Real-Time Embedded Systems

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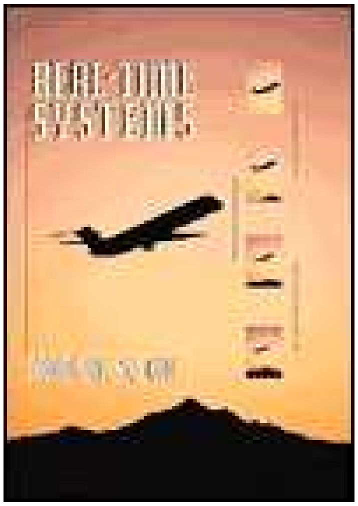
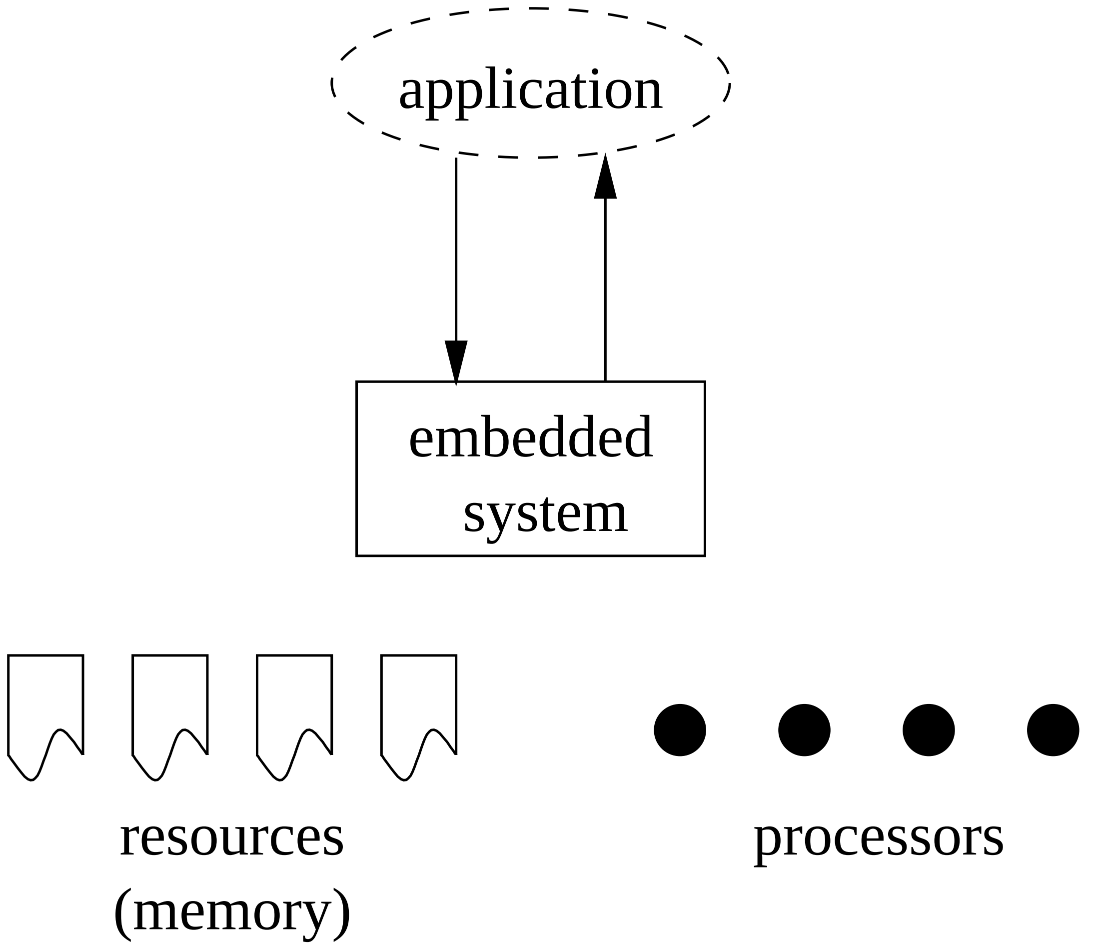


General Picture



Resources are allocated to processors.

Jobs

A job is a unit of work, scheduled and executed by the syste

Parameters of jobs are:

- functional behavior
- time constraints
- resource requirements

Job are divided over processors, and they are competing for

A scheduler decides in which order jobs are performed on a p
and which resources they can claim.

Terminology

release time: when a job becomes available for execution

execution time: amount of processor time needed to perform
(assuming it executes alone and all resources are available)

response time: length of time from arrival until completion o

(absolute) deadline: when a job is required to be completed

relative deadline: maximum allowed response time

hard deadline: late completion not allowed

soft deadline: late completion allowed

jitter: imprecise release and/or execution time

A preemptive job can be suspended at any time of its execut

Out of scope:

- use of distant resources
- communication between jobs
- migration of jobs
- overrun management
- penalty for missing a soft deadline
- performance
- different processor and resource types

Types of Tasks

A task is a set of related jobs.

A processor distinguishes three types of tasks:

- periodic: known input before the start of the system, an deadlines.

  Execution and interarrival times are fixed.

- aperiodic: executed in response to some external event, deadlines.

  Execution and interarrival times are according to some *p* *distribution*.

- sporadic: executed in response to some external event, w deadlines.

  Execution times are according to some *probability distr* interarrival times are *random*.

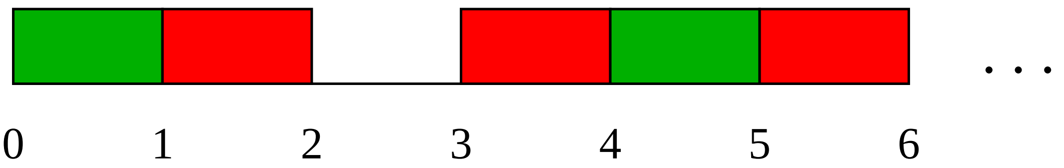
Periodic Tasks

A periodic task is defined by:

- release time r (of the first periodic job)
- period p (regular time interval, at the start of which a p
  is released)
- execution time e

For simplicity we assume that the relative deadline of each p
is equal to its period.

Example: $T_1 = (1, 2, 1)$ and $T_2 = (0, 3, 1)$.

