Real-Time Scheduling

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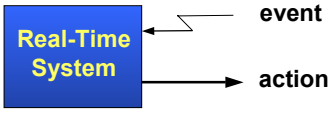
Goal

Provide some background of RT theory that you can apply for implementing RT control applications (using Shark):

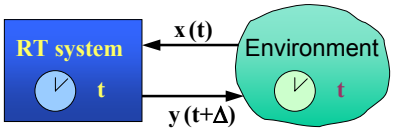
- Terminology and models
- Basic results on periodic scheduling
- Aperiodic task handling
- Inter-task communication
- Overload and QoS management

Real-Time system



A computing system able to respond to events within precise timing constraints.

Real-Time system



It is a system in which the correctness depends not only on the output values, but also on the **time** at which results are produced.

REAL TIME means that system time must be synchronized with the time in the environment.

Typical applications

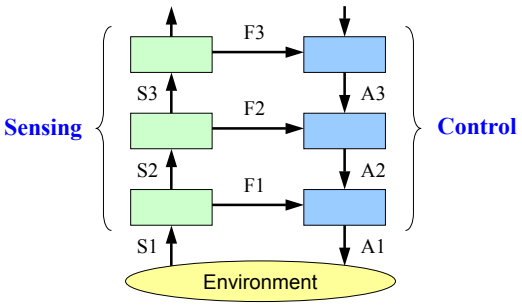
- automotive
- multimedia systems
- robotics
- small embedded devices
  - ⇒ cell phones
  - ⇒ digital TV
  - ⇒ videogames
  - ⇒ intelligent toys

Implications

- Timing constraints are imposed by the dynamics of the environment.
- The tight interaction with the environment requires the system to react to events within precise timing constraints.

➡ The operating system is responsible for enforcing such constraints on task execution.

Multi-level feedback control



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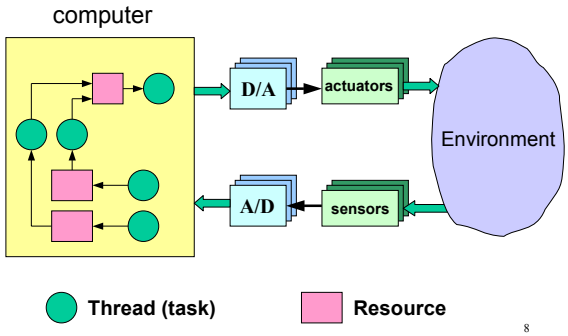
Software Vision



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Traditional Approach

- In spite of this large application domain, most of RT applications are designed using empirical techniques:
  - assembly programming
  - timing through dedicated timers
  - control through driver programming
  - priority manipulations

The resulting SW can be very efficient, but …

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Disadvantages

1. Tedious programming which heavily depends on programmer's ability
2. Difficult code understanding

$$\text{Readability} \propto \frac{1}{\text{efficiency}}$$

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Disadvantages

3. Difficult software maintainability
   - Complex appl.s consists of millions lines of code
   - Code understanding takes more that re-writing
   - But re-writing is VERY expensive and bug prone
4. Difficult to verify timing constraints without explicit support from the OS and the language

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Implications

- Such a way of programming RT applications is very dangerous.
- It may work in most situations, but the risk of a failure is high.
- When the system fails is very difficult to understand why.

→ **low reliability**

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Typical misconception

"RT system = Fast system"

It is not worth studying RT theory, because any timing constraint can be handled by a sufficiently fast computer.

Answers

- Given an arbitrary computer speed, we must always guarantee that timing constraints can be met. Testing is **NOT** sufficient.
- Increasing speed may not always work.

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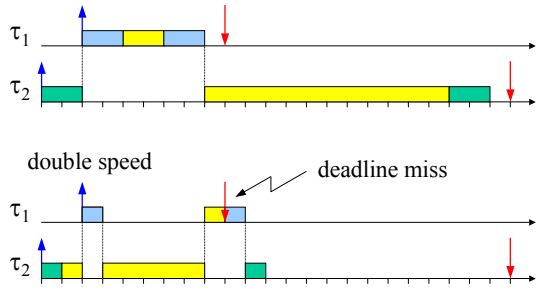
Increasing speed may not always work



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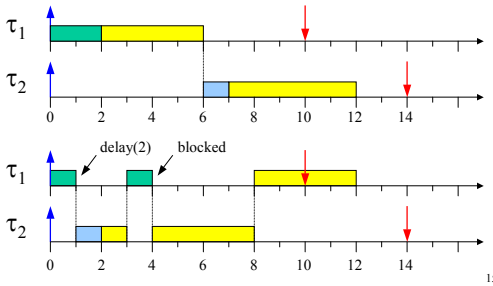
Never use DELAY

A **delay(Δ)** may cause a delay longer than Δ.



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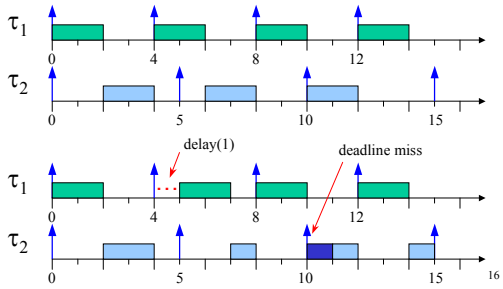
Never use DELAY

A **delay** in a task may also increase the response time of other tasks (example for fixed priorities):



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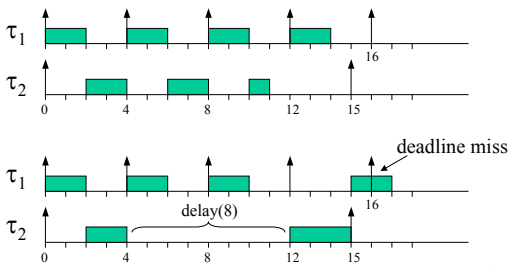
Never use DELAY

A **delay** in a task may also increase the response time of other tasks (example for deadline scheduling):



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Speed vs. Predictability

- The objective of a real-time system is to guarantee the timing behavior of each individual task.
- The objective of a fast system is to minimize the average response time of a task set.
  But …

Don't trust average when you have to guarantee individual performance

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Lessons learned

- Tests are not enough for real-time systems
- Intuitive solutions do not always work
- Delay should not be used in real-time tasks

A safe approach:
- ♦ use predictable kernel mechanisms
- ♦ analyze the system to predict its behavior

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Achieving predictability

- The operating system is the part most responsible for a predictable behavior.
- Concurrency control must be enforced by:
  - ⇒ appropriate scheduling algorithms
  - ⇒ appropriate syncronization protocols
  - ⇒ efficient communication mechanisms
  - ⇒ predictable interrupt handling
  - ⇒ overload management

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Let's review the main scheduling results

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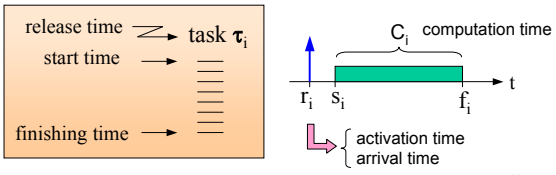
Terminology

- **Task** (or thread)

  is a sequence of instructions that in the absence of other activities is continuously executed by the processor until completion.



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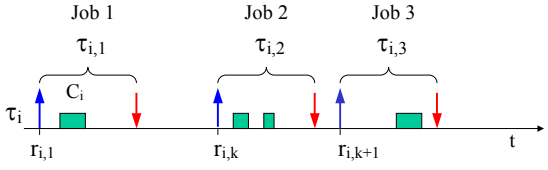
Tasks and jobs

A task is an infinite sequence of instances (jobs):



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Activation modes

- **Time driven**: **periodic** tasks

  the task is automatically activated by the kernel at regular intervals.

- **Event driven**: **aperiodic** tasks

  the task is activated upon the arrival of an event or through an explicit invocation of the activation primitive.

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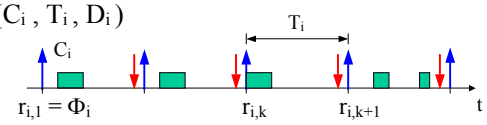
Periodic task model

$$\begin{cases} r_{i1} = \Phi_i \\ r_{i,k+1} = r_{i,k} + T_i \end{cases}$$

$\tau_i (C_i , T_i , D_i)$

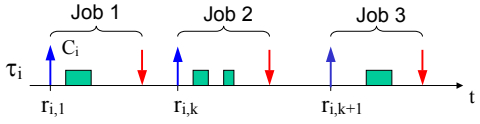


$$r_{i,k} = \Phi_i + (k-1)\,T_i$$
$$d_{i,k} = r_{i,k} + D_i$$

often $D_i = T_i$

Aperiodic task model

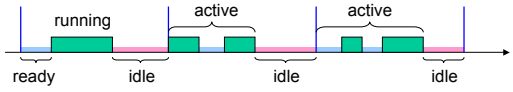
- **Aperiodic:** $r_{i,k+1} > r_{i,k}$
- **Sporadic:** $r_{i,k+1} \geq r_{i,k} + T_i$



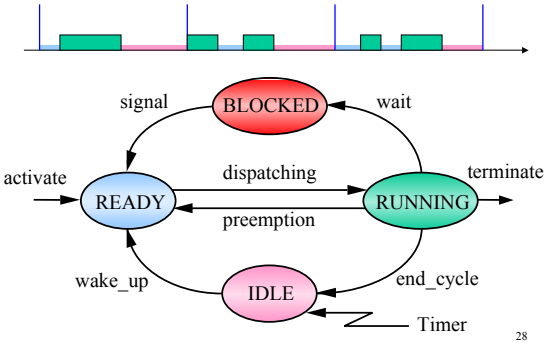
OS support for periodic tasks

task τ_i

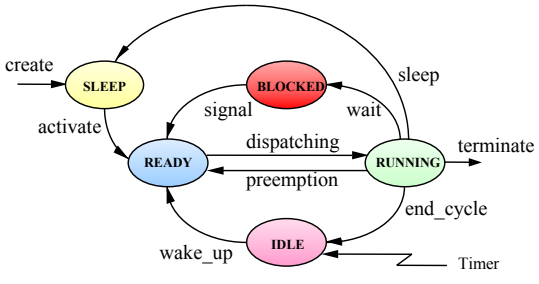
```
while (condition) {
    ...
    wait_for_next_period();
}
```



The IDLE state



SLEEP state



Scheduling

- A scheduling algorithm is said to be:
  - **preemptive**: if the running task can be temporarely suspended in the ready queue to execute a more important task.
  - **non preemptive**: if the running task cannot be suspended until completion.

Schedule

A **schedule** is a particular assignment of tasks to the processor.

Given a task set $\Gamma = \{\tau_1, \ldots, \tau_n\}$, a schedule is a mapping $\sigma : \mathbf{R}^+ \rightarrow \mathbf{N}$ such that $\forall t \in \mathbf{R}^+, \exists t_1, t_2 :$

$$t \in [t_1, t_2) \quad e \quad \forall t' \in [t_1, t_2) : \sigma(t) = \sigma(t')$$

$$\sigma(t) = \begin{cases} k > 0 & \text{if } \tau_k \text{ is running} \\ 0 & \text{if the processor is idle} \end{cases}$$

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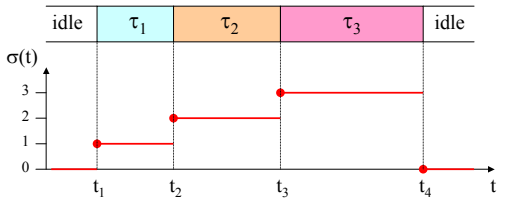
A sample schedule



At time t_1, t_2, t_3, e t_4 a **context switch** is performed.

Each interval $[t_i, t_{i+1})$ is called a **time slice**.

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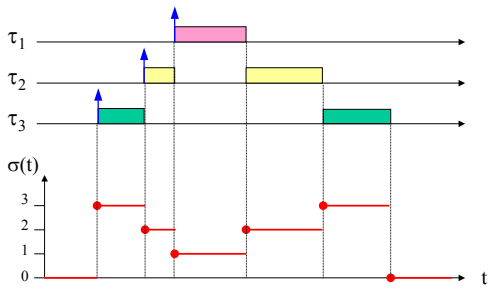
A preemptive schedule



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Definitions

- A schedule σ is said to be **feasible** if all the tasks are able to complete within a set of constraints.
- A set of tasks Γ is said to be **schedulable** if there exists a feasible schedule for it.

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Types of constraints

- **Timing constraints**
  - activation, completion, jitter.
- **Precedence constraints**
  - they impose an ordering in the execution.
- **Resource constraints**
  - they enforce a synchronization in the access of mutually exclusive resources.

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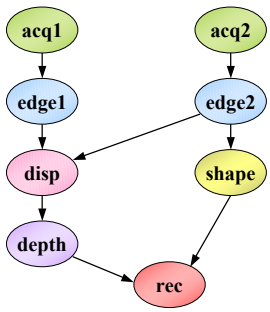
Precedence graph



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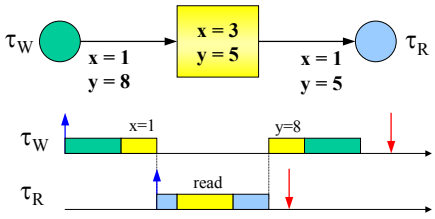
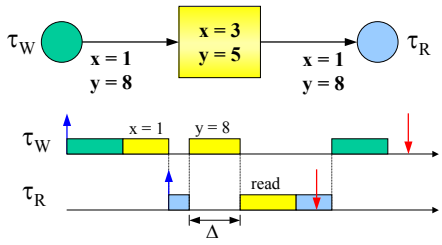
Resource constraints

To preserve data consistency, shared resources must be accessed in mutual exclusion:



Mutual exclusion

However, mutual exclusion introduces extra delays:



Timing constraints

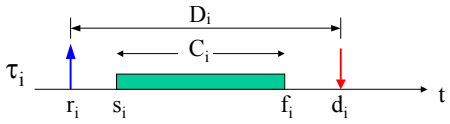
Can be explicit or implicit.

- **Explicit constraints**
  - Are included in the specification of the system activities.

Examples

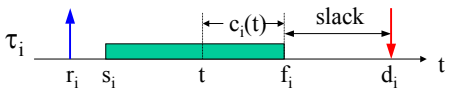
- open the valve **in** 10 seconds
- send the position **within** 40 ms
- read the altimeter **every** 200 ms

Real-Time tasks



$\mathbf{r_i}$	release time (arrival time $\mathbf{a_i}$)
$\mathbf{s_i}$	start time
$\mathbf{C_i}$	worst-case execution time (wcet)
$\mathbf{d_i}$	absolute deadline
$\mathbf{D_i}$	relative deadline
$\mathbf{f_i}$	finishing time

Other parameters



Lateness: $L_i = f_i - d_i$

Tardiness: $\max(0, L_i)$

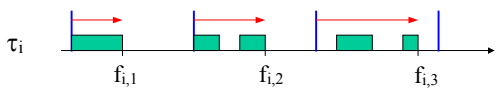
Residual wcet: $c_i(t)$ $c_i(r_i) = C_i$

Laxity (o slack): $d_i - t - c_i(t)$

Jitter

It is the time variation of a periodic event:

Finishing-time Jitter

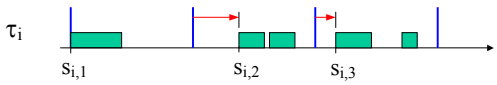


Absolute: $\max_k (f_{i,k} - r_{i,k}) - \min_k (f_{i,k} - r_{i,k})$

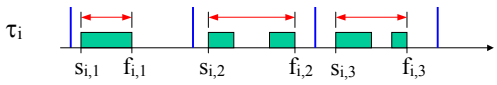
Relative: $\max_k \left| (f_{i,k} - r_{i,k}) - (f_{i,k-1} - r_{i,k-1}) \right|$

Other types of Jitter

Start-time Jitter



Completion-time Jitter (I/O jitter)



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Task Criticality

HARD tasks

All jobs must meet their deadlines. Missing a deadline may cause catastrophical effects.

