period)
  - example: (WCET,P); D=P



Deadline Monotonic Scheduling

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



- Conclusion (no proof):
  RM not optimal but DM if $D \leq P$ for all tasks

Optimality of Fixed Priority Schedulers

T: periodic tasks, independent, preemptable, one CPU

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 produces a feasible as well

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 $T_1 \ldots T_n$: $\sum e_i/P_i \leq m$ is a necessary but not sufficient condition for m processors.
- Can we establish a maximum bound X such that

  $T_1 \ldots T_n$: $\sum e_i/P_i \leq X$

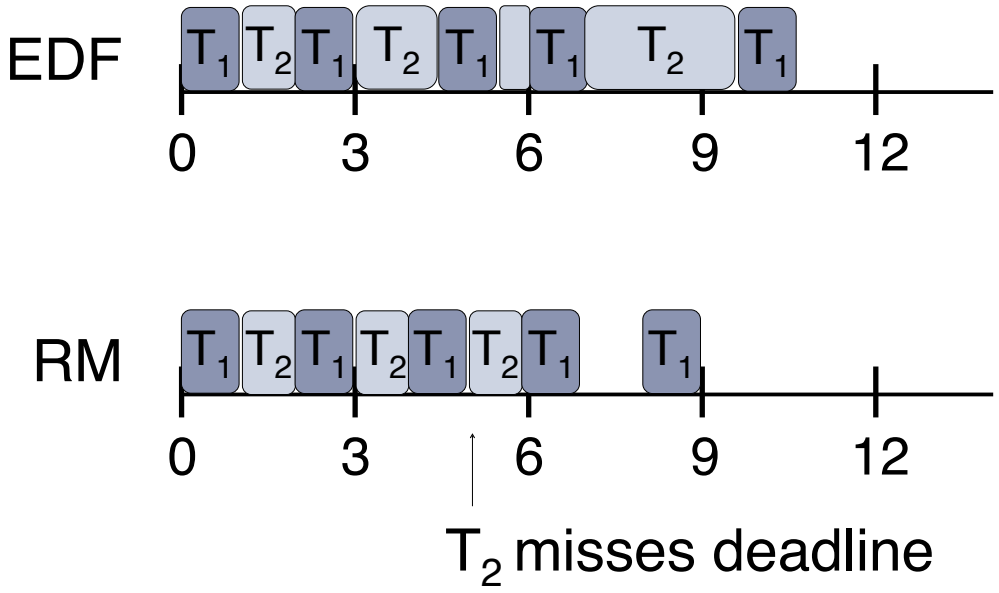
  is sufficient?

Such bounds are called *schedulable utilization* SU.

- SU depends on the scheduling algorithm.
- the higher the better.

Utilization: RMS / EDF

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



RMS not optimal in general

Some Schedulable Utilization (SU) Results

- independent tasks, preemptable,
  relative deadline = period, m = 1 processor
- n ... Number of Tasks
- EDF: SU = 1
- RMS: SU = $n\,(2^{1/n} - 1)$ $n \rightarrow \infty$: ln(2)
- RMS with harmonic periods: SU = 1
- harmonic periods (also called simply periodic):
  for all pairs of tasks Ti,Tj: if Pi <= Pj then Pj = nij* Pi

Schedulability Test for Fixed Priority Schedulers

for task sets with $D_i \leq P_i$ (+ some more cases)

Critical Instant Analysis / Time Demand Analysis:

- critical instant for task T_i:

  release of jobs such that they have the maximum response time

- 1 CPU, preemptable, independent:

  Critical instant occurs when all tasks are released simultaneously.

  => It is sufficient to check schedulability for the simultaneous release for the longest envolved period.