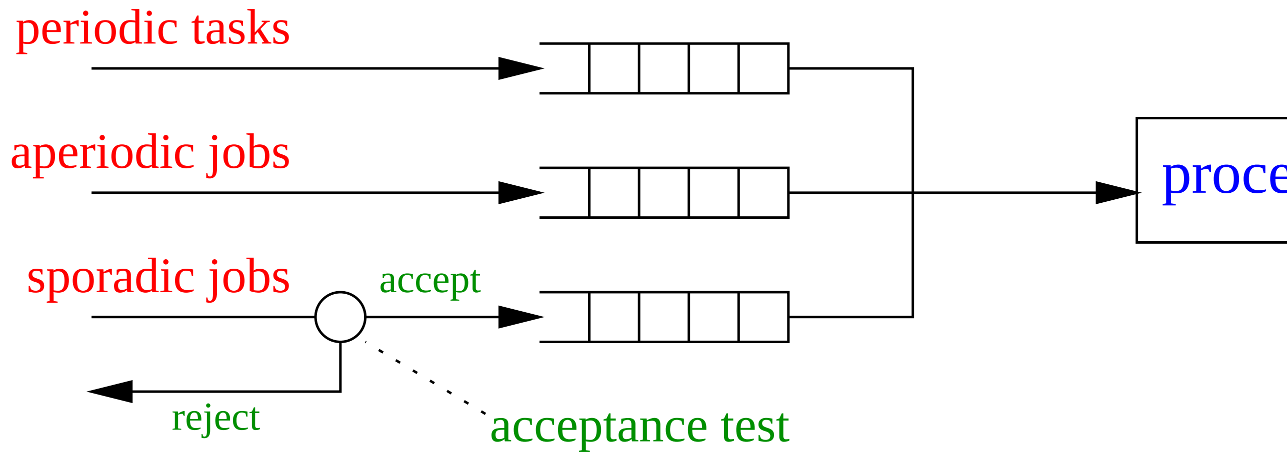


The conflict at time 3 is resolved by some scheduler.

The hyperperiod is 6.

Job Queues at a Processor

We focus on individual aperiodic and sporadic *jobs*.



- *Sporadic jobs* are only accepted when they can be comp
time.
- *Aperiodic jobs* are always accepted, and performed such
periodic and accepted sporadic jobs do not miss their de

Average Response Time

The queueing discipline of aperiodic jobs tries to minimize e.
tardiness (completion time monus deadline) or the number o
soft deadlines.

The average response time of aperiodic jobs can be analyzec

- simulation and measurement
- Queueing Theory
- Integer Linear Programming

In the last two cases, values for e.g. average execution time
aperiodic jobs must in general still be estimated using simula
measurement.

Scheduler

The scheduler of a processor schedules and allocates resourc
(according to some scheduling algorithms and resource acces
protocols).

A schedule is valid if:

- jobs are not scheduled before their release times
- the total amount of processor time assigned to a job equ
  (maximum) execution time

A (valid) schedule is feasible if all hard deadlines are met.

A scheduler is optimal if it produces a feasible schedule whe
possible.

Clock-Driven Scheduler

Off-line scheduling: the schedule for periodic tasks is comput
beforehand (typically with an algorithm for an NP-complete
problem).

Time is divided into regular time intervals called frames.

In each frame, a predetermined set of periodic tasks is execu

Jobs may be sliced into subjobs, to accommodate frame leng

Clock-driven scheduling is conceptually simple, but cannot c
with:

- jitter
- system modifications
- nondeterminism

Slack

Idle time in a frame can be used to execute aperiodic and sp
jobs.

Slack of a frame $[s, c]$ at time t is $t - c$ minus the total exec
of periodic and accepted sporadic jobs in the frame after t.

Slack stealing: execution of aperiodic jobs until the slack of
current frame is zero.

Acceptance test: straightforward check (in absence of jitter)
newly arrived sporadic job can be completed before its deadl
whether there is sufficient slack).

Resources: are in general distributed according to some prec
cyclic schedule.

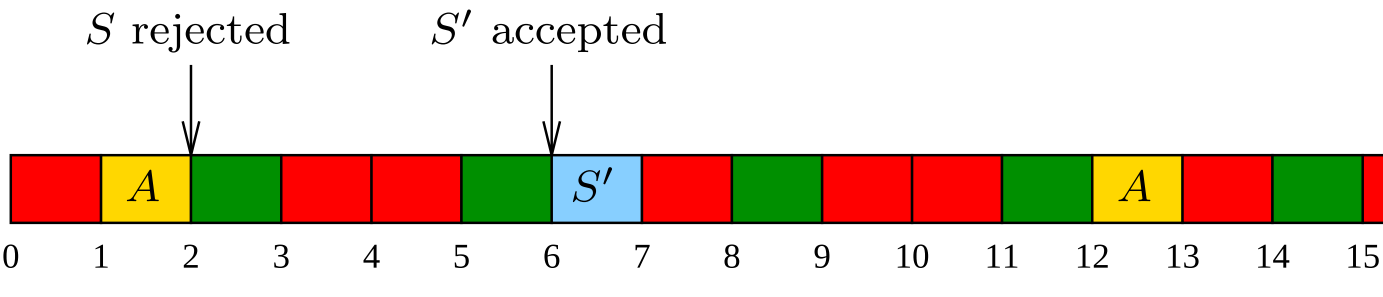
Example: $Periodic$ jobs $T_1 = (0, 2, 1)$ and $T_2 = (0, 3, 1)$.

Frame length is 6.

$Aperiodic$ job A, with execution time 2, arrives at 1.

$Sporadic$ job S, with execution time 1, arrives at 2 with dea

$Sporadic$ job S', with execution time 1, arrives at 6 with dea



Priority-Driven Scheduling

On-line scheduling: the schedule is computed at run-time.

Scheduling decisions are taken when:

- periodic jobs are released or aperiodic/sporadic jobs arriv
- jobs are completed
- resources are required or released

Released jobs are placed in priority queues, e.g. ordered by:

- release time (FIFO, LIFO)
- execution time (SETF, LETF)
- period of the task (RM)
- deadline (EDF) or slack (LST)

We focus on EDF scheduling.

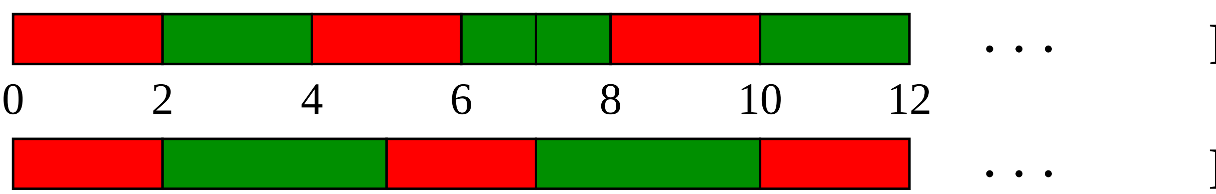
RM Scheduler

Rate Monotonic: Shorter period gives a higher priority.

Advantage: Priority on the level of tasks makes RM easier to
than EDF/LST.