SOFT tasks

Missing deadlines is not desired but causes only a performace degradation.

An operating system able to handle hard tasks is called a **hard real-time** system.

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Typical HARD tasks

– sensory acquisition
– low-level control
– sensory-motor planning

Typical SOFT tasks

– reading data from the keyboard
– user command interpretation
– message displaying
– graphical activities

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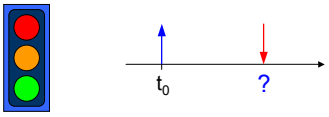
- **Implicit constraints**
  – do not appear in the system specification, but must be respected to meet the requirements.

Example

What's the time validity of a sensory data?



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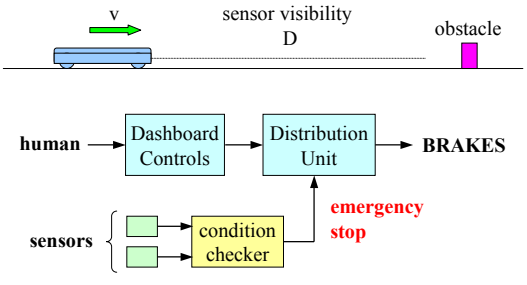
Example: automatic breaking



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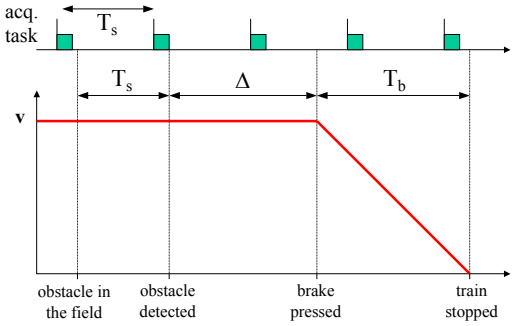
Worst-case reasoning



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D = sensor visibility

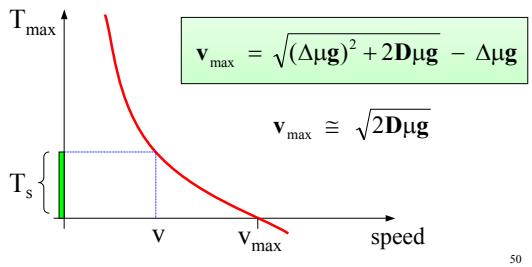
$$v(T_s + \Delta) + X_b < D$$

$$\begin{cases} X_b = vt - \frac{1}{2}at^2 \\ v = a\,t \end{cases} \qquad a = \mu g$$

$$X_b = \frac{v^2}{2\mu g}$$

$$v(T_s + \Delta) + \frac{v^2}{2\mu g} < D$$

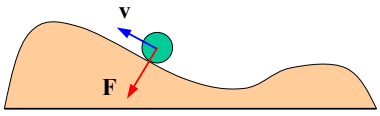
$$T_s < \frac{D}{v} - \frac{v}{2\mu g} - \Delta$$



$$\mathbf{v}_{max} = \sqrt{(\Delta\mu\mathbf{g})^2 + 2\mathbf{D}\mu\mathbf{g}} - \Delta\mu\mathbf{g}$$

$$\mathbf{v}_{max} \cong \sqrt{2\mathbf{D}\mu\mathbf{g}}$$

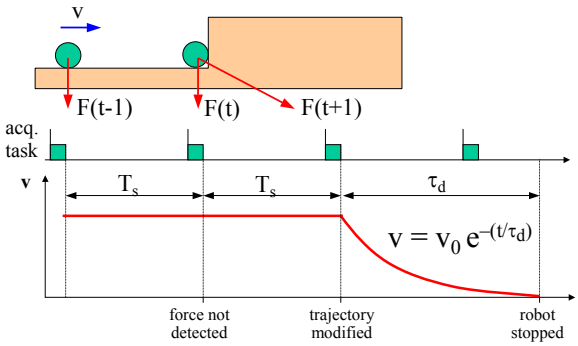
Esempio2: contour following



Goal

Move at velocity **v** along the surface tangent, exerting a force **F < F_{max}** along its normal direction.

Worst-case reasoning



Lenght covered by the robot after the contact:

$$L = vT_s + x_f$$

$$x_f = \int_0^\infty v(t)dt = \int_0^\infty v_0 e^{-t/\tau_d} dt = -v_0\tau_d(e^{-\infty} - e^0) = v_0\tau_d$$

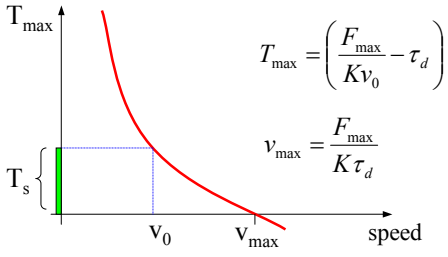
$$L = v(T_s + \tau_d)$$

Force on the robot tool: (K = elastic coefficient)

$$F = KL = v(T_s + \tau_d) < F_{max}$$

Condition on the sampling period:

$$T_s < \frac{F_{max}}{Kv_0} - \tau_d$$

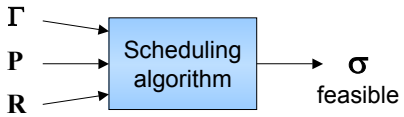


$$T_{max} = \left(\frac{F_{max}}{Kv_0} - \tau_d\right)$$

$$v_{max} = \frac{F_{max}}{K\tau_d}$$

The general scheduling problem

Given a set **Γ** of n tasks, a set **P** of m processors, and a set **R** of r resources, find an assignment of **P** and **R** to **Γ** which produces a feasible schedule.



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Complexity

- In 1975, Garey and Johnson showed that the general scheduling problem is NP hard.
- However, polynomial time algorithms can be found under particular conditions.

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Complexity

It's important to find polynomial time algorithms.

number of tasks $n = 30$
elementary step = $1\mu s$

- Alg. 1: $O(n)$ **30 μs**
- Alg. 2: $O(n^6)$ **12 min**
- Alg. 3: $O(6^n)$ **7 billions of years**

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Simplifying assumptions

- Single processor
- Omogeneous task sets
- Fully preemptive tasks
- Simultanoeus activations
- No precedence constraints
- No resource constraints

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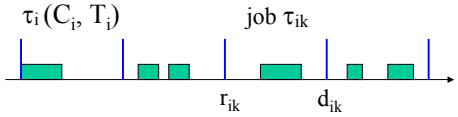
Periodic Task Scheduling

Problem formulation



For each periodic task, guarantee that:

- each job τ_{ik} is activated at $r_{ik} = (k-1)T_i$
- each job τ_{ik} completes within $d_{ik} = r_{ik} + D_i$

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Timeline Scheduling (cyclic scheduling)

It has been used for 30 years in military systems, navigation, and monitoring systems.

Examples

- Air traffic control
- Space Shuttle
- Boeing 777

Timeline Scheduling

Method

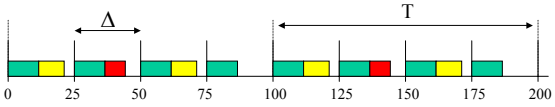
- The time axis is divided in intervals of equal length (***time slots***).
- Each task is statically allocated in a slot in order to meet the desired request rate.
- The execution in each slot is activated by a timer.

Example

task	f	T
A	40 Hz	25 ms
B	20 Hz	50 ms
C	10 Hz	100 ms

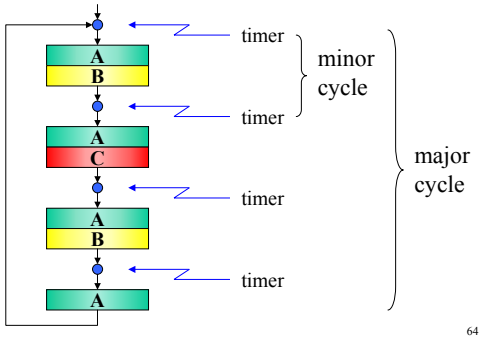
Δ = GCD (minor cycle)

T = lcm (major cycle)



Guarantee: $\begin{cases} C_A + C_B \le \Delta \\ C_A + C_C \le \Delta \end{cases}$

Implementation



Timeline scheduling

Advantages

- Simple implementation (no real-time operating system is required).
- Low run-time overhead.
- It allows jitter control.

Timeline scheduling

Disadvantages

- It is not robust during overloads.
- It is difficult to expand the schedule.
- It is not easy to handle aperiodic activities.

Problems during overloads

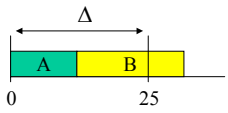
What do we do during task overruns?

- Let the task continue
  - we can have a ***domino effect*** on all the other tasks (timeline break)
- Abort the task
  - the system can remain in inconsistent states.

Expandibility

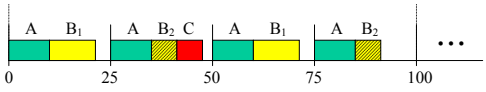
If one or more tasks need to be upgraded, we may have to re-design the whole schedule again.

Example: B is updated but $C_A + C_B > \Delta$



Expandibility

- We have to split task B in two subtasks (B_1, B_2) and re-build the schedule:



Guarantee: $C_A + C_{B1} \le \Delta$ and $C_A + C_{B2} + C_C \le \Delta$

Expandibility

If the frequency of some task is changed, the impact can be even more significant:

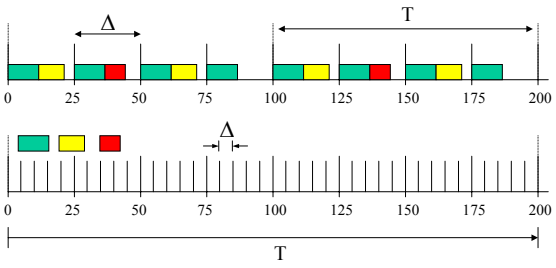
task	T	T
A	25 ms	25 ms
B	50 ms	**40 ms**
C	100 ms	100 ms
	before	**after**

minor cycle: $\Delta = 25$ $\Delta = 5$

major cycle: $T = 100$ $T = 200$

(40 sync. per cycle!)

Example



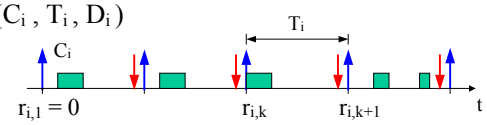
Priority Scheduling

Method

- Each task is assigned a priority based on its timing constraints.
- We verify the feasibility of the schedule using analytical techniques.
- Tasks are executed on a priority-based kernel.

Priority Assignments

$\tau_i (C_i , T_i , D_i)$



$D_i = T_i$

- **Rate Monotonic (RM):**

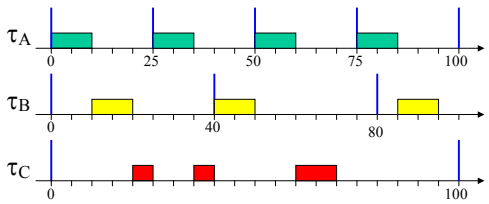
  $p_i \propto 1/T_i$ (static)

- **Earliest Deadline First (EDF):**

  $p_i \propto 1/d_i$ (dynamic) $d_{i,k} = r_{i,k} + D_i$

Rate Monotonic (RM)

- Each task is assigned a fixed priority proportional to its rate.



How can we verify feasibility?

- Each task uses the processor for a fraction of time:

$$U_i = \frac{C_i}{T_i}$$

- Hence the total **processor utilization** is:

$$U_p = \sum_{i=1}^{n} \frac{C_i}{T_i}$$

- U_p is a misure of the **processor load**

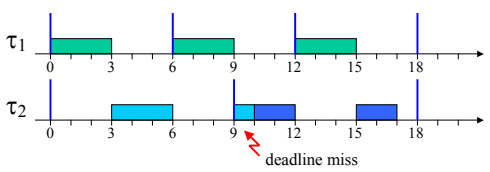
A necessary condition

If $U_p > 1$ the processor is overloaded hence the task set cannot be schedulable.

However, there are cases in which $U_p < 1$ but the task is not schedulable by RM.

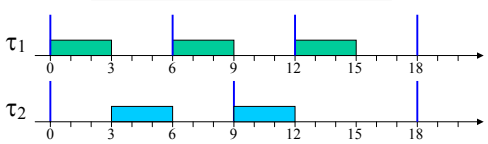
An unfeasible RM schedule

$$U_p = \frac{3}{6} + \frac{4}{9} = 0.944$$



Utilization upper bound

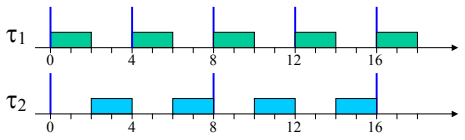
$$U_p = \frac{3}{6} + \frac{3}{9} = 0.833$$



NOTE: If C_1 or C_2 is increased, τ_2 will miss its deadline!

A different upper bound

$$U_p = \frac{2}{4} + \frac{4}{8} = 1$$



The upper bound U_{ub} depends on the specific task set.

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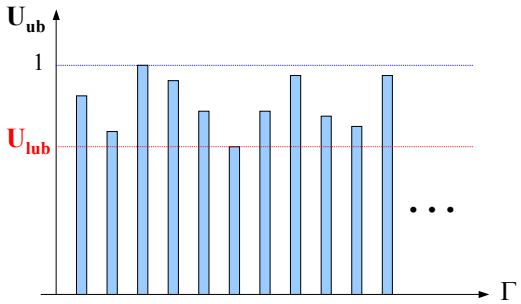
The least upper bound



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A sufficient condition

If $U_p \leq U_{lub}$ the task set is certainly schedulable with the RM algorithm.

NOTE

If $U_{lub} < U_p \leq 1$ we cannot say anything about the feasibility of that task set.