Non Negligible Context Switch Time

- 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 context switch overhead in WCET:
  - $WCET_i := WCET_{i\_original}$ + 2 context switches

Static and Dynamic (priority)

If no new tasks arrive: static vs. dynamic priorities

- Task static: Task T does not change its priority,
  i.e. all jobs of T have same fixed priority
- Job static: Jobs do not change their priorities
- Job dynamic: Jobs change their priorities

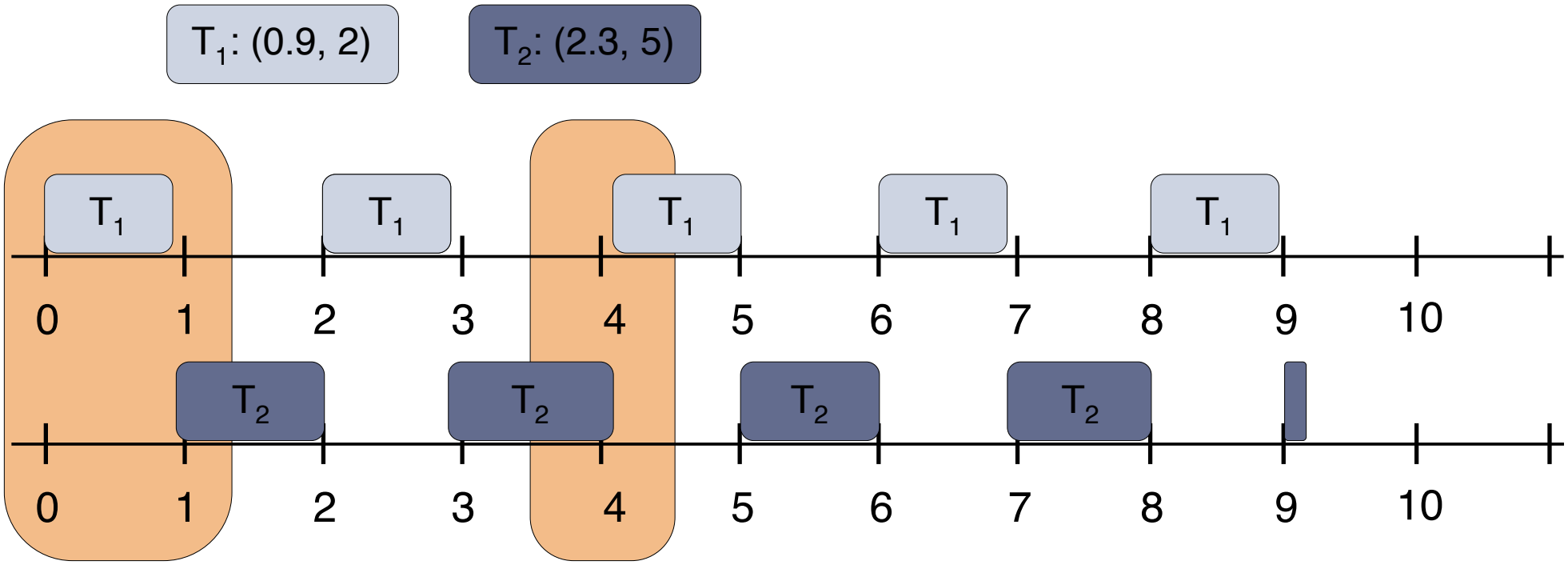
Careful:

Job static is often called dynamic as well

Earliest Deadline First, priority assignment:

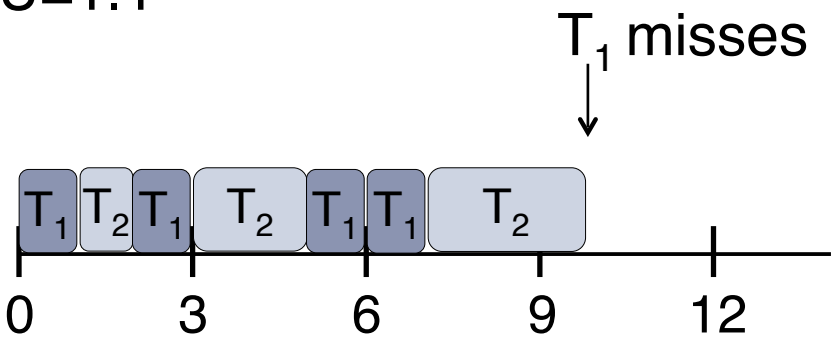
- fixed per job, dynamic at task level:
  - the nearer the absolute deadline of a job at release time