Non-optimality of the RM scheduler (one processor, preempt
no competition for resources):

Let $T_1 = (0, 4, 2)$ and $T_2 = (0, 6, 3)$.



Remark: If for periods $p < p'$, p is always a divisor of p', the
scheduler is optimal.

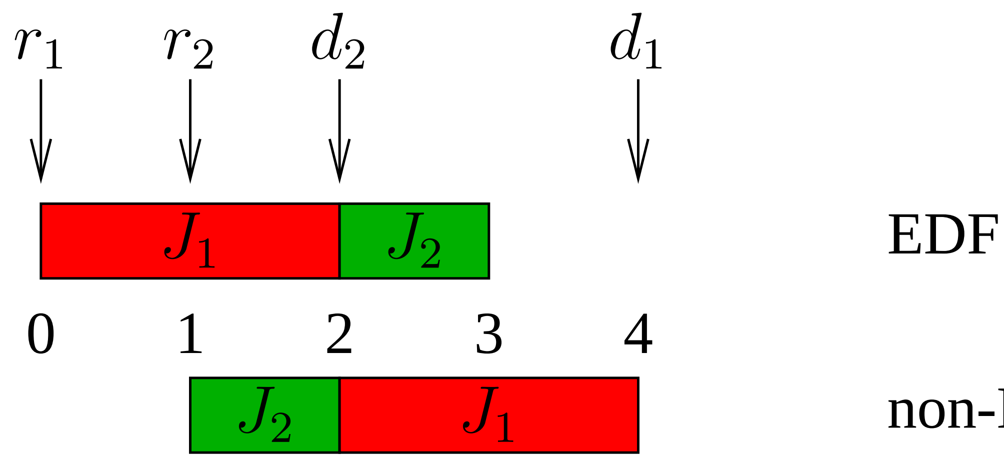
EDF Scheduler

Earliest Deadline First: the earlier the deadline, the higher th

Consider a single processor, and preemptive jobs.

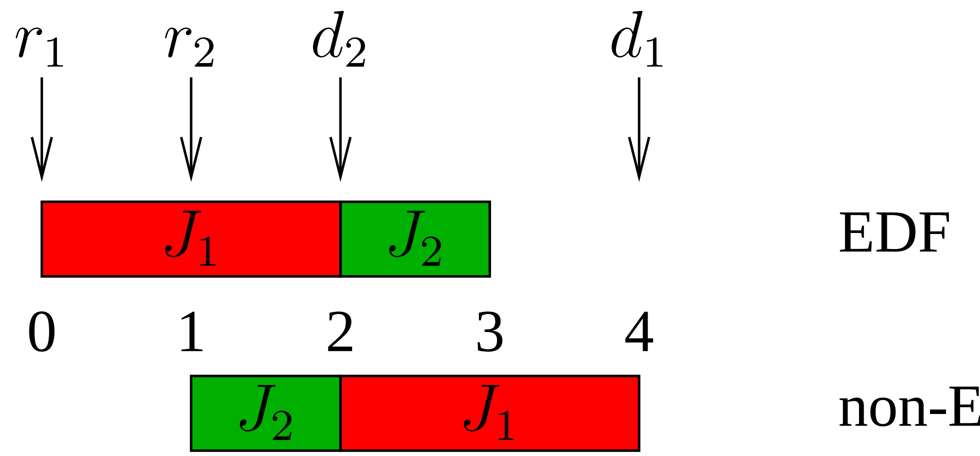
Theorem: When jobs do not compete for resources, the EDF
is optimal.

Non-optimality in case of non-preemption:

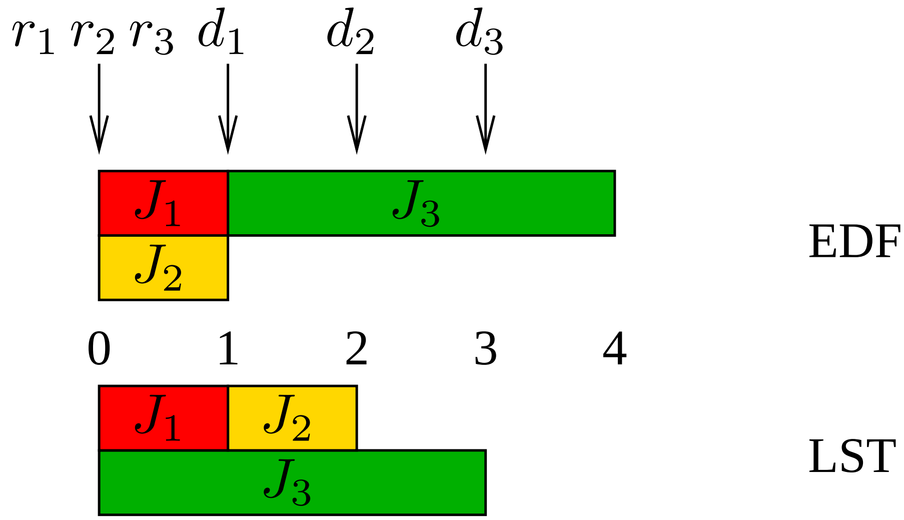


Non-optimality in case of resource competition:

Let J_1 and J_2 both require resource R.



Non-optimality in case of two processors (with migration):



Drawbacks of EDF:

- dynamic priority of periodic tasks makes it difficult to an
  which deadlines are met in case of overloads
- late jobs can cause other jobs to miss their deadlines (go
  overrun management is needed)

LST Scheduler

Least Slack Time first: less slack gives a higher priority.

Slack of a job at time t is the idle time of the job until its de

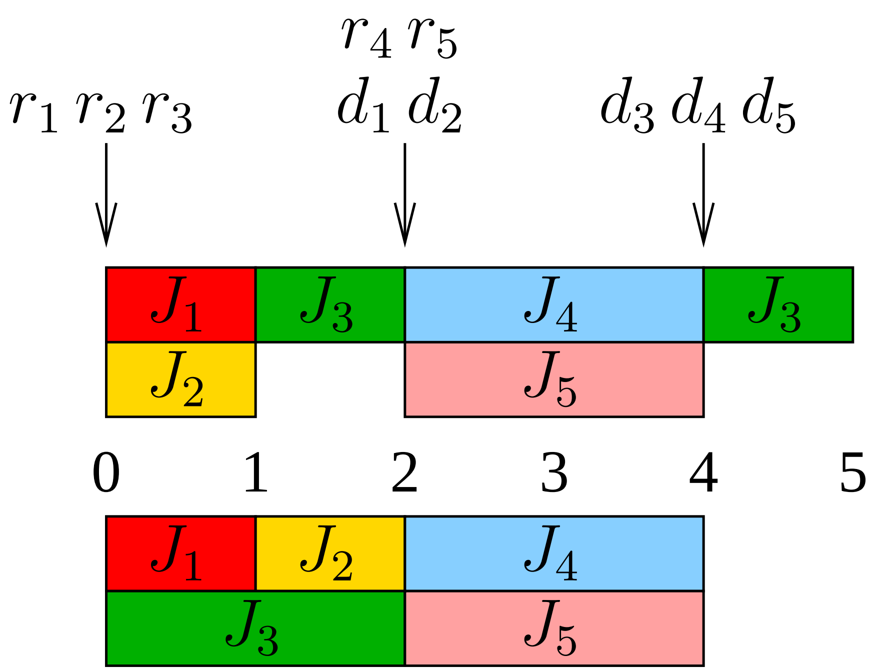
Theorem: When jobs do not compete for resources, the LST

is optimal.