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Basic results

Assumptions: Independent tasks; $\Phi_i = 0$; $D_i = T_i$

In 1973, Liu & Layland proved that a set of *n* periodic tasks can be feasibly scheduled

under RM if $\sum_{i=1}^{n} \frac{C_i}{T_i} \leq n\left(2^{1/n} - 1\right)$

under EDF if and only if $\sum_{i=1}^{n} \frac{C_i}{T_i} \leq 1$

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RM bound for large *n*

$$U_{\text{lub}}^{RM} = n\left(2^{1/n} - 1\right)$$

for $n \to \infty$ $U_{lub} \to ln\ 2$

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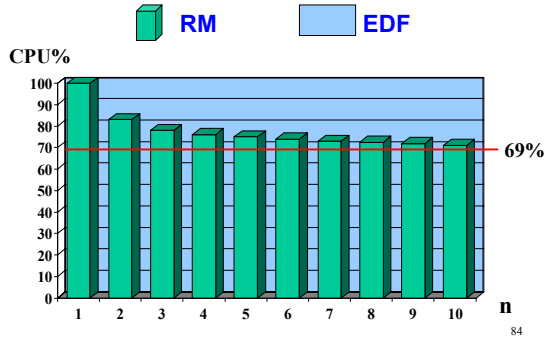
Schedulability bound



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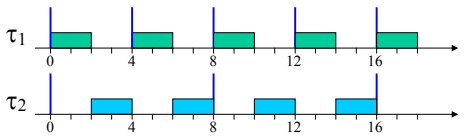
A special case

If tasks have harmonic periods $U_{lub} = 1$.

$$U_p = \frac{2}{4} + \frac{4}{8} = 1$$



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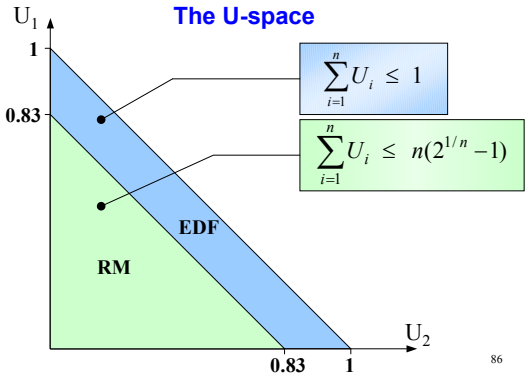
Schedulability region



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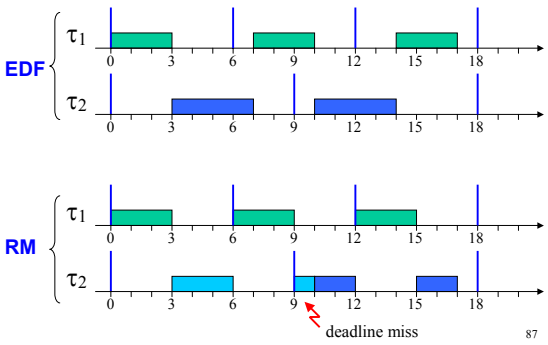
Schedule



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RM Optimality

RM is **optimal** among all fixed priority algorithms:

If there exists a fixed priority assignment which leads to a feasible schedule for Γ, then the RM assignment is feasible for Γ.

⇕

If Γ is not schedulable by RM, then it cannot be scheduled by any fixed priority assignment.

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EDF Optimality

EDF is **optimal** among all algorithms:

If there exists a feasible schedule for Γ, then EDF will generate a feasible schedule.

⇕

If Γ is not schedulable by EDF, then it cannot be scheduled by any algorithm.

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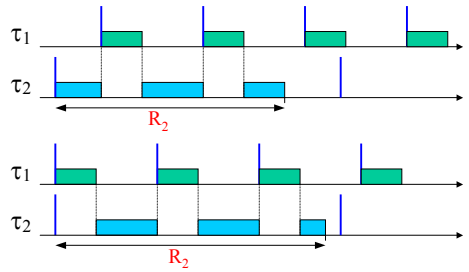
Critical Instant

For any task τ_i, the longest response time occurs when it arrives together with all higher priority tasks.



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The Hyperbolic Bound

- In 2000, **Bini et al.** proved that a set of *n* periodic tasks is schedulable with RM if:

$$\prod_{i=1}^{n}(U_i+1) \le 2$$

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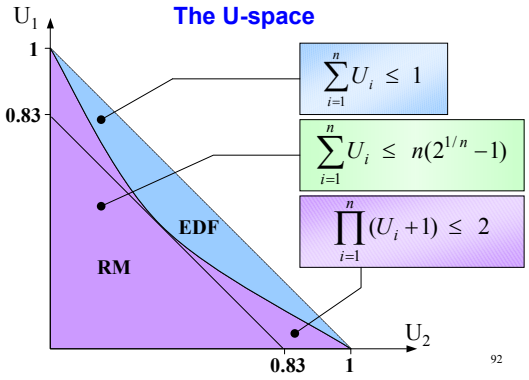
Schedulability region



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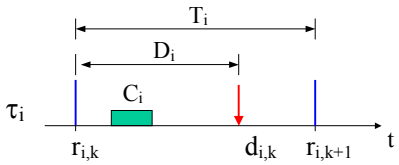
Extension to tasks with D < T



Scheduling algorithms

- Deadline Monotonic: $p_i \propto 1/D_i$ (static)
- Earliest Deadline First: $p_i \propto 1/d_i$ (dynamic)

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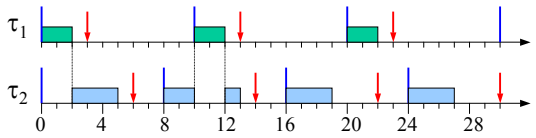
Deadline Monotonic



Problem with the Utilization Bound

$$U_p = \sum_{i=1}^{n}\frac{C_i}{D_i} = \frac{2}{3}+\frac{3}{6} = 1.16 > 1$$

but the task set is schedulable.

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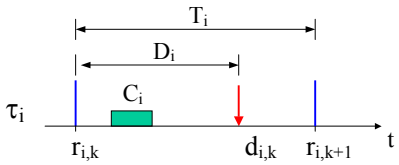
How to guarantee feasibility?



- Fixed priority: Response Time Analysis (RTA)
- EDF: Processor Demand Criterion (PDC)

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Response Time Analysis [Audsley '90]

- For each task τ_i compute the interference due to higher priority tasks:

$$I_i = \sum_{D_k < D_i} C_k$$

- compute its response time as

$$R_i = C_i + I_i$$

- verify if $R_i \le D_i$

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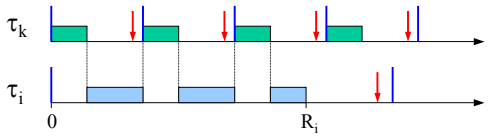
Computing the interference



Interference of τ_k on τ_i in the interval $[0, R_i]$:

$$I_{ik} = \left\lceil \frac{R_i}{T_k} \right\rceil C_k$$

Interference of high priority tasks on τ_i:

$$I_i = \sum_{k=1}^{i-1} \left\lceil \frac{R_i}{T_k} \right\rceil C_k$$

Computing the response time

$$R_i = C_i + \sum_{k=1}^{i-1} \left\lceil \frac{R_i}{T_k} \right\rceil C_k$$

Iterative solution:

$$\begin{cases} R_i^0 = C_i \\ R_i^s = C_i + \sum_{k=1}^{i-1} \left\lceil \frac{R_i^{(s-1)}}{T_k} \right\rceil C_k \end{cases}$$

iterate until $R_i^s > R_i^{(s-1)}$

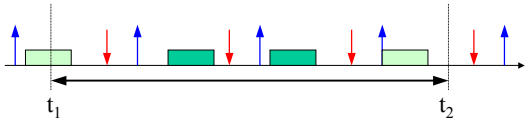
Processor Demand Criterion

[Baruah, Howell, Rosier 1990]

In any interval of time, the computation demanded by the task set must be no greater than the available time.

$$\forall t_1, t_2 > 0, \quad g(t_1, t_2) \leq (t_2 - t_1)$$

Processor Demand

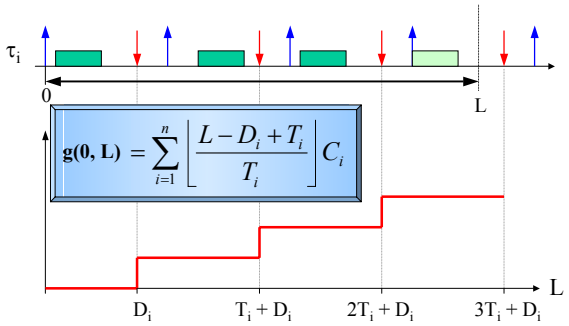


The demand in $[t_1, t_2]$ is the computation time of those jobs started at or after t_1 with deadline less than or equal to t_2:

$$g(t_1, t_2) = \sum_{\substack{d_i \leq t_2 \\ r_i \geq t_1}} C_i$$

Processor Demand

For synchronous task sets we can only analyze intervals [0,L]



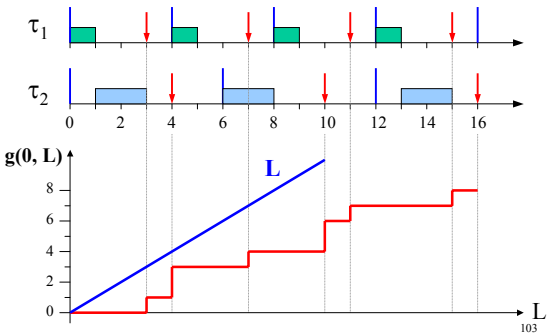
Processor Demand Test

$$\forall L > 0 \quad \sum_{i=1}^{n} \left\lfloor \frac{L - D_i + T_i}{T_i} \right\rfloor C_i \leq L$$

Question

How can we bound the number of intervals in which the test has to be performed?

Example



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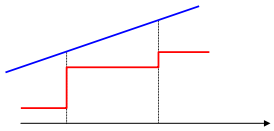
Bounding complexity

- Since g(0,L) is a step function, we can check feasibility only at deadline points.



- If tasks are synchronous and $U_p < 1$, we can check feasiblity up to the hyperperiod H:

$$H = lcm(T_1, \ldots, T_n)$$

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Bounding complexity

- Moreover we note that: $g(0, L) \le G(0, L)$

$$G(0,L) = \sum_{i=1}^{n} \left(\frac{L + T_i - D_i}{T_i} \right) C_i$$

$$= \sum_{i=1}^{n} L \frac{C_i}{T_i} + \sum_{i=1}^{n} (T_i - D_i) \frac{C_i}{T_i}$$

$$= LU + \sum_{i=1}^{n} (T_i - D_i) U_i$$

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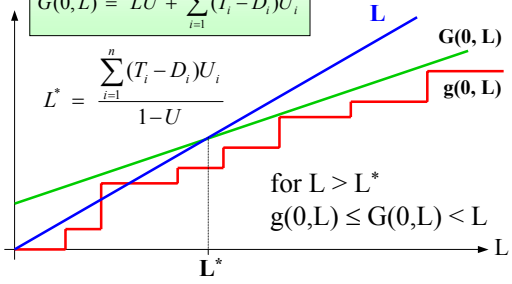
Limiting L

$$G(0,L) = LU + \sum_{i=1}^{n} (T_i - D_i) U_i$$

$$L^* = \frac{\sum_{i=1}^{n} (T_i - D_i) U_i}{1 - U}$$



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Processor Demand Test

A set of *n* periodic tasks with D ≤ T is schedulable by EDF if and only if

$$U < 1 \quad \text{AND} \quad \forall L > 0 \quad \sum_{i=1}^{n} \left\lfloor \frac{L - D_i + T_i}{T_i} \right\rfloor C_i \le L$$

$$D = \{ d_k \mid d_k \le min\,(H, L^*) \}$$

$$\begin{cases} H = lcm(T_1, \ldots, T_n) \\ L^* = \dfrac{\sum_{i=1}^{n} (T_i - D_i) U_i}{1 - U} \end{cases}$$

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Summarizing: RM vs. EDF

	$D_i = T_i$	$D_i \le T_i$
RM	***Suff.:*** ***polynomial*** $O(n)$ LL: $\Sigma U_i \le n(2^{1/n} - 1)$ HB: $\Pi(U_i + 1) \le 2$ ***Exact*** ***pseudo-polynomial*** RTA	***pseudo-polynomial*** Response Time Analysis $\forall i \quad R_i \le D_i$ $R_i = C_i + \sum_{k=1}^{i-1} \left\lceil \frac{R_i}{T_k} \right\rceil C_k$
EDF	***polynomial:*** $O(n)$ $\Sigma U_i \le 1$	***pseudo-polynomial*** Processor Demand Analysis $\forall L > 0, \quad g(0,L) \le L$

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Questions

- If EDF is more efficient than RM, why commercial RT systems are still based on RM?

Main reason

- RM is simpler to implement on top of commercial (fixed priority) kernels.
- EDF requires explicit kernel support for deadline scheduling, but gives other advantages.

Advantages of EDF

However, EDF offers the following advantages with respect to RM:

- Less overhaed due to preemptions;
- More flexible behavior in overload situations;
- More uniform jitter control;
- Better aperiodic responsiveness.

Runtime overhead

Two different types of overhead are considered:

1. **Overhead for job release**

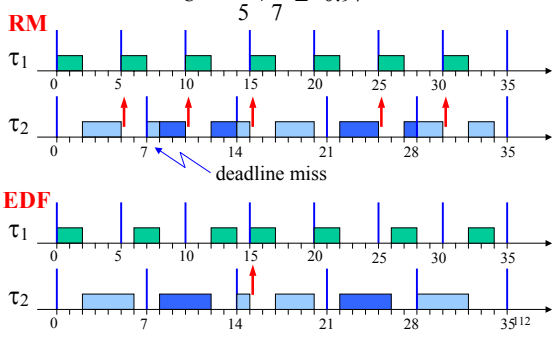
   ⇒ EDF has more than RM, because the absolute deadline must be updated at each job activation

2. **Overhead for context switch**

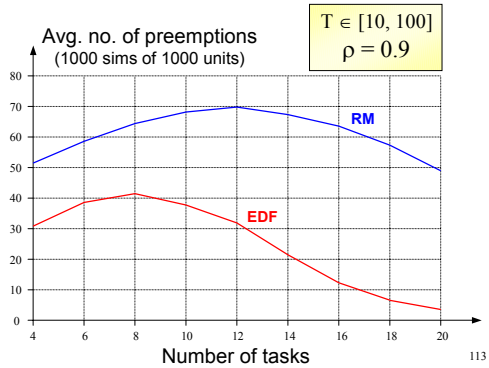
   ⇒ RM has more than EDF because of the higher number of preemptions

Preemptions

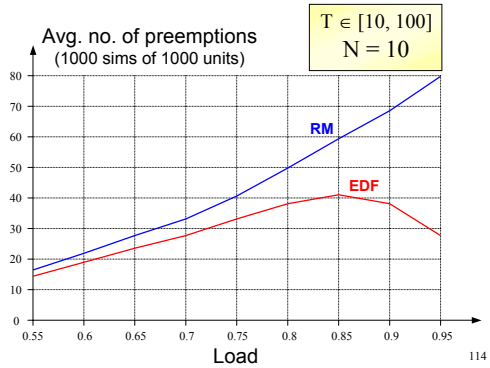
$$U = \frac{2}{5} + \frac{4}{7} \cong 0.97$$



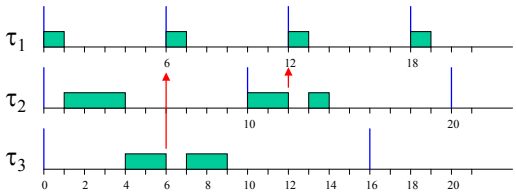
Preemptions



Preemptions



Example with RM



Under **RM**, preemptions increase as computation times increase

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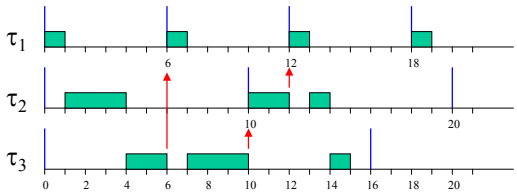
Example with RM



Under **RM**, preemptions increase as computation times increase

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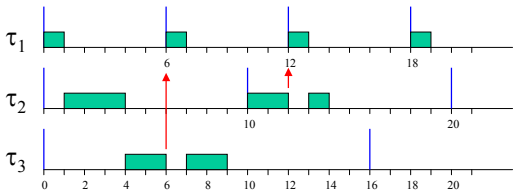
Example with EDF



Under **EDF**, preemptions may decrease as computation times increase

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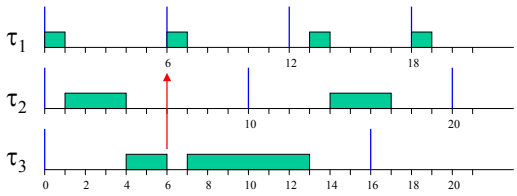
Example with EDF



Under **EDF**, preemptions may decrease as computation times increase

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Robustness under overloads

Two situations are considered:

1. Permanent overload

⇒ This occurs when U > 1

2. Transient overload

⇒ This occurs when some job executes more than expected

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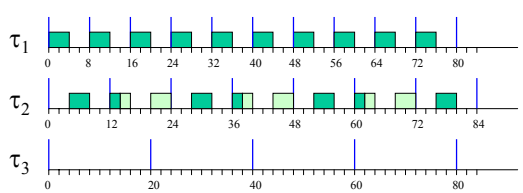
RM under permanent overload

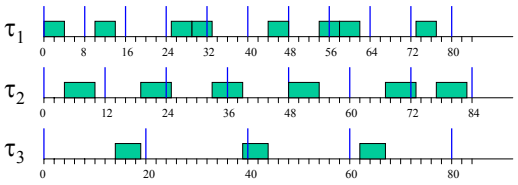
$$U = \frac{4}{8} + \frac{6}{12} + \frac{5}{20} = 1.25$$



- High priority tasks execute at the proper rate
- Low priority tasks are completely blocked

EDF under permanent overload

$$U = \frac{4}{8} + \frac{6}{12} + \frac{5}{20} = 1.25$$

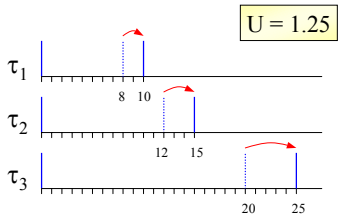


- All tasks execute at a slower rate
- No task is blocked

EDF is predictable in overloads

Theorem (Cervin '03)

If U > 1, EDF executes tasks with an average period $T'_i = T_i U$.