    the higher the priority

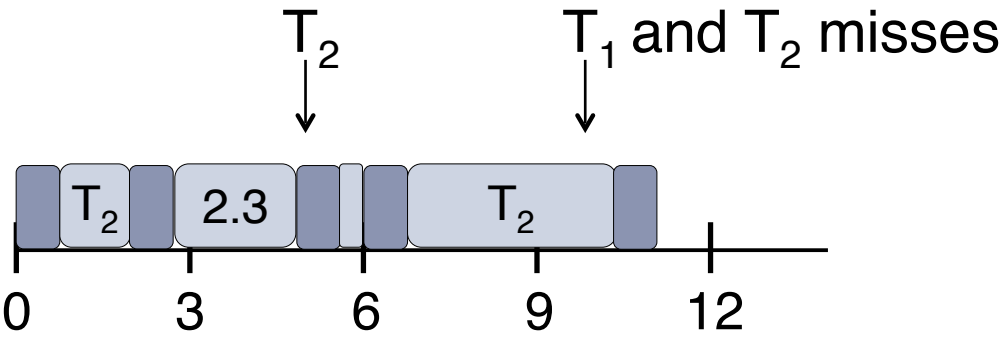


EDF and Overload, examples

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

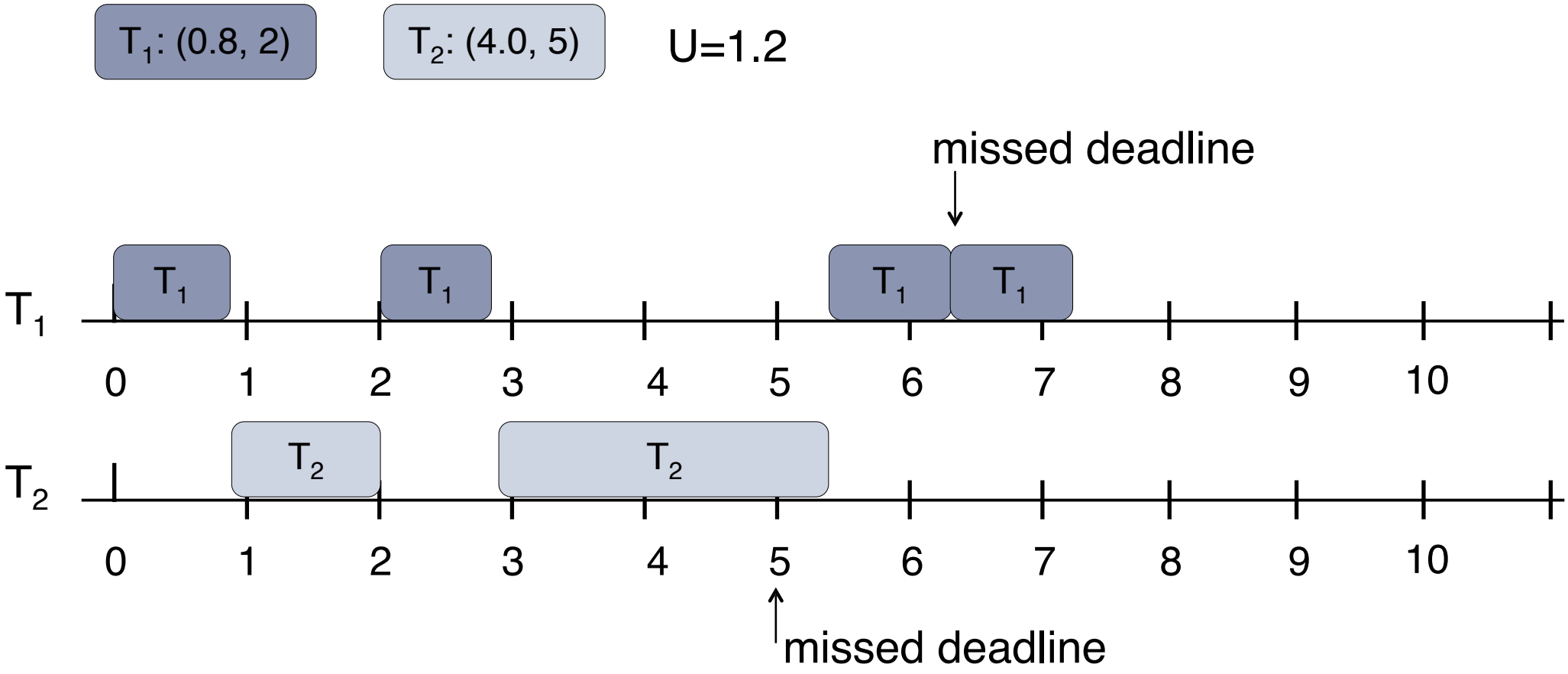


T_1: (0.8, 2) T_2: (3.5, 5) U=1.1