Remarks for the LST scheduler:

- Priorities of jobs change dynamically.
- Continuous scheduling decisions would lead to context s
  overhead in case of two jobs with the same slack.

Non-optimality of the LST scheduler in case of two processo
migration):

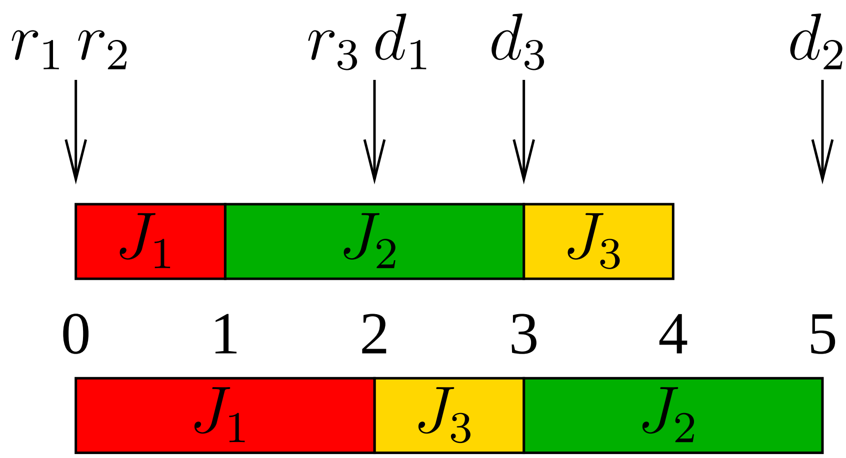


Drawback of LST: computationally expensive

Scheduling Anomaly

Let jobs be non-preemptive. Then shorter execution times ca
violation of deadlines.

Consider the EDF (or LST) scheduler:



If jobs are preemptive, and there is no competition for resou
there is no scheduling anomaly.

Utilization

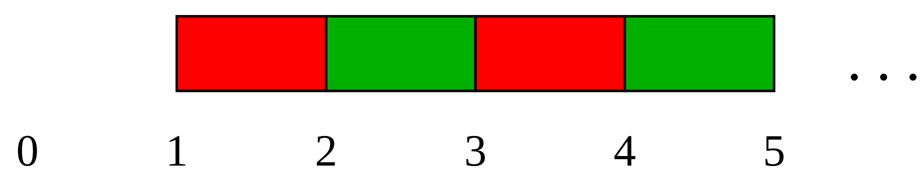
Utilization of a *periodic task* $T = (r, p, e)$ is $\frac{e}{p}$.

Utilization of a *processor* is the sum of utilizations of its peri

Assumptions: jobs preemptive, no resource competition.

Theorem: Utilization of a processor is ≤ 1 if and only if sche
periodic tasks is feasible.

Example: $T_1 = (1, 2, 1)$ and $T_2 = (1, 2, 1)$.



Assignment of Periodic Tasks to Processors

Goal: To fit periodic tasks on a minimal number of processo

Remark: Load balancing is not taken into account here.

Simple approach: Assume processors $P_1, \ldots, P_k$.

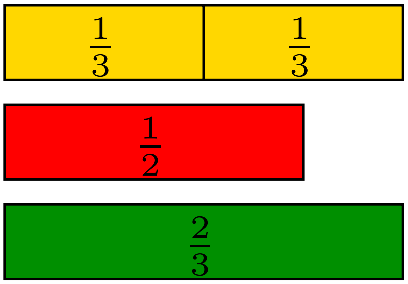
Periodic tasks $T_1, \ldots, T_\ell$ are assigned to processors as follow

Let $T_1, \ldots, T_{i-1}$ have been assigned. T_i is assigned to P_j if not fit on $P_1, \ldots, P_{j-1}$ (i.e., utilization of these processors w beyond 1) and does fit on P_j.

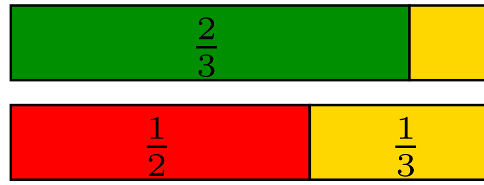
Smart approach: First sort periodic tasks by their utilization (T_1 has largest utilization, T_ℓ smallest utilization).

This improves worst-case and average complexity (in numbe required processors).

Example: Utilizations $\frac{1}{3}$ $\frac{1}{3}$ $\frac{1}{2}$ $\frac{2}{3}$.



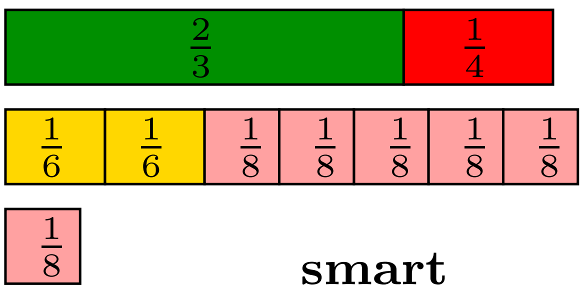
simple



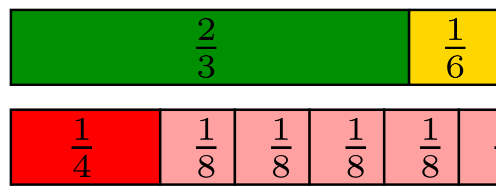
sma

However, the smart approach is not optimal. Fitting periodic
a minimal number of processors is NP-complete.

Example: Utilizations $\frac{1}{8}$ $\frac{1}{8}$ $\frac{1}{8}$ $\frac{1}{8}$ $\frac{1}{8}$ $\frac{1}{8}$ $\frac{1}{6}$ $\frac{1}{6}$ $\frac{1}{4}$ $\frac{2}{3}$.



smart



optima

Remark: Communication overhead between jobs on different
processors, or between a job and a remote resource, may be
account.