	T_i	T'_i
τ_1	8	10
τ_2	12	15
τ_3	20	25

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Big misconceptions

~~EDF is not predictable during overloads because we don't know which tasks are going to miss their deadlines.~~

~~RM is predictable during overloads because the tasks that miss their deadlines are low priority tasks.~~

We now show that this is not true

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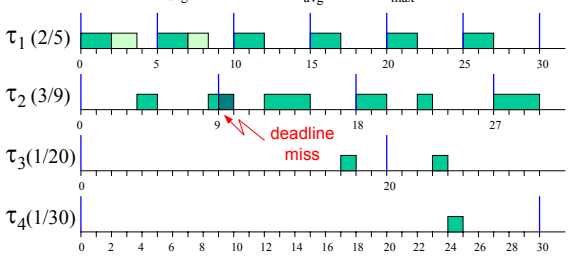
RM during transient overruns

$U_{avg} = 0.817 \quad C_{1avg} = 2, \; C_{1max} = 4$



Who is missing its deadline is not the lowest priority task

Another misconception

RM reduces jitter during task execution more than EDF

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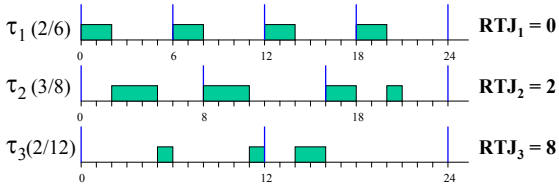
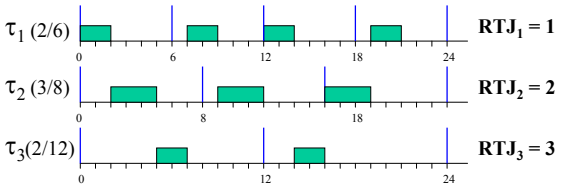
Jitter under RM



τ_3 experiences a very high jitter

126

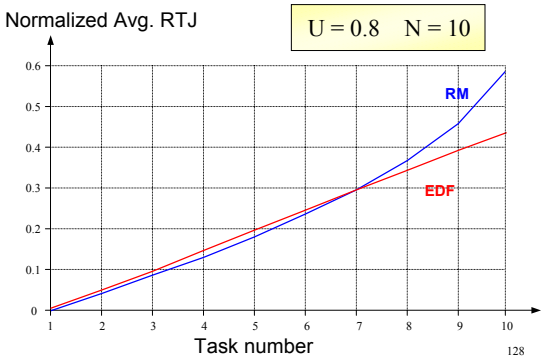
Jitter under EDF



For a little increase of RTJ_1, RTJ_3 decreases a lot

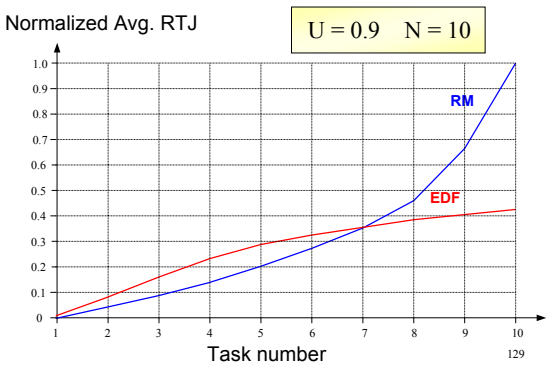
127

Jitter experiments



128

Jitter experiments



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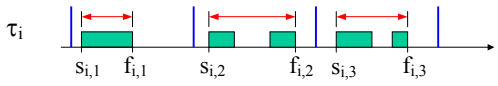
Another result on Jitter

Input-Output Jitter

$$IOJ_i = \max (f_{i,k} - s_{i,k}) - \min (f_{i,k} - s_{i,k})$$

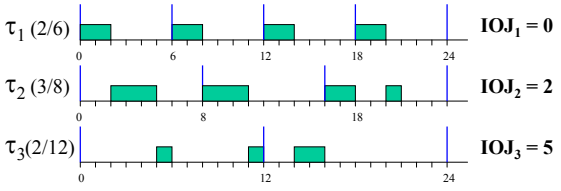


Theorem (Cervin 03)

$$IOJ_i^{EDF} \leq IOJ_i^{RM}$$

130

I/O Jitter under RM



All tasks except τ_1 experience I/O jitter

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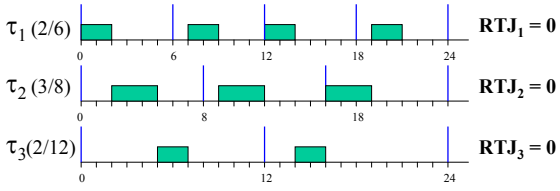
I/O Jitter under EDF



All tasks experience no I/O Jitter

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Handling Aperiodic Tasks

Handling Criticality

- Aperiodic tasks with **HARD** deadlines must be guaranteed under worst-case conditions.
- Off-line guarantee is only possible if we can bound interarrival times (**sporadic tasks**).
- Hence **sporadic tasks** can be guaranteed as periodic tasks with $C_i = WCET_i$ and $T_i = MIT_i$

$$\begin{bmatrix} WCET & = & \text{Worst-Case Execution Time} \\ MIT & = & \text{Minimum Interarrival Time} \end{bmatrix}$$

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SOFT aperiodic tasks

- Aperiodic tasks with **SOFT** deadlines should be executed as soon as possible, but without jeopardizing HARD tasks.
- We may be interested in
  - → minimizing the average response time
  - → performing an on-line guarantee

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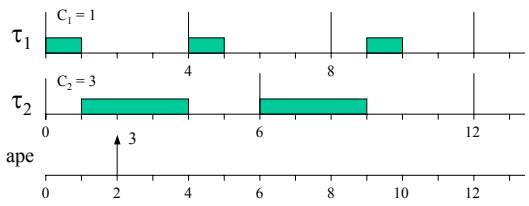
Periodic Scheduling
(EDF)



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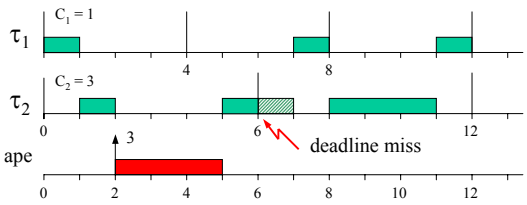
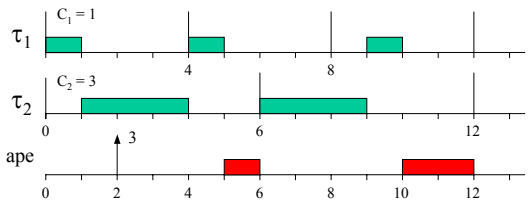
Immediate service



Response Time = 3

137

Background service



Response Time = 10

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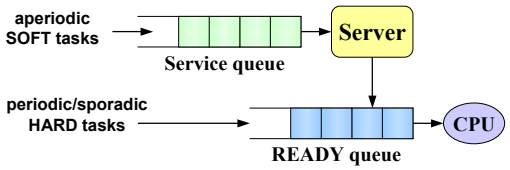
Aperiodic Servers

- A server is a kernel activity aimed at controlling the execution of aperiodic tasks.
- Normally, a server is a periodic task having two parameters:

C_s capacity (or budget)
T_s server period

To preserve periodic tasks, no more than C_s units must be executed every period T_s

Aperiodic service queue



- The server is scheduled as any periodic task.
- Priority ties are broken in favor of the server.
- Aperiodic tasks can be selected using an arbitrary queueing discipline.

Fixed-priority Servers

- Polling Server
- Deferrable Server
- Sporadic Server
- Slack Stealer

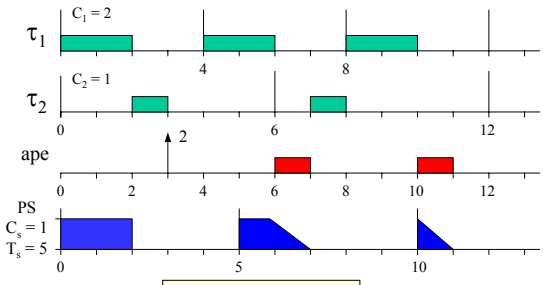
Dynamic-priority Servers

- Dynamic Polling Server
- Dynamic Sporadic Server
- Total Bandwidth Server
- Tunable Bandwidth Server
- Constant Bandwidth Server

Polling Server (PS)

- At the beginning of each period, the budget is recharged at its maximum value.
- Budget is consumed during job execution.
- When the server becomes active and there are no pending jobs, C_s is discharged to zero.
- When the server becomes active and there are pending jobs, they are served until $C_s > 0$.

RM + Polling Server



Response Time = 8

PS properties

- In the worst-case, the PS behaves as a periodic task with utilization $U_s = C_s/T_s$.
- Aperiodic tasks execute at the highest priority if $T_s = \min(T_1, \ldots, T_n)$.
- Liu & Layland analysis gives that:

$$U_{lub}^{RM+PS}(n) = U_s + n\left[\left(\frac{2}{U_s+1}\right)^{1/n} - 1\right]$$

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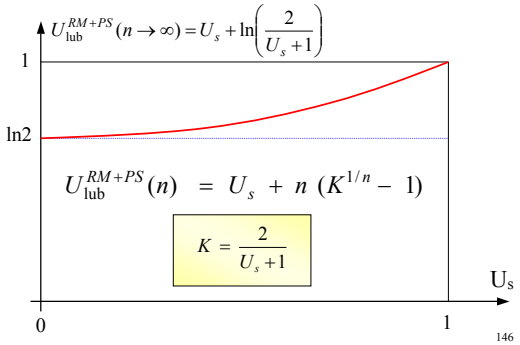
RM + PS schedulability



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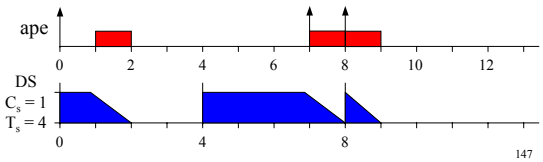
Deferrable Server (DS)

- Is similar to the PS, but the budget is not discharged if there are no pending requests.
- Keeping the budget improves responsiveness, but decreases the utilization bound.



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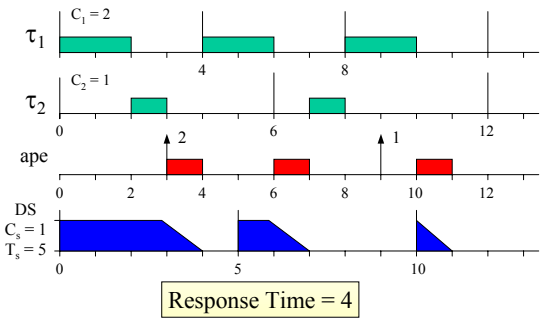
RM + Deferrable Server



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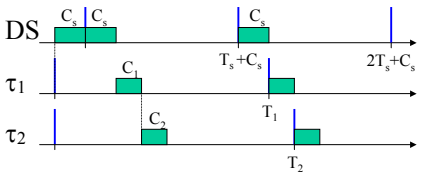
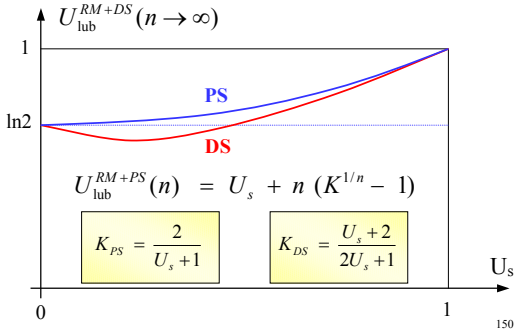
Analysis of RM + DS



$$U_{lub}^{RM+DS}(n) = U_s + n\left[\left(\frac{U_s+2}{2U_s+1}\right)^{1/n} - 1\right]$$

149

RM + DS schedulability



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Designing server parameters

- Determine U_s^{max} from $U_p \leq n\left[\left(\frac{U_s+2}{2U_s+1}\right)^{1/n} - 1\right]$
- Define $U_s \leq U_s^{max}$
- Define $T_s = \min(T_1, \ldots, T_n)$
- Compute $C_s = U_s T_s$

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Total Bandwidth Server (TBS)

- It is a dynamic priority server, used along with EDF.
- Each aperiodic request is assigned a deadline so that the server demand does not exceed a given bandwidth U_s.
- Aperiodic jobs are inserted in the ready queue and scheduled together with the HARD tasks.