No easy way to determine which jobs miss deadline

EDF and Overload, one more example



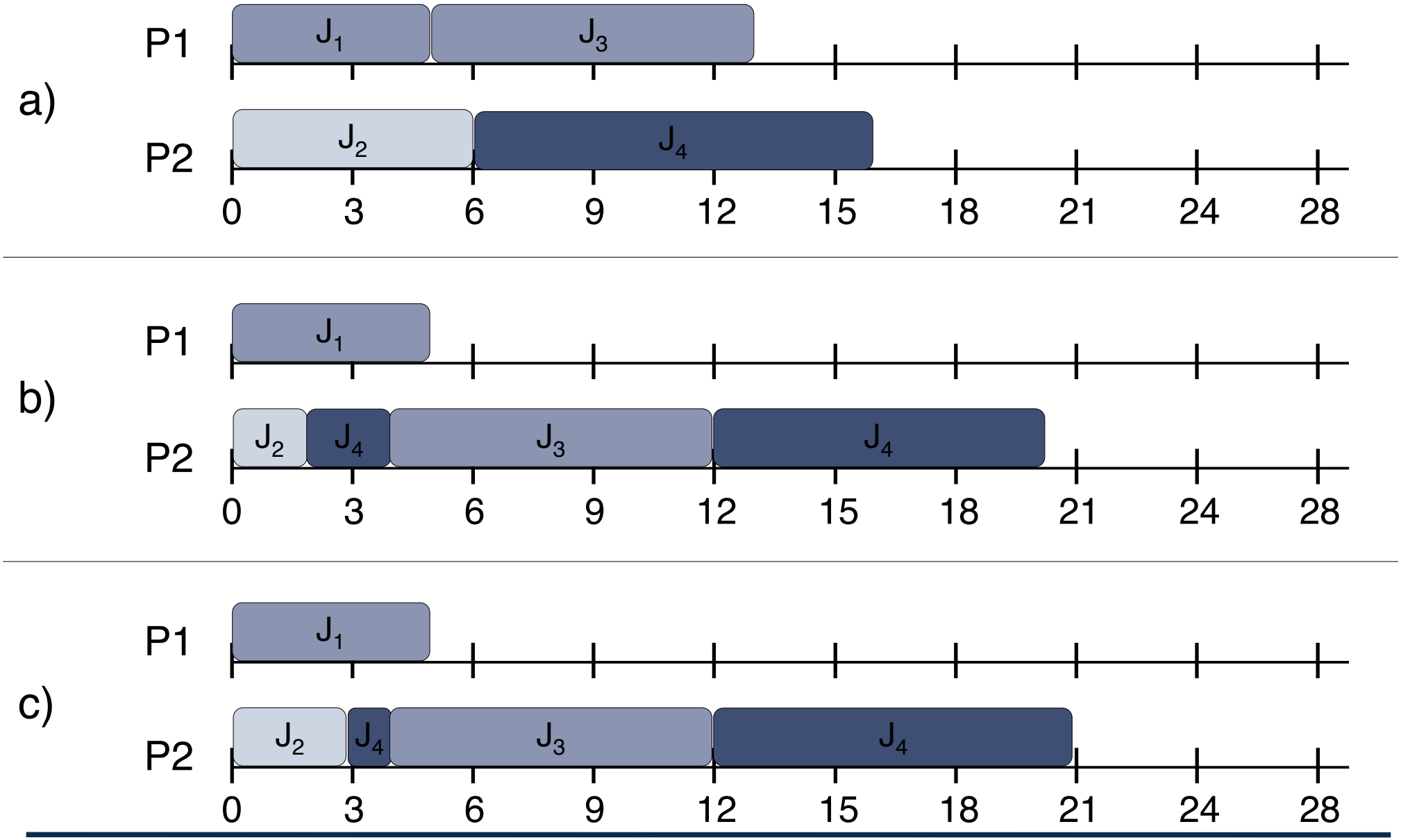
in fixed priority systems it is possible to predict which tasks are affected by overruns