The problem of assigning periodic tasks to processors with m
communication overhead can be reformulated into Integer Li
Programming.

Scheduling Aperiodic Jobs

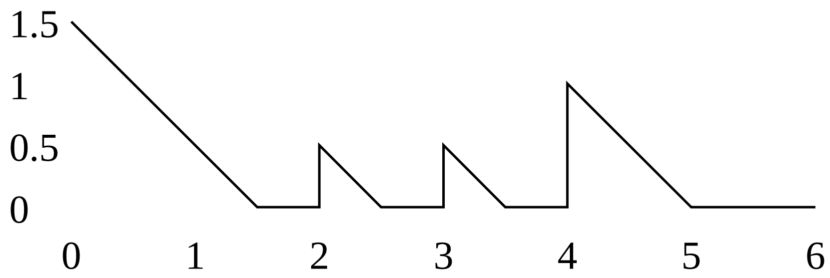
Background: aperiodic jobs are only scheduled in idle time.

Drawback: needless delay of aperiodic jobs.

Slack stealing: periodic tasks and accepted sporadic jobs ma
interrupted if there is sufficient slack.

Example: $T_1 = (0, 2, \frac{1}{2})$ and $T_2 = (1, 3, \frac{1}{2})$.

Aperiodic jobs available in $[0, 6]$.



Drawback: difficult to compute in case of jitter.

Polling: gives a period p_s, and an execution time e_s for aper
in such a period.

At the start of a new period, *the first* e_s *time units* can be
execute aperiodic jobs.

Consider periodic tasks $T_k = (r_k, p_k, e_k)$ for $k = 1, \ldots, n$. T
server works if

$$\sum_{k=1}^{n} \frac{e_k}{p_k} + \frac{e_s}{p_s} \leq 1$$

Drawback: aperiodic jobs released just after a polling may b
needlessly.

We proceed to present two servers based on polling that try
this drawback.

For the moment, we ignore sporadic jobs.

Deferrable Server

Allows a polling server to save its execution time within a pe
(but not after this period!) if the aperiodic queue is empty.

In case of an EDF scheduler, the deadline of a deferrable ser
end of a period p_s can be treated as a hard deadline.

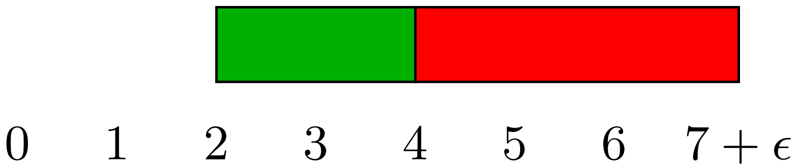
Then the deferrable server works if

$$\sum_{k=1}^{n} \frac{e_k}{p_k} + \frac{e_s}{p_s}(1 + \frac{p_s - e_s}{p_i}) \leq 1$$

for $i = 1, \ldots, n$ (Ghazalie & Baker, 1995).

Remark: $\sum_{k=1}^{n} \frac{e_k}{p_k} + \frac{e_s}{p_s} \leq 1$ is not good enough.

Example: $T_1 = (2, 5, 3 + \epsilon)$ and $p_s = 3$, $e_s = 1$.



T_1 misses its deadline at 7

Drawback: only partial use of available bandwidth.

Total Bandwidth Server

Fix an allowed utilization rate $\tilde{u}_s$ for the server, such that

$$\sum_{k=1}^{n} \frac{e_k}{p_k} + \tilde{u}_s \leq 1$$

When the aperiodic queue is non-empty, a deadline d is dete
the head of the queue, according to the following rules.
(Let the head of the aperiodic queue have execution time e.)

- When a job arrives at the *empty* aperiodic queue at tim

$$d := \max(d, t) + \frac{e}{\tilde{u}_s}$$

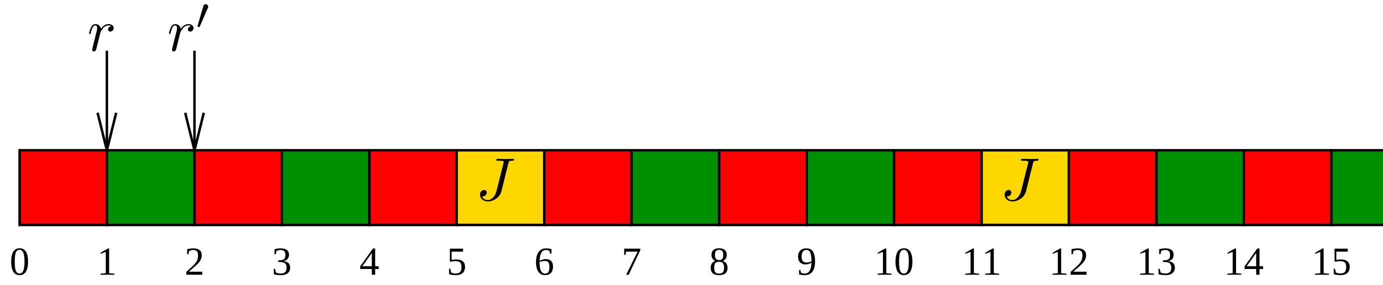
- When an aperiodic job *completes* and the *tail* of the ap
queue is *non-empty*:

$$d := d + \frac{e}{\tilde{u}_s}$$

Initially, $d = 0$.

Aperiodic jobs can now be treated as periodic jobs by the ED
scheduler.

Example: $T_1 = (0, 2, 1)$ and $T_2 = (0, 3, 1)$. We fix $\tilde{u}_s = \frac{1}{6}$.



J released at 1 with $e = 2$ gets (at 1) deadline 1+12=13.
J' released at 2 with $e' = 1$ gets (at 12) deadline 13+6=19.

Drawback: unfair in case of multiple servers; and

computationally expensive compared to the deferrable server

Generalized processor sharing divides available time over serv
round-robin fashion.

Acceptance Test for Sporadic Jobs

A sporadic job with deadline d and execution time e is accep
time t if utilization (of the periodic and accepted sporadic jo
time interval $[t, d]$ is never more than $1 - \frac{e}{d-t}$.

If accepted, utilization in $[t, d]$ is increased with $\frac{e}{d-t}$.

Example: Periodic task $T_1 = (0, 2, 1)$.

Sporadic job with $r = 1$, $e = 2$ and $d = 6$ is accepted. Utiliz
$[1, 6]$ is increased to $\frac{9}{10}$.

Sporadic job with $r = 2$, $e = 2$ and $d = 20$ is rejected.