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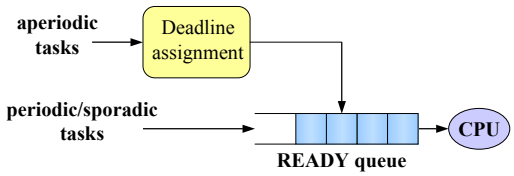
The TBS mechanism



- Deadlines ties are broken in favor of the server.
- Periodic tasks are guaranteed *if and only if*

$$U_p + U_s \leq 1$$

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Deadline assignment rule

- Deadline has to be assigned not to jeopardize periodic tasks.
- A safe relative deadline is equal to the minimum period that can be assigned to a new periodic task with utilization U_s:

$$U_s = C_k/T_k \Rightarrow T_k = d_k - r_k = C_k/U_s$$

- Hence, the absolute deadline can be set as:

$$d_k = r_k + C_k/U_s$$

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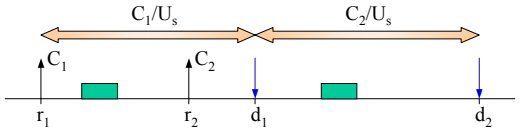
Deadline assignment rule



- To keep track of the bandwidth assigned to previous jobs, d_k must be computed as:

$$d_k = \max(r_k, d_{k-1}) + C_k/U_s$$

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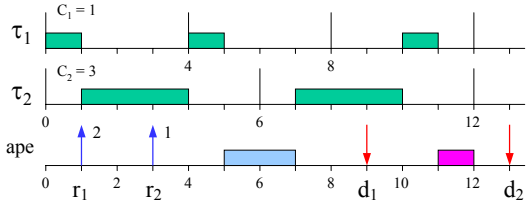
EDF + TBS schedule



$$U_s = 1 - U_p = 1/4$$

$$\begin{cases} d_1 = r_1 + C_1/U_s = 1 + 2 \cdot 4 = 9 \\ d_2 = \max(r_2, d_1) + C_2/U_s = 9 + 1 \cdot 4 = 13 \end{cases}$$

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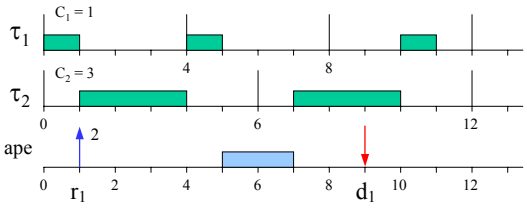
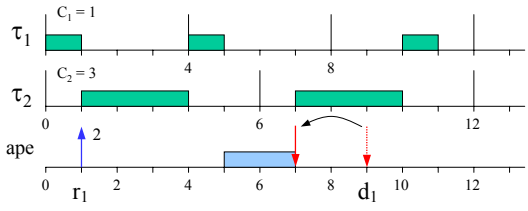
Improving TBS

- What's the minimum deadline that can be assigned to an aperiodic job?



Improving TBS

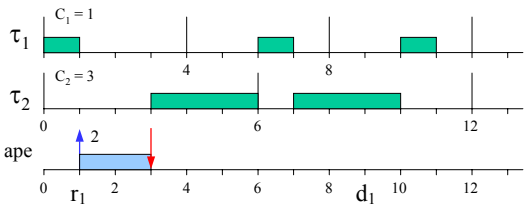
- If we freeze the schedule and advance d_1 to 7, no task misses its deadline, but the schedule is not EDF:



Feasible schedule ≠ EDF

Improving TBS

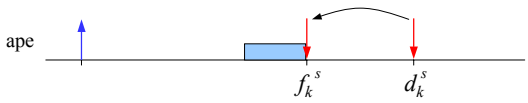
- Clearly, advancing the deadline now does not produce any enhancement:



Computing the deadline

- In general, the new deadline has to be set to the finishing time of the current job:

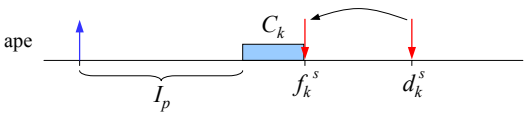
$$\begin{cases} d_k^0 = \max(r_k, d_{k-1}^0) \\ d_k^{s+1} = f_k^s = f_k(d_k^s) \end{cases}$$



Computing the deadline

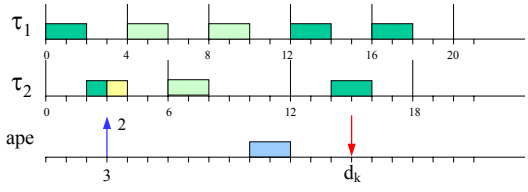
- The actual finishing time can be estimated based on the periodic interference:

$$f_k^s = C_k + I_p(r_k, d_k^s)$$



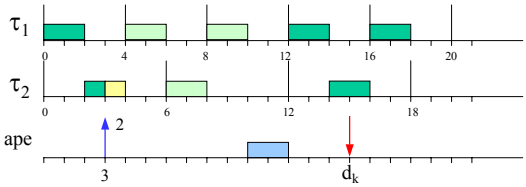
Periodic Interference

$$\begin{cases} U_p = 1/2 + 1/3 = 5/6 \\ U_s = 1 - U_p = 1/6 \end{cases} \qquad \begin{cases} C_k = 2 \\ d_k = 3 + 2/U_s = 15 \end{cases}$$



$$I_p(t, d_k^s) = I_a(t, d_k^s) + I_f(t, d_k^s)$$

Computing interference

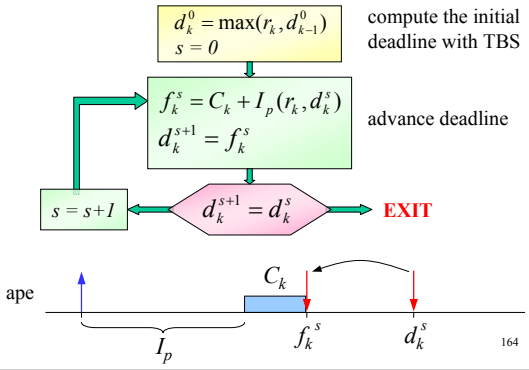


$$I_a(t,d_k^s) = \sum_{\tau_i \text{ active}} c_i(t)$$

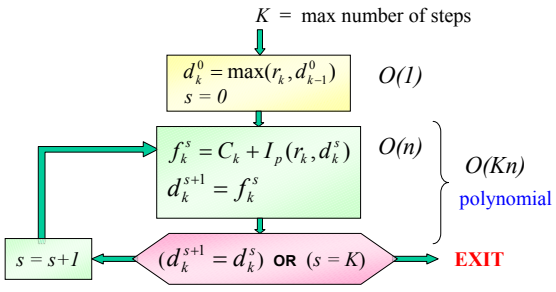
$next_i(t)$ = next release time of task τ_i after t

$$I_f(t,d_k^s) = \sum_{i=1}^{n} \left(\left\lceil \frac{d_k^s - next_i(t)}{T_i} \right\rceil - 1 \right) C_i$$

The Optimal Server

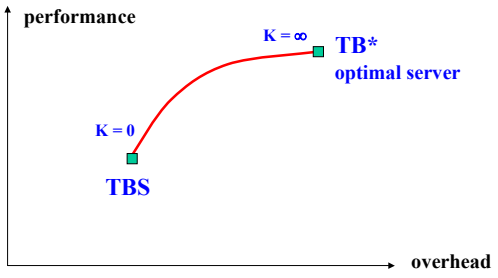


Tunable Bandwidth Server TB(K)

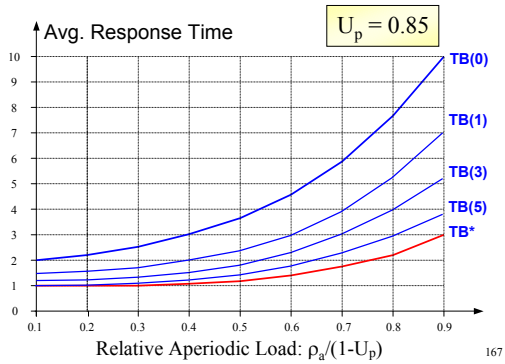


TB(0) = TBS **TB(∞) = TB***

Tuning performance vs. overhead

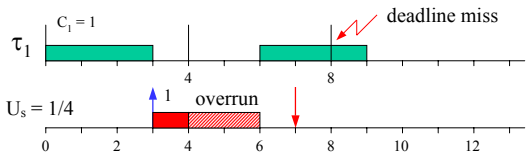


Aperiodic responsiveness



Problems with the TBS

- Without a budget management, there is no protection against execution overruns.
- If a job executes more than expected, hard tasks could miss their deadlines.

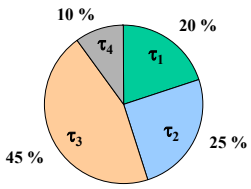


Solution: task isolation

- In the presence of overruns, only the faulty task should be delayed.
- Each task τ_i should not demand more than its declared utilization ($U_i = C_i/T_i$).
- If a task executes more than expected, its priority should be decreased (i.e., its deadline postponed).

Bandwidth partitioning

- Ideally, each task should be assigned a given bandwidth and never demand more.



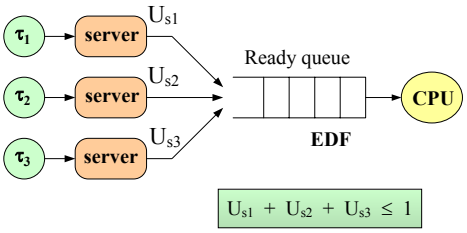
Questions

- **What do we do if a task overruns?**
  - Only that task should be delayed.
- **Consequences**
  - if the task is hard => exception
  - if the task is soft => QoS degradation

Achieving isolation

- Isolation among tasks can be achieved through a **bandwidth reservation**.
- Each task is managed by a dedicated server having bandwidth U_s .
- The server assigns priorities (or deadlines) to tasks so that they do not exceed the reserved bandwidth.

Implementation



Constant Bandwidth Server (CBS)

- It assigns deadlines to tasks as the TBS, but keeps track of job executions through a budget mechanism.
- When the budget is exhausted it is immediately replenished, but the deadline is postponed to keep the demand constant.

CBS parameters

Given by the user

- Maximum budget: Q_s
- Server period: T_s

$U_s = Q_s / T_s$ (server bandwidth)

Maintained by the server

- Current budget: c_s (initialized to 0)
- Server deadline: d_s (initialized to 0)

Basic CBS rules

- **Arrival of job J_k ⇒ assign d_s**

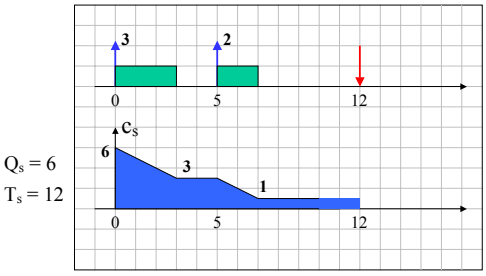
$$\textbf{if } (r_k + c_s/U_s \le d_s) \textbf{ then } \text{recycle } (c_s, d_s)$$

$$\textbf{else } \begin{cases} d_s = r_k + T_s \\ c_s = Q_s \end{cases}$$

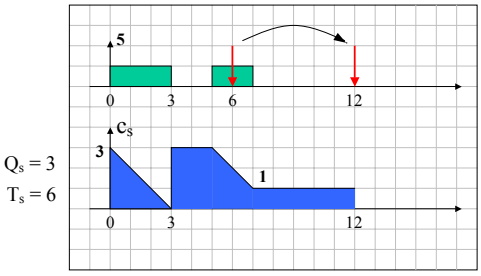
- **Budget exhausted ⇒ postpone d_s**

$$\begin{cases} d_s = d_s + T_s \\ c_s = Q_s \end{cases}$$

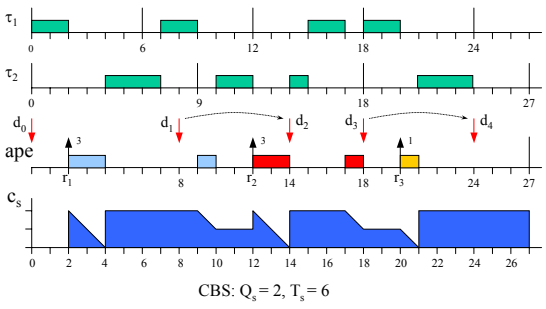
Deadline assignment



Budget exhausted



EDF + CBS schedule



CBS: $Q_s = 2$, $T_s = 6$

CBS properties

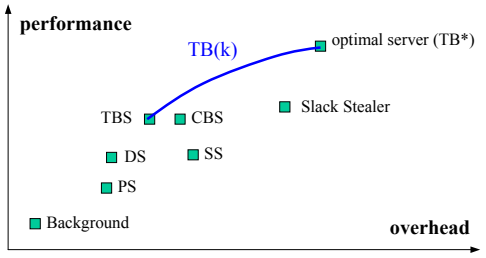
- **Bandwidth Isolation**

  If a task τ_i is served by a CBS with bandwidth U_s then, in any interval Δt, τ_i will never demand more than $U_s \Delta t$.

- **Hard schedulability**

  A hard task τ_i (C_i, T_i) is schedulable by a CBS with $Q_s = C_i$ and $T_s = T_i$, iff τ_i is schedulable by EDF.

Selecting the most suitable service mechanism



It depends on the price (overhead) we want to pay to reduce task response times

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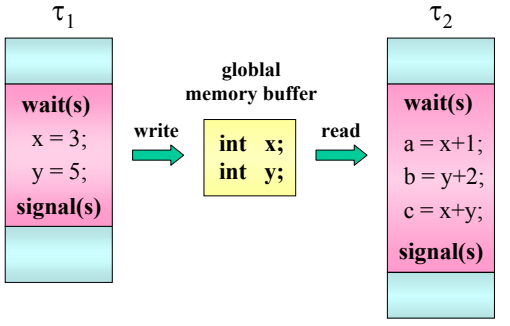
Inter-task communication mechanisms

- Shared memory
- Message passing ports
- Asynchonous buffers

Handling shared resources

Problems caused by mutual exclusion

Critical sections



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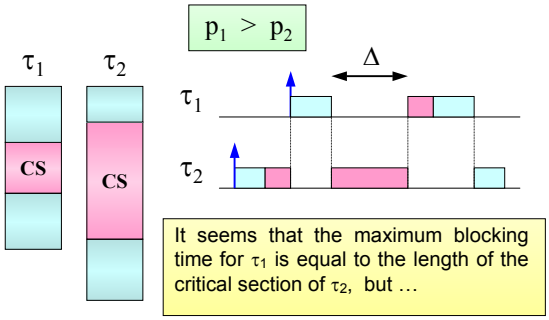
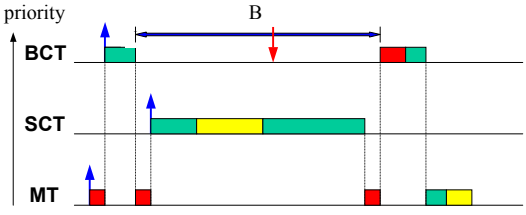
Blocking on a semaphore



It seems that the maximum blocking time for τ_1 is equal to the length of the critical section of τ_2, but …

185

Conflict on a critical section



186

Priority Inversion

A high priority task is blocked by a lower-priority task a for an unbounded interval of time.

Solution

Introduce a concurrency control protocol for accessing critical sections.

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Resource Access Protocols

Under fixed priorities

- Non Preemptive Protocol (NPP)
- Highest Locker Priority (HLP)
- Priority Inheritance Protocol (PIP)
- Priority Ceiling Protocol (PCP)

Under EDF

- Stack Resource Policy (SRP)

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Non Preemptive Protocol

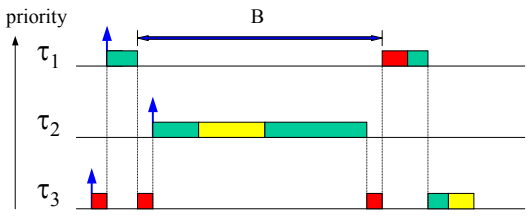
- Preemption is forbidden in critical sections.
- Implementation: when a task enters a CS, its priority is increased at the maximum value.