Scheduling Anomaly

	release	deadline	execution
J1	0	10	5
J2	0	10	[2,6] varies
J3	4	15	8
J4	0	20	10

- increasing priorities:
  - $i < k \Rightarrow$ 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

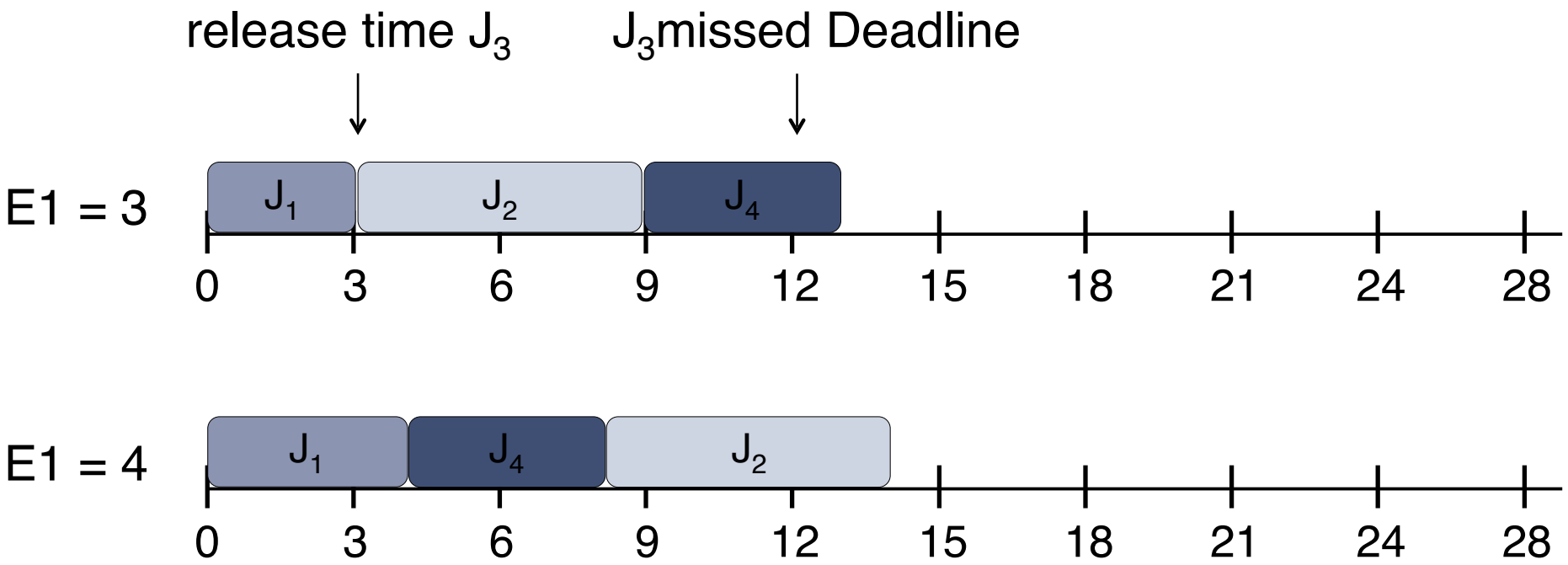


Scheduling Anomaly on One Processor

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

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

- Not preemptable



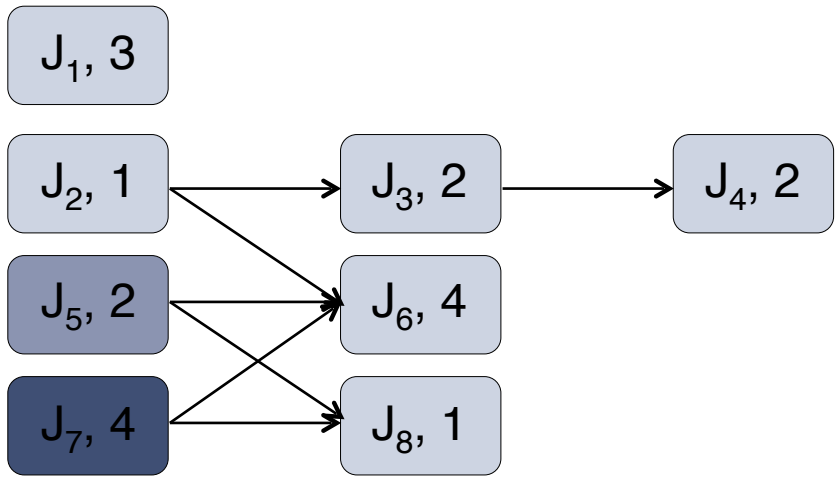
Predictable/Sustainable Execution

Informal definition:

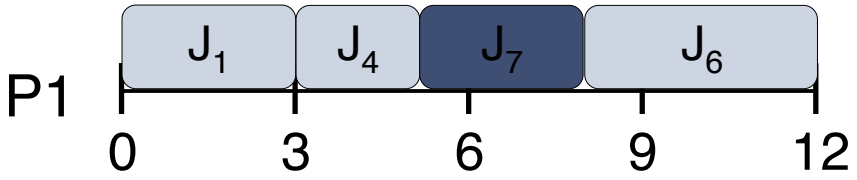
- Given a set of periodic tasks with *known minimal and maximal* execution times and a scheduling algorithm.
- A schedule produced by the scheduler when the execution time of each job has its maximum (minimum) value is called a *maximum (minimum) schedule.*
- An execution is called *predictable,* if for each actual schedule the start and completion times for each job are bound by these times in 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.

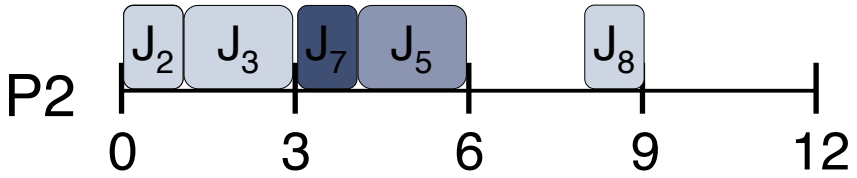
Preemptive vs. Non-Preemptive Scheduling

- 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)
- Jobs can “migrate”
- precedence graph:

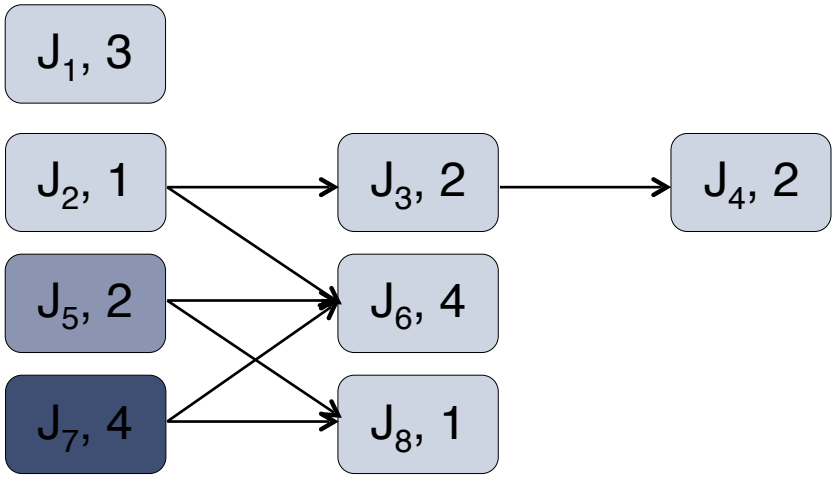


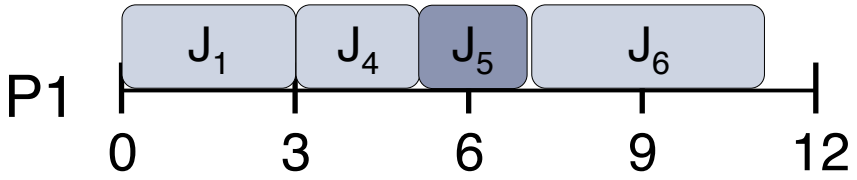
Example, executions

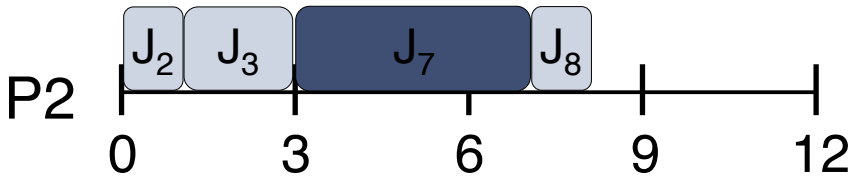




preemptiv

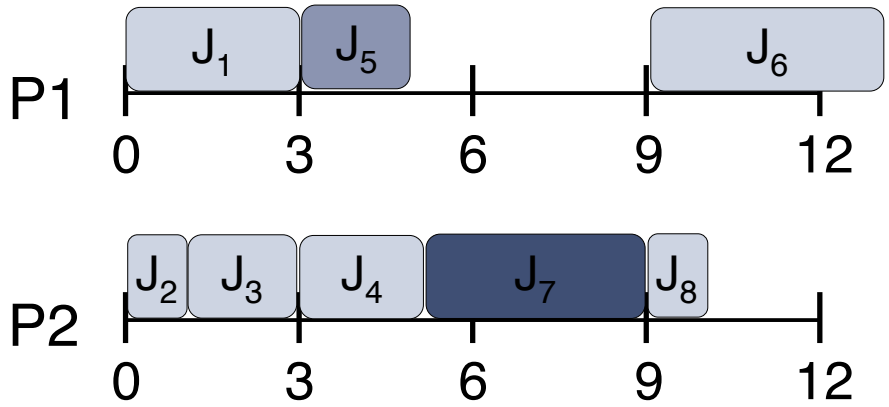






non-preemptiv

Modified Example: release time of $J_5 = 0$



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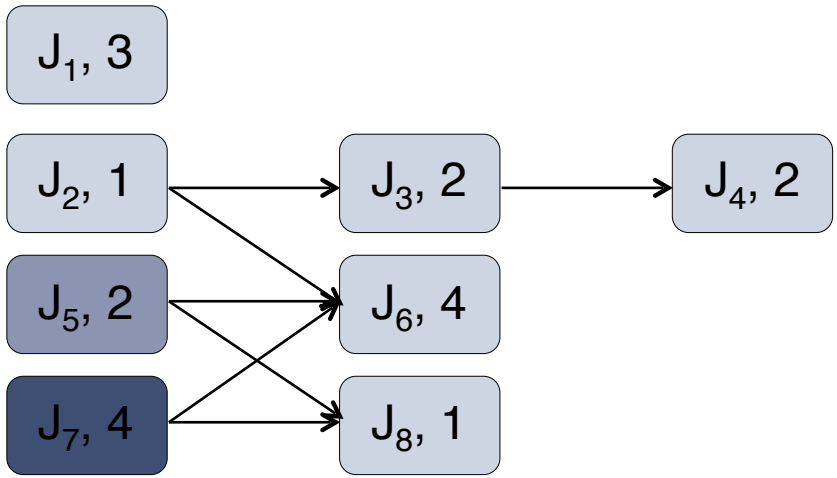

Which is better?

- 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)

Multiple Processors

- Static vs dynamic allocation to processors
  - Partitioned tasks are assigned to processors
  - Static: jobs are assigned to processors once
  - Dynamic: jobs “migrate”
    - example: one run queue served by all processors
- EDF not optimal
  general: “static-job” scheduling not optimal
- There are optimal “dynamic-job” schedulers

Lessons Learned

- Schedulers: static, static and dynamic (RMS, EDF, LST)
- Schedulability Analysis:

  Critical Instant, Schedulability Utilization
- RMS and EDF are optimal under simplistic assumptions
- Anomalies