Sporadic job with $r = 3$, $e = 1$ and $d = 13$ is accepted. Utili
$[3, 6]$ is increased to 1, and utilization in $[6, 13]$ to $\frac{3}{5}$.

The acceptance test may reject schedulable sporadic jobs.

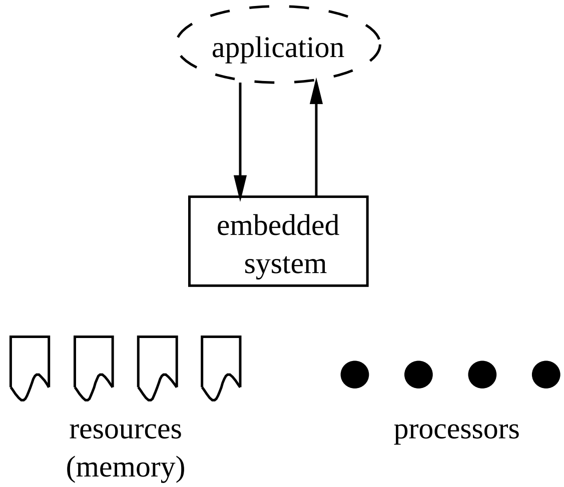
Example: Periodic task $T_1 = (0, 2, 1)$.

A sporadic job is released at time 0 with $e = 1$ and $d = 1$.

Utilization until time 1 is 1.5, but still the sporadic job coulc scheduled.

Remark: The total bandwidth server can be integrated with acceptance test for sporadic jobs (e.g. by making the allowec utilization rate $\tilde{u}_s$ dynamic.)

Remote Access Control Protocols



Resource units can be requested by jobs during their executi
are allocated to jobs in a mutually exclusive fashion.

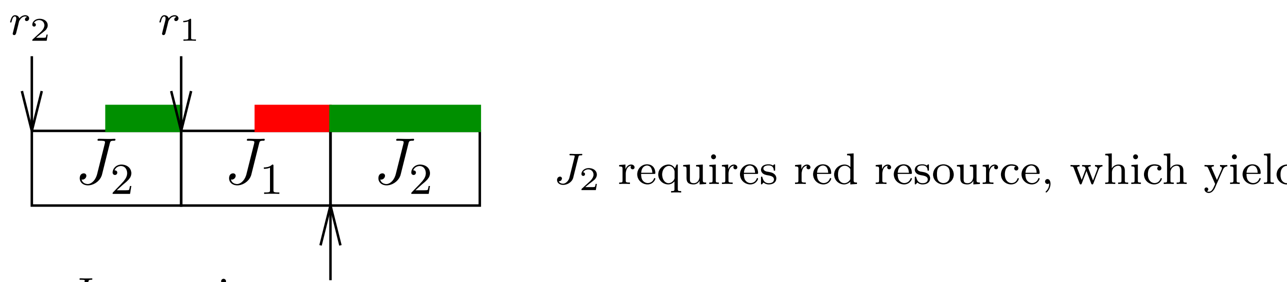
When a requested resource is refused, the job is preempted (

Remark: Resource sharing gives rise to scheduling anomaly.

Dangers of Resource Sharing

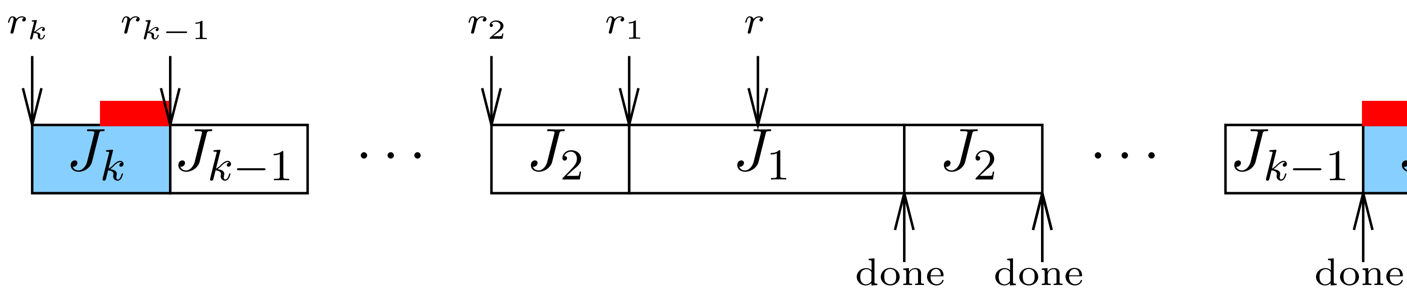
(1) Deadlock can occur.

Example: $J_1 > J_2$.



(2) A job J can be blocked by subsequent lower-priority job

Example: $J > J_1 > \cdots > J_k$, and J, J_k require the red reso

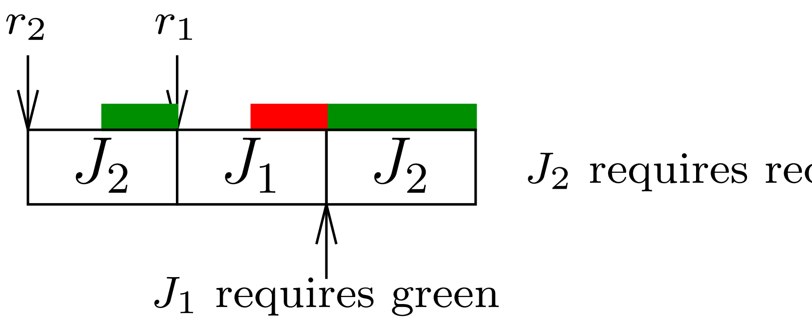


Priority Inheritance

When a job J requires a resource R and becomes blocked, t
holding R inherits the priority of J until it releases R.

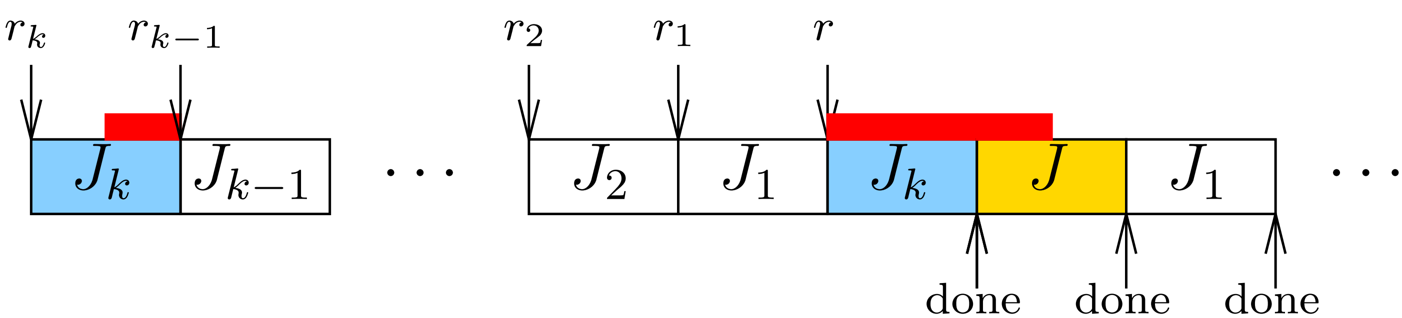
(1) Deadlock can still occur.