ADVANTAGES: simplicity

PROBLEMS: high priority tasks that do not use CS may also block

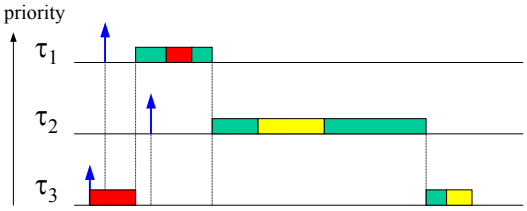
189

Conflict on critical section



190

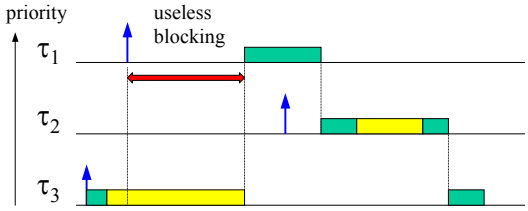
Schedule with NPP



$P_{CS} = \max\{P_1, \ldots P_n\}$

191

Problem with NPP



τ_1 cannot preemt, although it could

192

Highest Locker Priority

A task in a CS gets the highest priority among the tasks that use it.

FEATURES:

- Simple implementation.
- A task is blocked when attempting to preempt, not when entering the CS.

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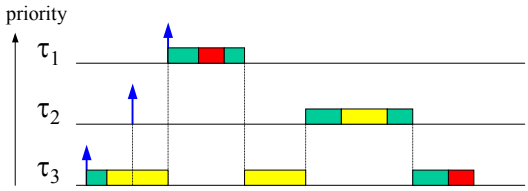
Schedule with HLP

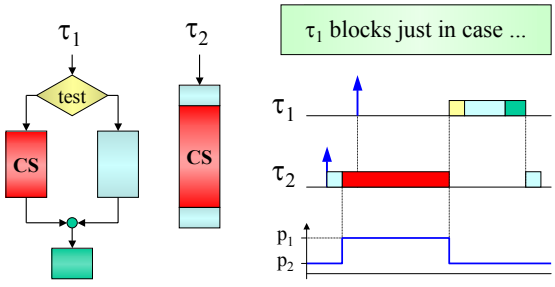


$P_{CS} = \max \{P_k \mid \tau_k \text{ uses CS}\}$

τ_2 is blocked, but τ_1 can preempt within a CS

194

Problem with HLP



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Priority Inheritance Protocol

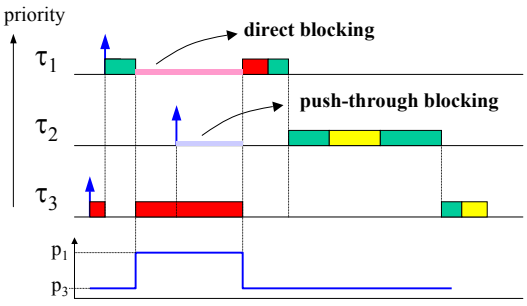
[Sha, Rajkumar, Lehoczky, 90]

- A task in a CS increases its priority only if it blocks other tasks.
- A task in a CS inherits the highest priority among those tasks it blocks.

$P_{CS} = \max \{P_k \mid \tau_k \text{ blocked on CS}\}$

196

Schedule with PIP



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Types of blocking

- **Direct blocking**

  A task blocks on a locked semaphore

- **Push-through blocking**

  A task blocks because a lower priority task inherited a higher priority.

BLOCKING:
a delay caused by a lower priority task

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Identifying blocking resources

- A task τ_i can be blocked by those semaphores used by lower priority tasks and
  - directly shared with τ_i (direct blocking) or
  - shared with tasks having priority higher than τ_i (push-through blocking).

Theorem: τ_i can be blocked at most once by each of such semaphores

Theorem: τ_i can be blocked at most once by each lower priority task

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Bounding blocking times

- If **n** is the number of tasks with priority less than τ_i
- and **m** is the number of semaphores on which τ_i can be blocked, **then**

Theorem: τ_i can be blocked at most for the duration of **min(n,m)** critical sections

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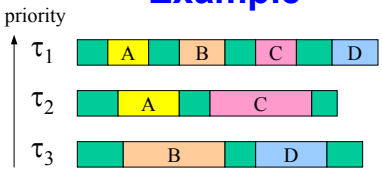
Example



- τ_1 can be blocked once by τ_2 (on A_2 or C_2) and once by τ_3 (on B_3 or D_3)
- τ_2 can be blocked once by τ_3 (on B_3 or D_3)
- τ_3 cannot be blocked

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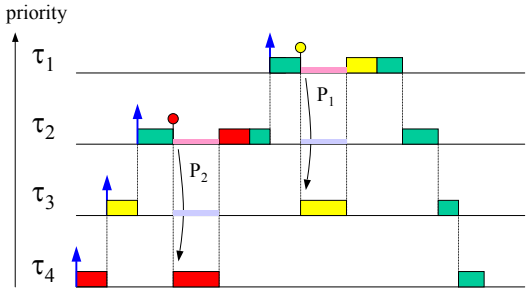
Schedule with PIP



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Remarks on PIP

ADVANTAGES

- It is transparent to the programmer.
- It bounds priority inversion.

PROBLEMS

- It does not avoid deadlocks and chained blocking.

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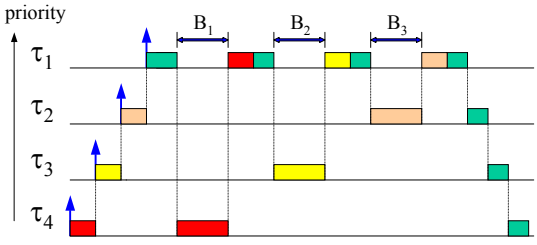
Chained blocking with PIP



Theorem: τ_i can be blocked at most once by each lower priority task

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Priority Ceiling Protocol

- Can be viewed as PIP + access test.
- A task can enter a CS only if it is free and there is no risk of chained blocking.

To prevent chained blocking, a task may stop at the entrance of a free CS (***ceiling blocking***).

Resource Ceilings

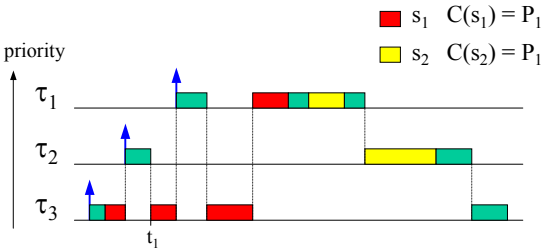
- Each semaphore s_k is assigned a ceiling:

$$C(s_k) = \max \{P_j : \tau_j \text{ uses } s_k\}$$

- A task τ_i can enter a CS only if

$$P_i > \max \{C(s_k) : s_k \text{ locked by tasks} \neq \tau_i\}$$

Schedule with PCP



t_1: τ_2 is blocked by the PCP, since $P_2 < C(s_1)$

Remarks on PCP

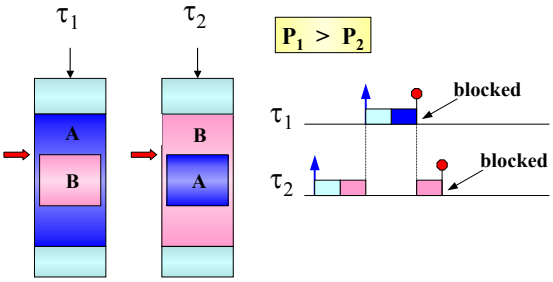
ADVANTAGES

- Blocking is reduced to only one CS
- It prevents deadlocks

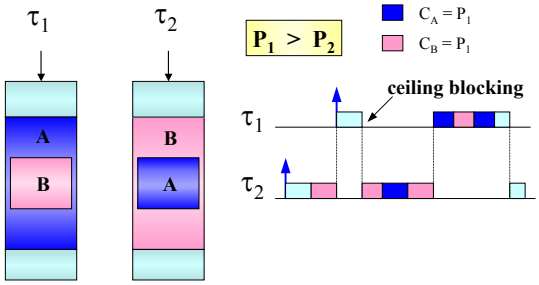
PROBLEMS

- It is not transparent to the programmer: semaphores need ceilings

Typical Deadlock



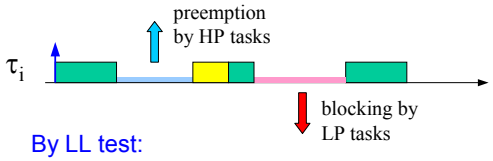
Deadlock avoidance with PCP



Guarantee with resource constraints

- We select a scheduling algorithm and a resource access protocol.
- We compute the maximum blocking times (B_i) for each task.
- We perform the guarantee test including the blocking terms.

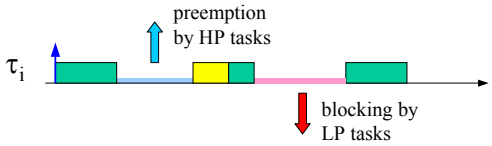
Guarantee with RM (D = T)



By LL test:

$$\forall i \quad \sum_{k=1}^{i-1} \frac{C_k}{T_k} + \frac{C_i + B_i}{T_i} \leq i\left(2^{1/i} - 1\right)$$

Guarantee with RM (D ≤ T)



By RTA test: $\forall i \quad R_i \leq D_i$

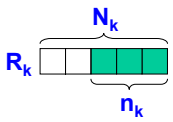
$$R_i = C_i + B_i + \sum_{k=1}^{i-1} \left\lceil \frac{R_i}{T_k} \right\rceil C_k$$

Stack Resource Policy [Baker 1990]

- It works both with fixed and dynamic priority
- It limits blocking to 1 critical section
- It prevents deadlock
- It supports multi-unit resources
- It allows stack sharing
- It is easy to implement

Stack Resource Policy [Baker 90]

- For each resource R_k:
  - ⇒ Maximum units: N_k
  - ⇒ Available units: n_k



- For each task τ_i the system keeps:
  - ⇒ its resource requirements: $\mu_i(R_k)$
  - ⇒ a priority p_i: RM $p_i \propto 1/T_i$ EDF $p_i \propto 1/d_i$
  - ⇒ a static preemption level: $\pi_i \propto 1/D_i$

Stack Resource Policy [Baker 90]

Resource ceiling

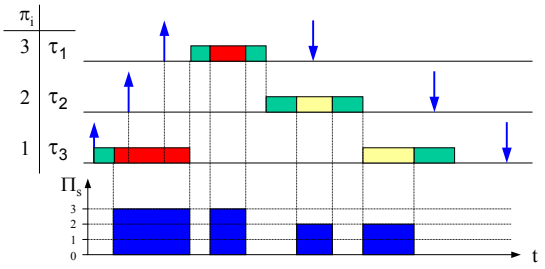
$$C_k(n_k) = \max_j \left\{ \pi_j : n_k < \mu_j(R_k) \right\}$$

System ceiling $\Pi_s = \max_k \{C_k(n_k)\}$

SRP Rule

A job cannot preempt until p_i is the highest and $\pi_i > \Pi_s$

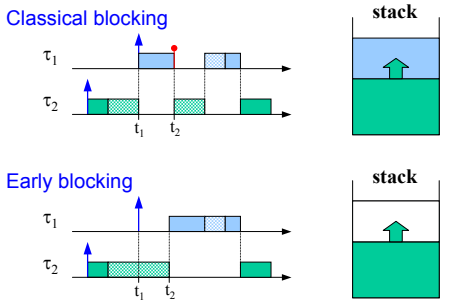
Example



SRP: Notes

- Blocking always occurs at preemption time
- A task never blocks on a wait primitive (semaphore queues are not needed)
- Semaphores are still needed to update the system ceiling
- Early blocking allows stack sharing

SRP: Stack sharing

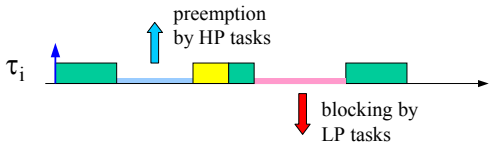


SRP: Stack sharing

- If tasks can be grouped in **M** subsets with the same preemption level, then tasks within a group cannot preempt each other.
- Then the stack size is the sum of the stack memory needed by **M** tasks.
- If we have 100 tasks with 10 preemption levels, and each task requires 10 Kb of stack, then

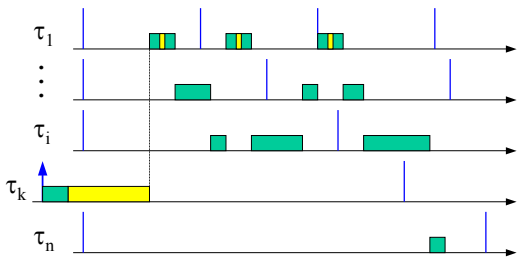
Stack size = { **1 Mb** without SRP ; **100 Kb** under SRP (90% less)

EDF Guarantee ($D_i = T_i$)



$$\forall i \quad \sum_{k=1}^{i-1} \frac{C_k}{T_k} + \frac{C_i + B_i}{T_i} \leq 1$$

EDF Guarantee: PD test ($D_i \leq T_i$)



Tasks are ordered by decreasing preemption level

EDF Guarantee: PD test ($D_i \le T_i$)

$$\forall i \quad \forall L: \; D_i \le L \le \max(D_n, L_i^*)$$
$$U < 1 \quad \text{AND} \quad g_i(0,L) \le L$$

$$\begin{cases} g_i(0,L) = B_i + \sum_{k=1}^{i} \left\lceil \frac{L - D_k + T_k}{T_k} \right\rceil C_k \\ L_i^* = \frac{B_i + \sum_{k=1}^{i} (T_k - D_k) U_k}{1 - \sum_{k=1}^{i} U_k} \end{cases}$$

Message passing paradigm

Every task operates on a private memory space, exchanging messages through channels:

Channel: logical link by which two tasks can communicate.

Message: set of data having a predefined format.

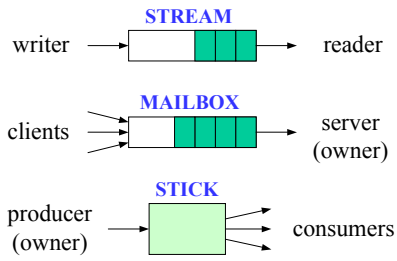
Communication Ports

- The operating system provides the channel abstraction through the **port** construct.
- A task can use a port to exchange messages by means of two primitives:

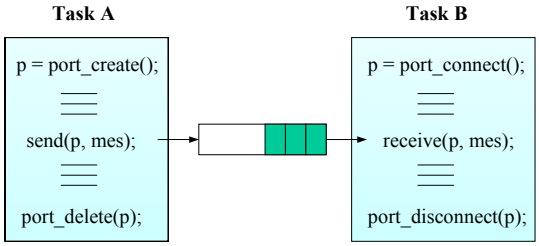
send sends a message to a port

receive receives a message from a port

Port types



Using a port



NOTE: Task A is the owner and must start first.

Port primitives

- ***port_create****(name, size, num, type, access);*

  name: identification string
  size: message size (in bytes)
  num: maximum number of messages
  type: STREAM, MAILBOX, STICK
  access: READ, WRITE
  It returns a port identifier.

- ***port_delete****(port_id);*

  Deletes the specified port.

Port primitives

- ***port_connect****(name, size, type, access);*

  name: stringa di identificazione
  size: message size (in bytes)
  type: STREAM, MAILBOX, STICK
  access: READ, WRITE
  It returns a port identifier.

- ***port_disconnect****(port_id);*

  Deletes the specified port.

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Port primitives

- ***port_send*** *(port_id, msg_ptr, sync)*

  sends the message pointed by *msg_ptr* to the port identified by *port_id*.
  sync = BLOCK blocks on a full buffer
  sync = NON_BLOCK returns 0

- ***port_receive****(port_id, msg_ptr, sync)*

  receives a message from *port_id* and copies it into the buffer pointed by *msg_ptr*.
  sync = BLOCK blocks on an empty buffer
  sync = NON_BLOCK returns 0

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A task creates a port to send messages of 6 bytes. The port can keep up to 8 messages.

```
TASK    writer(void)
{
PORT    p;
char    mes[6];

    p = port_create("door", 6, 8, STREAM, WRITE);
    while (condition) {
        build_message(mes);
        port_send(p, mes, BLOCK);
        task_endcycle();
    }
    port_delete(p);
}
```

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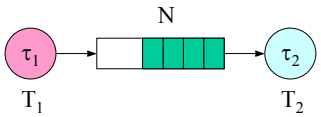
A task connects to an already opened port to receive messages of 2 bytes.

```
TASK    reader(void)
{
PORT    q;
char    data[2];

    q = port_connect("door", 2, STREAM, READ);
    while (condition) {
        if (port_receive(q, data, NON_BLOCK))
                action1();
        else    action2();
        task_endcycle();
    }
    port_disconnect(q);
}
```

Periodic task communication



- If $T_1 < T_2$, τ_1 puts more messages than τ_2 can read.
- When the buffer is full, τ_1 must proceed with the same rate of τ_2.

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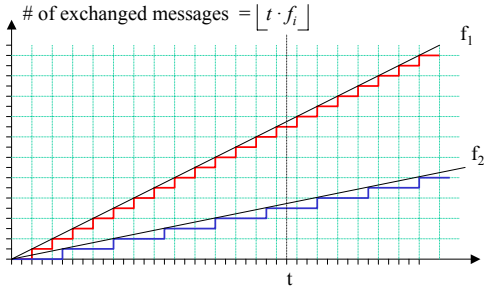
Exchanged messages



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Buffer Saturation

If $T_1 < T_2$, the buffer saturates when:

$$\left\lfloor \frac{t}{T_1} \right\rfloor - \left\lfloor \frac{t}{T_2} \right\rfloor > N$$

Hence, the tasks proceed at their proprer rate while:

$$\left\lfloor \frac{t}{T_1} \right\rfloor - \left\lfloor \frac{t}{T_2} \right\rfloor < \frac{t}{T_1} - \frac{t}{T_2} + 1 < N$$

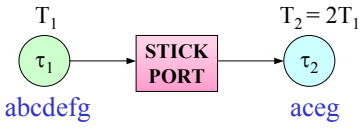
That is, while:

$$t < (N-1)\frac{T_1 T_2}{T_2 - T_1}$$

STICK Ports

- If $T_1 < T_2$, τ_1 overwrites previous messages.

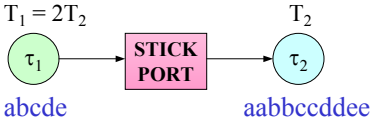
Example:



STICK Ports

- If $T_1 > T_2$, τ_2 reads the same message more than once (messages are not consumed).

Example:



Blocking on STICK ports

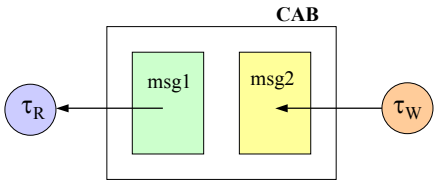
- STICK ports use a semaphore to avoid simultaneous accesses to the internal buffer.
- Long messages may cause long blocking delays on the semaphore.
- A more efficient solution avoids blocking through a buffer replication mechanism.

Cyclic Asynchronous Buffer

- It is a mechanism for exchanging messages among periodic tasks with different rates.
- It avoids memory conflicts by replicating the internal buffers.
- *State message* semantics: messages are overridden by senders and are not consumed by receivers.

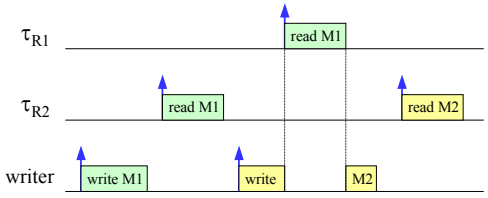
Simultaneous accesses

If a writer task τ_W arrives while a task τ_R is reading, the new message is written in a new buffer:



Reading from a CAB

Once written, a message becomes available to the next reader:



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Accessing a CAB

- CABs are accessed through a memory pointer.
- Hence, a reader is not forced to copy the message in its memory space.
- More tasks can simultaneously read the same message.
- At each instant, a pointer (**mrd**) points to the most recent message stored in the CAB.

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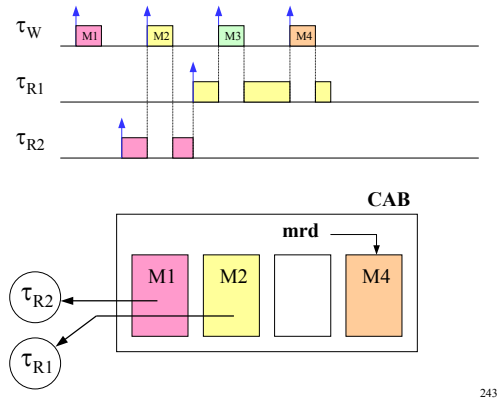

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Dimensioning a CAB

If a CAB is used by N tasks, to avoid blocking, it must have at least N +1 buffers.

- The (N+1)-th buffer is needed for keeping the most recent message in the case all the other buffers are used.

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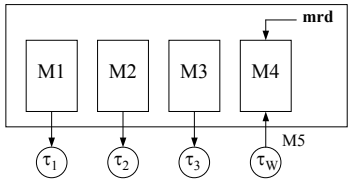
Inconsistency with N buffers



- Assume all buffers are used and τ_W overwrites the most recent message (M4) with M5.
- If (while τ_W is writing) τ_1 finishes and requests a new message, it finds the CAB inconsistent.

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Writing in a CAB

```
    . . .
p = cab_reserve(cab_id);
<copy message in *p>
cab_putmes(cab_id, p);
    . . .
```

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Reading from a CAB

```
    . . .
p = cab_getmes(cab_id);
<process message with *p>
cab_unget(cab_id, p);
    . . .
```

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CAB Primitives

- ***cab_create****(cab_name, buf_size, max_buf);*

  creates a CAB with *max_buf* buffers
  with size *buf_size* bytes.
  It returns a global CAB identifier.

- ***cab_delete****(cab_id);*

  deletes the specified CAB.

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CAB Primitives

- ***cab_reserve****(cab_id)*

  returns a pointer to write in a free buffer

- ***cab_putmes****(cab_id, pointer)*

  releases the pointer after a write operation

- ***cab_getmes****(cab_id)*

  returns a pointer to the most recent message

- ***cab_unget****(cab_id, pointer)*

  releases the pointer after a read operation

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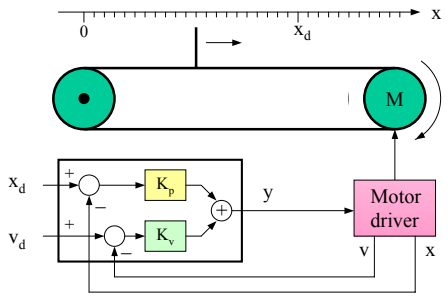
Position control



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PD regulator

```
TASK    pos_control()
{
int     xd, vd, x, v;
float   y, Kp, Kv;
    while (1) {
        get_gains(&Kp, &Kv);
        get_setpoint(&xd, &vd);
        read_sensors(&x, &v);
        y = Kp*(xd - x) - Kv*(vd - v);
        output(y);
        task_endcycle();
    }
}
```

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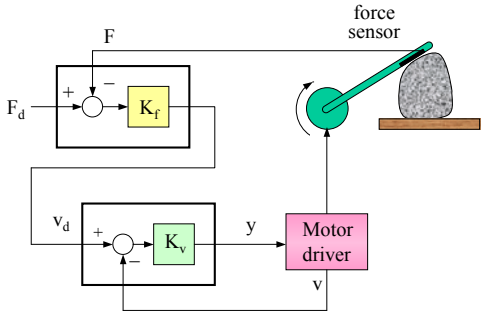
Two-level control loop



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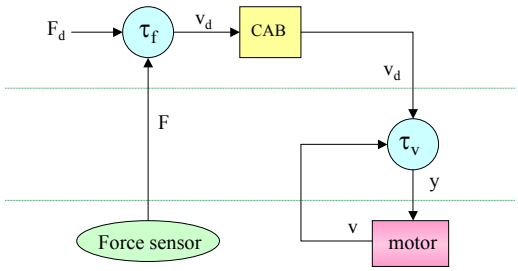
Using CABs



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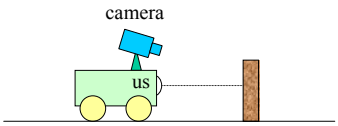
Using visual feedback



- An ultrasound sensor is used for speed control
- The camera is used for stear control

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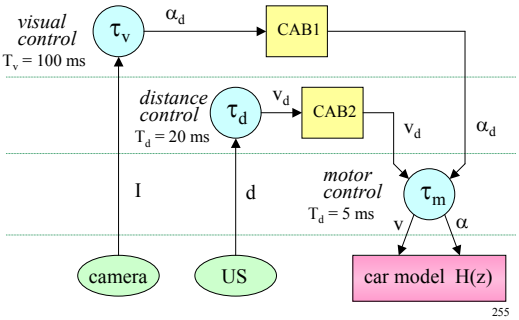
Three-level control



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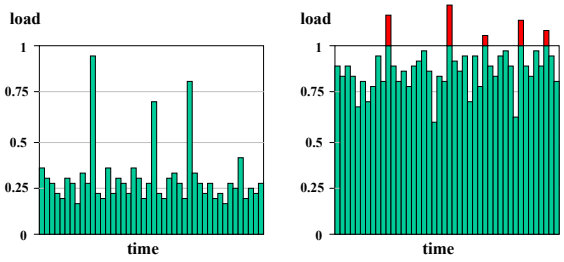
Overload management

Examples of load

System designed under worst-case assumptions

System designed under average-case assumptions



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Transient vs. permanent overload conditions

Transient overload: $\rho_{avg} < 1$, $\rho_{max} > 1$

Possible causes

- ⇒ Arrival of aperiodic activities
- ⇒ Exceptions raised by the kernel
- ⇒ Malfunctioning of input devices
- ⇒ Task with variable execution
- ⇒ Sporadic overruns

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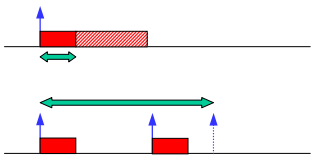
Types of overruns

- A task is said to be in overrun if the time demanded for execution exceeds the expected value according to which the task has been guaranteed.
- There are two types of overrun:

Execution overrun
A job executes more than expected

Activation overrun
A job arrives before the time it is expected



Transient vs. permanent overload conditions

Permanent overload: $\rho_{avg} > 1$

Possible causes

⇒ Activation of a new periodic task
⇒ Increase in the task frequencies
⇒ Increase in the task quality (execution times)
⇒ Changes in the environment
⇒ Bad system design

Overload management methods

- **Activation overruns of aperiodic tasks**
  - ⇒ **Value-based scheduling**
    - tasks are assigned values and executed accordingly
  - ⇒ **Admission control**
    - least importance tasks are rejected
    - important tasks receive full service
- **Activation/Execution overruns**
  - ⇒ **Resource Reservation**
    - Tasks cannot use more than reserved
- **Permanent overload of periodic tasks**
  - ⇒ **Performance degradation**
    - all tasks are executed
    - but with reduced requirements

Value-based scheduling

- If $\rho > 1$, no all tasks can finish within their deadline.
- To avoid domino effects, the load is reduced by rejecting the least important tasks.
- To do that, the system must be able to handle tasks with both timing constraints and importance values.

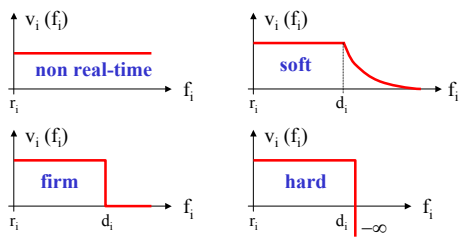
How to assign values

A task τ_i can be assigned a value v_i according to different criteria. Those most common are:

$v_i = V_i$	arbitrary constant
$v_i = C_i$	computation time
$v_i = V_i/C_i$	value density

Value as a function of time

In a real-time system, the value of a task depends on its completion time and criticality:



Performance evaluation

- The performance of a scheduling algorithm A on a task set T can be evalutated through its ***Cumulative Value***:

$$\Gamma_A(T) = \sum_{i=1}^{n} v_i(f_i)$$

- Note that: $\Gamma_A(T) < \Gamma_{max}(T) = \sum_{i=1}^{n} V_i$

Optimality under overloads

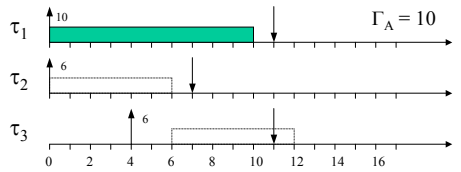
$$\Gamma^*(T) = \max_A \Gamma_A(T)$$

The performance of an algorithm can be evalutated with respect to Γ^*.

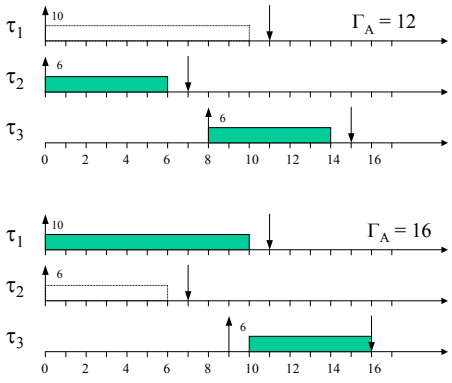
In overload conditions, there are no optimal **on-line** algorithms able to guarantee a cumulative value equal to Γ^*.

Proof (assume: $V_i = C_i$)

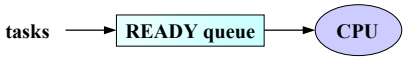
To maximize Γ_A we should know the future.



If at time t = 0 r_3 is not know, we cannot select the task that maximizes the cumulative value.

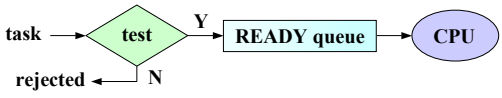


Best-effort scheduling



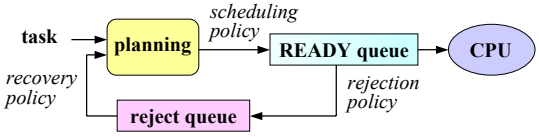
- Tasks are always accepted in the system.
- Performance is controlled through a suitable (value-based) priority assignment.
- **Problem:** domino effect.

Admission control



- Every task is subject to an acceptance test which keeps the load ≤ 1.
- It prevents domino effects, but does not take values into account.
- Low efficiency due to the worst-case guarantee (tasks may be unnecessarily rejected).

Robust scheduling



- Task scheduling and task rejection are controlled by two separate policies.
- Tasks are scheduled by deadline, rejected by value.
- In case of early completions, rejected tasks can be recovered by a reclaiming mechanism.

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Robust EDF

- **Scheduling Policy** ⇒ **EDF**
- **Rejection policy**

  when an overload is detected, reject the least value task which can bring the load below 1.
- **Recovery policy**
  - keep rejected tasks by decreasing values;
  - when there is enough spare time, re-accept the highest value task which is still feasible.