Example: $J_1 > J_2$.



(2) Blocking by subsequent lower-priority jobs becomes less

Example: $J > J_1 > \cdots > J_k$, and J, J_k require red.



Priority Ceiling

The priority ceiling of a *resource* R at time t is the highest p
(known) jobs that require R at some time $\geq t$.

The priority ceiling of the *system* at time t is the highest pri
ceiling of resources that are in use at time t.

(It has a special bottom value Ω when no resources are in us

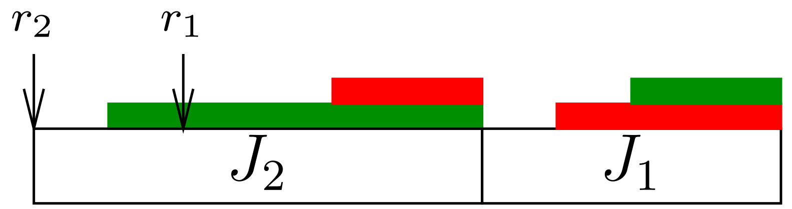
In a priority ceiling protocol, from the arrival of a job, this jo
released until its priority is higher than the priority ceiling of
system.

Assumption: The resources required by a job are known befo

Note: In the pictures to follow, r denotes the *arrival* of a jo

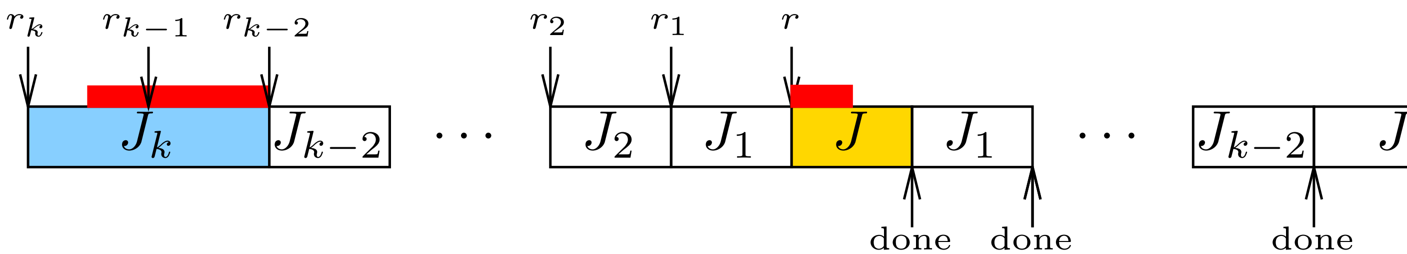
(1) No deadlocks. Because a job can only start executing w
resources it will require are free.

Example: $J_1 > J_2$.



(2) Blocking by subsequent lower-priority jobs becomes less

Example: $J > J_1 > \cdots > J_k$, and J, J_k require the red resou



This example assumes that the arrival of J is known at time

Question: What would happen if J were only known at its a

Preemption Ceiling

Motivation: with dynamic priorities of tasks, the overhead of computing priority ceilings is high.

The preemption level of jobs must be such that if $J > J'$, ar arrives after J', then J has a higher preemption level than J

Idea: J' will never preempt J.

Example: The preemption level can coincide with $priorities$, $arrival\ times$.

Ideally, the preemption level can be defined for periodic $task$ of jobs). For instance,

EDF: preemption level can coincide with RM-priorities of tas

$FIFO$: any preemption level is allowed

$LIFO$: in general, preemption level cannot be defined for tas

The preemption ceiling of a resource R at time t is the highe
preemption level of (known) jobs that require R at some tim

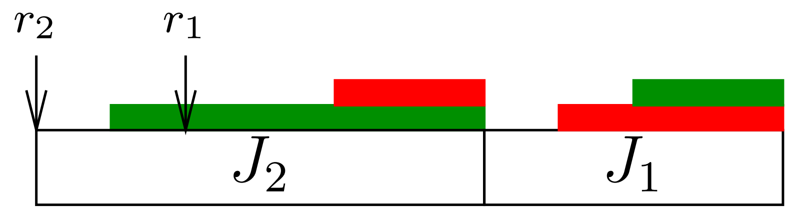
The preemption ceiling of the *system* at time t is the highes
preemption level of resources that are in use at time t.

In a preemption ceiling protocol, from the arrival of a job, th
not released until its preemption level is higher than the pree
ceiling of the system.

(*Moreover, there is a priority inheritance rule.*)

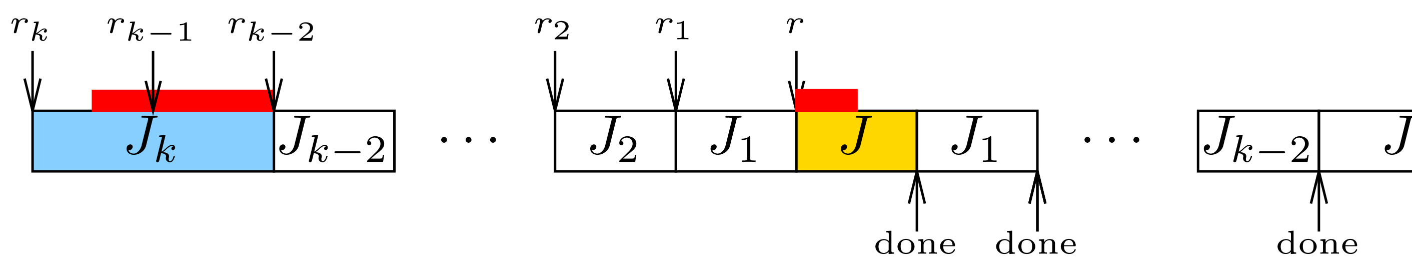
(1) No deadlocks. Because a job can only start executing w
resources it will require are free.

Example: $J_1 > J_2$.



(2) Blocking by subsequent lower-priority jobs becomes less

Example: $J > J_1 > \cdots > J_k$, and J, J_k require the red resou



Note that the preemption level of J is the highest of all jobs

This example assumes that the arrival of J is known at time

Multiple Resource Units

The notions of *priority* and *preemption ceiling* assumed onl
per resource type.