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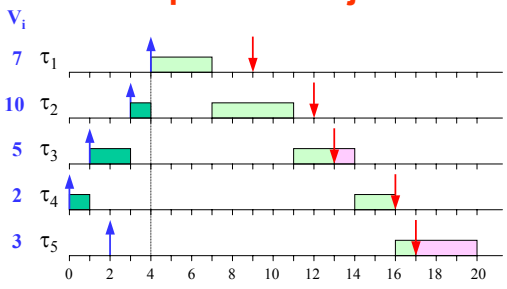
Example: task rejection



at time t = 4 ⇒ τ_3 rejected

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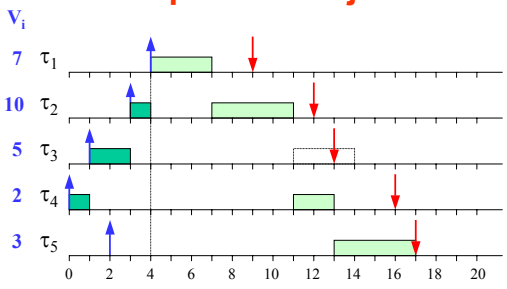
Example: task rejection



at time t = 4 ⇒ τ_3 rejected

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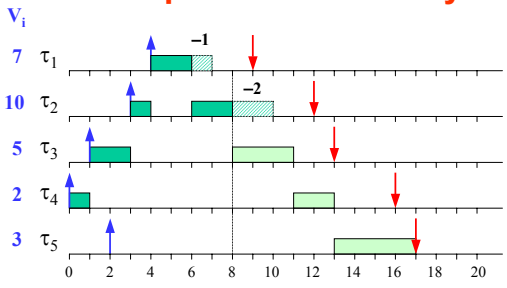
Example: task recovery



at time t = 8 ⇒ τ_3 can be recovered

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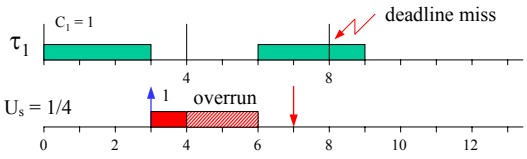
Resource Reservation

Handling sporadic overruns

Problems with overruns

- Without a budget management, there is no protection against execution overruns.
- If a job executes more than expected, hard tasks could miss their deadlines.



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Solution: Temporal Isolation

- The execution of a task should not affect the guarantee performed on the other tasks.
- Each task τ_i receives a fraction U_i of the processor (its *bandwidth*) and behaves as it were executing alone on a slower processor of speed U_i.

Temporal isolation ⇨ **bandwidth reservation**, **bandwidth enforcement**

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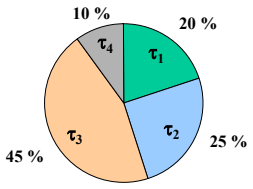
Bandwidth reservation

- Ideally, each task should be assigned a given bandwidth and never demand more.



- However, tasks are subject to **overruns** or the reserved bandwidth can be **insufficient** for the task.

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Bandwidth enforcement

- It is a mechanism needed for degrading the QoS when a task demands more than the reserved bandwidth.
- If a task executes more than expected, its priority should be decreased (i.e., its deadline postponed).
- When a task experiences an overrun, only that task is delayed, so that the guarantee performed on the other tasks is preserved.

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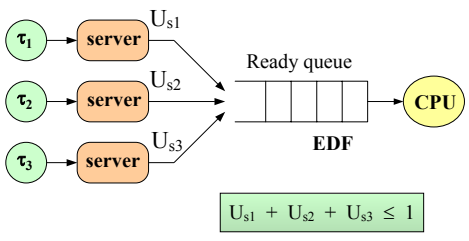
Implementation



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Handling permanent overload

Performance Degradation

The load can be decreased not only by rejecting tasks, but also by reducing their performance requirements.

This can be done by:

- reducing precision of results
- skipping some jobs;
- relaxing timing constraints.

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Reducing precision

In many applications, computation can be performed at different level of precision: the higher the precision, the longer the computation. Examples are:

- binary search algorithms
- image processing and computer graphics
- neural learning

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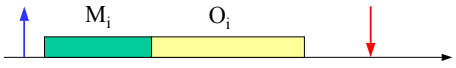
Imprecise computation

In this model, each task $\tau_i (C_i, D_i, w_i)$ is divided in two portions:

- a **mandatory** part: $\tau^m_i (M_i, D_i)$
- an **optional** part: $\tau^o_i (O_i, D_i)$



w_i is an importance weight

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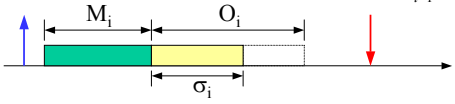
Imprecise computation

In this model, a schedule is said to be:

- **feasible**, if all mandatory parts complete in D_i
- **precise**, if also the optional parts are completed.

error: $\varepsilon_i = O_i - \sigma_i$ **average error**: $\varepsilon_a = \sum_{i=1}^{n} w_i \varepsilon_i$



GOAL: minimize the average error

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Job skipping

Periodic load can also be reduced by skipping some jobs, once in a while.

Many systems tolerate skips, if they do not occur too often:

- multimedia systems (video reproduction)
- inertial systems (robots)
- monitoring systems (sporadic data loss)

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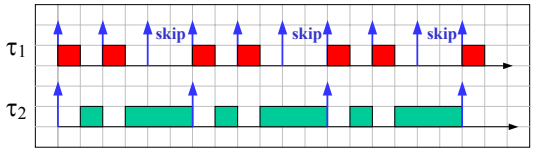
Example

The system is overloaded, but tasks can be schedulable if t_1 skips one instance every 3:

$$U_p = \frac{1}{2} + \frac{4}{6} = 1.17 > 1$$



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FIRM task model

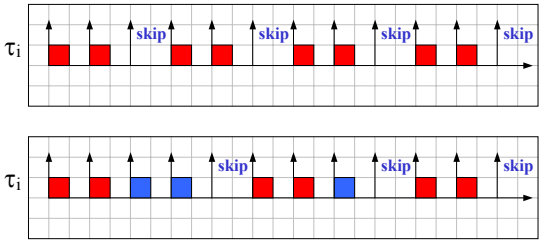
- Every job can either be executed within its deadline, or completely rejected (skipped).
- A percentage of task instances must be guaranteed off line to finish in time.
- Each task τ_i is described by (C_i, T_i, D_i, S_i):

  S_i is the minimum number of jobs that must be executed between two consecutive skips.

- Every instance can be **red** or **blue**:
  - **red** instances must finish within their deadline
  - **blue** instances can be aborted
- If a **blue** instance is aborted, the next S_i-1 instances must be **red**.
- If a **blue** instance is completed within its deadline, the next instance is still **blue**.
- The first S_i-1 instances of every task must be **red**.

Example

$C_i = 1 \quad T_i = 2 \quad D_i = 2 \quad S_i = 3$



Equivalent utilizazion factor

$$U_p^* = \max_{L \geq 0} \left\{ \frac{\sum_{i=1}^{n} g_i(0,L)}{L} \right\}$$

$$g_i(0,L) = \left(\left\lfloor \frac{L}{T_i} \right\rfloor - \left\lfloor \frac{L}{T_i S_i} \right\rfloor \right) C_i$$

Schedulability Analysis

A sufficient condition

Theorem: *A set of firm periodic tasks is schedulable if*

$$U_p^* \leq 1$$

A necessary condition

Theorem: *A set of firm periodic tasks is not schedulable if*

$$\sum_{i=1}^{n} \frac{C_i(S_i - 1)}{T_i S_i} > 1$$

NOTE: the sum represents the utilization of the computation that must take place.

Bandwidth saving

- In general, skipping jobs of periodic tasks causes a bandwidth saving:

$$\Delta U = U_p - U_p^*$$

- Such a bandwidth can be used for
  - improving aperiodic responsiveness (by increasing their reserved bandwidth);
  - accepting a larger number of periodic tasks.

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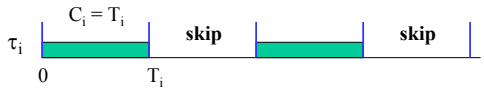
Not always skips save bandwidth:



In this case: $U_p^* = 1$

In fact, for $L = T_i$ we have $g_i(0,L) = C_i = T_i$

Hence: $\frac{g_i(0,L)}{L} = \frac{T_i}{T_i} = 1$

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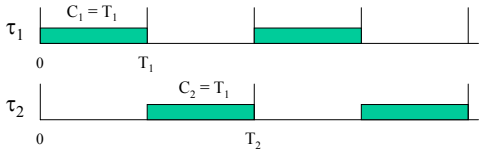
However, notice that:



In this case we still have: $U_p^* = 1$

In fact: $g(0, T_1) = T_1$ e $g(0, T_2) = T_2$

Hence: $\frac{g(0,T_1)}{T_1} = \frac{g(0,T_2)}{T_2} = 1$

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Relaxing timing constraints

- The idea is to reduce the load by increasing deadlines and/or periods.
- Each task must specify a range of values in which its period must be included.
- Periods are increased during overloads, and reduced when the overload is over.

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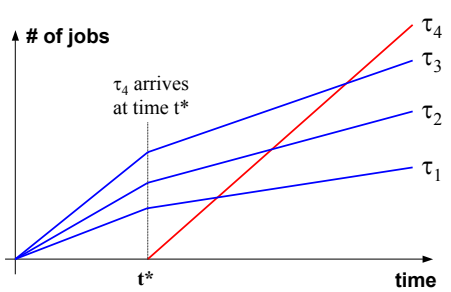
Overload handling due to a new arrival



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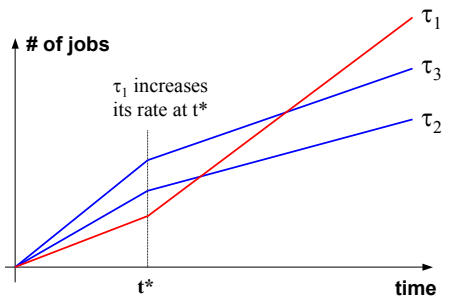
Overload handling due to an increased rate



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Example

task	C_i	T_{i0}	T_{min}	T_{max}
τ_1	10	20	20	25
τ_2	10	40	40	50
τ_3	15	70	35	80

$$U_p = \frac{10}{20} + \frac{10}{40} + \frac{15}{70} = 0.96$$

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Load adaptation

If τ_4 arrives with: $\mathbf{C_4 = 5,\ T_4 = 30}$ the system is not schedulable any more:

$$U_p = \frac{10}{20} + \frac{10}{40} + \frac{15}{70} + \frac{5}{30} = 1.13$$

However, there exists a feasible schedule within the specified ranges:

$$U_p = \frac{10}{23} + \frac{10}{50} + \frac{15}{80} + \frac{5}{30} = 0.99$$

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Elastic task model

- Tasks' utilizations are treated as elastic springs and can be changed by period variations.
- The resistance of a task to a period variation is controlled by an **elastic coefficient E_i**:

  ⇒ the greater E_i the greater the elasticity

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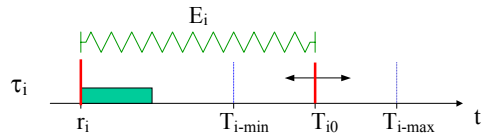
Elastic task model

- A periodic task τ_i is characterized by:

  $(C_i, T_{i0}, T_{i\text{-}min}, T_{i\text{-}max}, E_i)$
- The actual period $T_i \in [T_{i\text{-}min}, T_{i\text{-}max}]$



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Special cases

- A task with $T_{min} = T_{max}$, is equivalent to a hard task.
- A task with $E_i = 0$ can intentionally change its period but does not allows the system to do that.

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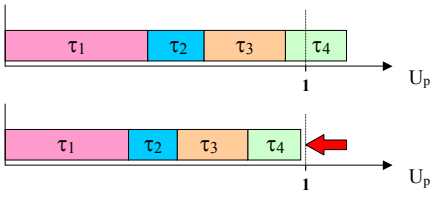
Compression algorithm

During overloads, utilizations must be compressed to bring the load below one.



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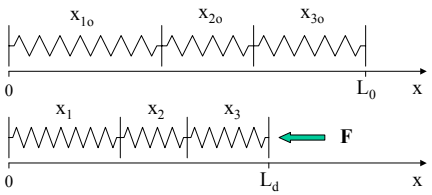
The linear spring analogy



$$\begin{cases} F = k_1(x_{1o} - x_1) \\ F = k_2(x_{2o} - x_2) \\ F = k_3(x_{3o} - x_3) \end{cases} \qquad \begin{cases} x_1 + x_2 + x_3 = L_d \\ x_{1o} + x_{2o} + x_{3o} = L_0 \end{cases}$$

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Solution without constraints

Summing the equations, we have:

$$F\left(\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}\right) = (x_{1o}+x_{2o}+x_{3o}) - (x_1+x_2+x_3)$$
$$= (L_0 - L_d)$$

That is:

$$F = \frac{(L_0 - L_d)}{\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}}$$

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Solution without constraints

Substituting F in the equations, we have:

$$F = k_1(x_{1o} - x_1) = \frac{(L_0 - L_d)}{\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}}$$

That is:

$$x_1 = x_{1o} - (L_0 - L_d)\frac{1/k_1}{\frac{1}{k_1}+\frac{1}{k_2}+\frac{1}{k_3}}$$

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Solution without constraints

$$x_i = x_{io} - (L_0 - L_d)\frac{K_{//}}{k_i} \qquad K_{//} = \frac{1}{\sum_{i=1}^{n}\frac{1}{k_i}}$$

And defining: $E_i = 1/k_i$

$$x_i = x_{io} - (L_0 - L_d)\frac{E_i}{E_s} \qquad E_s = \sum_{i=1}^{n} E_i$$

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Period computation

$$U_i = U_{io} - (U_0 - U_d)\frac{E_i}{E_s}$$

And then: $T_i = \frac{C_i}{U_i}$

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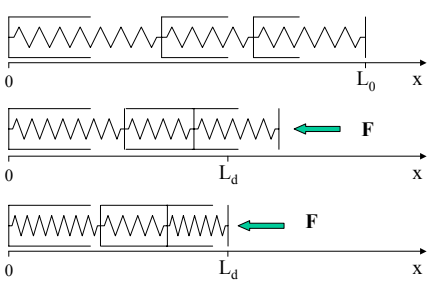
Solution with constraints

Iterative solution:



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Other use of elastic tasks

- Quickly find new period configurations during negotiation.
- Dynamically adjust the rates to fully utilize the processor.

Problem Understanding

- Real-Time applications are usually guaranteed based on worst-case execution times (WCETs).
- However, a precise WCET estimation is very difficult to achieve (due to interrupts, prefetch, cache, and DMA mechanisms).
- A wrong WCET estimate may cause the following problems:

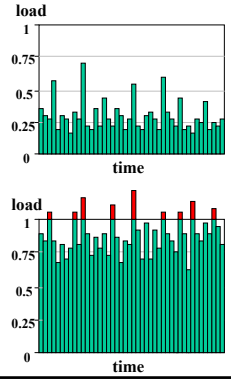
Predictability vs. efficiency

Over-estimation of WCETs

- high predictability
- low efficiency

Under-estimation of WCETs

- high efficiency
- low predictability



Adaptive solution

- The user does not specify any WCET.
- The system:
  - monitors tasks' execution times to estimate the actual load ($\mathbf{U_e}$);
  - adapts the task rates to keep the processor utilization close to a desired value ($\mathbf{U_d}$).

Task importance must be taken into account while performing rate adaptation.

Execution Time Estimator

- Monitored parameters (for each task t_i):

c_i current average execution time

C_i current worst-case execution time

- Building a prediction:

$$Q_i = c_i + k\,(C_i - c_i)$$

k = balancing factor

Load as a feedback