In case of multiple units of the same resource type, the defin
priority and preemption ceiling need to be adapted:

The priority (or preemption) ceiling of a resource R with k f
at time t is the highest priority (or preemption level) of know
that require $> k$ units of R at some time $\geq t$.

Multiple Processors

In a multiprocessor setting, jobs that require a global critical
general are given higher priority than jobs that only require l
resources.

Greedy Synchronization Protocol

Consider a *multiprocessor* environment, where each processo
some periodic tasks. There may be dependencies between jo

In the greedy synchronization protocol, jobs are released asa

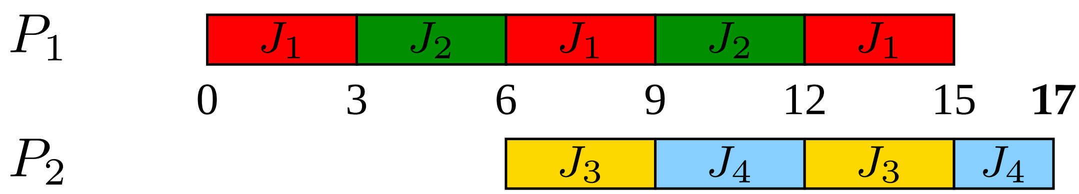
This schedule is not always optimal!

Example: Two processors P_1 and P_2.

P_1 runs $T_1 = (0, 6, 3)$ and $T_2 = (0, 9, 3)$, with $T_1 > T_2$.

P_2 runs $T_3 = (0, 9, 3)$ and $T_4 = (6, 10, 5)$, with $T_3 > T_4$.

A job of T_3 can only be released if a job of T_2 completed.

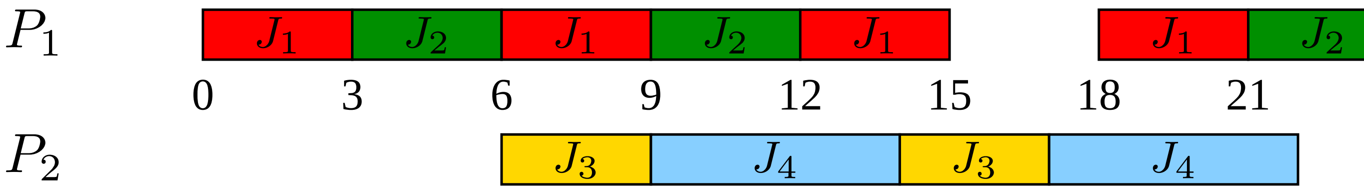


Example: Consider the same example, but now with the EDF scheduler.

P_1 runs $T_1 = (0, 6, 3)$ and $T_2 = (0, 9, 3)$.

P_2 runs $T_3 = (0, 9, 3)$ and $T_4 = (6, 10, 5)$.

A job of T_3 can only be released if a job of T_2 completed.



All deadlines are met.

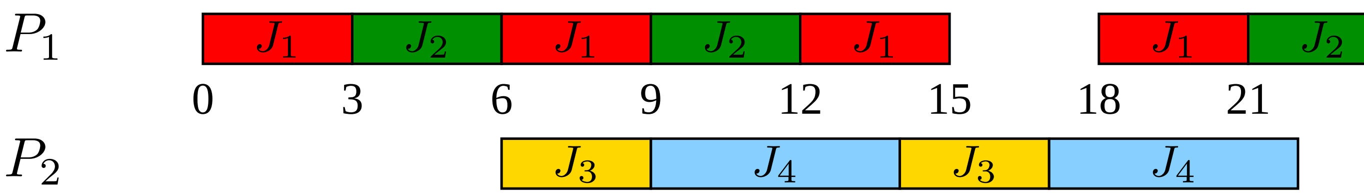
But the response time of a pair of jobs from (T_2, T_3) can bec
and the completion time can become unpredictable.

Release-Guard Protocol

Suppose a job of periodic task $T_2 = (r, p, e)$ can only be rele
job of periodic task T_1 completed.

In the release-guard protocol, the k-th job of T_2 is released a
with:

- $t \geq r + (k{-}1)p$;
- the k-th job of T_1 completed before t; and
- either T_2's processor is idle at t, or t is at least p time u
  the release of the $(k{-}1)$-th job of T_2.



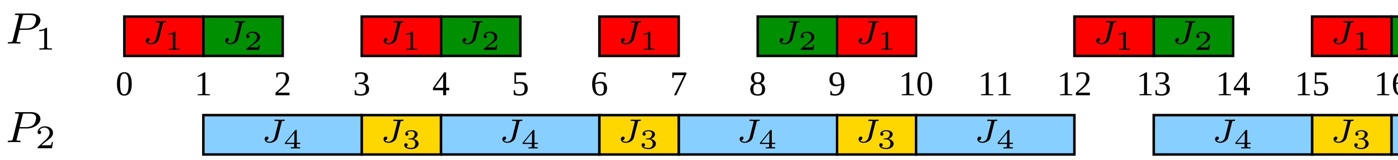
Example: Two processors P_1 and P_2.

P_1 runs $T_1 = (0, 3, 1)$ and $T_2 = (0, 4, 1)$.

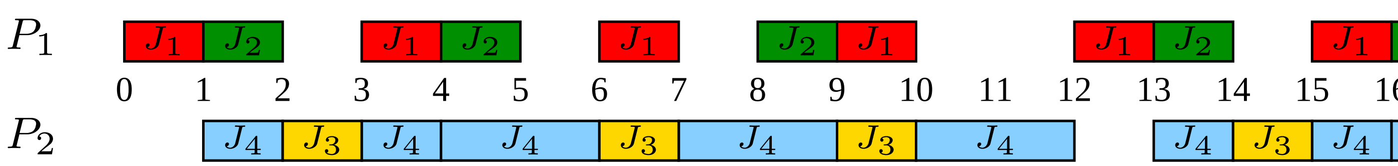
P_2 runs $T_3 = (0, 4, 1)$ and $T_4 = (1, 3, 2)$.

A job of T_3 can only be released if a job of T_2 completed.

First consider the greedy synchronization protocol, with EDF



Now consider the release-guard protocol, with $T_1 > T_2$ and



Summary:

- clock-driven vs. priority-driven scheduling
- fixed priority of RM vs. dynamic priority of EDF/LST
- optimality of EDF/LST vs. non-optimality of RM
- divide periodic tasks over processors
- scheduling of aperiodic jobs
  (slack stealing / polling / total bandwidth)
- acceptance test for sporadic jobs *(based on utilization)*
- resource sharing
  (priority inheritance / priority ceiling / preemption c
- dependencies between jobs
  (greedy synchronization / release-guard)