# Supporting Component-Based Development with Hierarchical Scheduling

## Introduction

- Partitioning into multiple simpler **subsystems**
  - Lower complexity;
  - Component reuse;
  - Team-base development;
  - Outsourcing.

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  - Lower complexity;
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  - Team-base development;
  - Outsourcing.

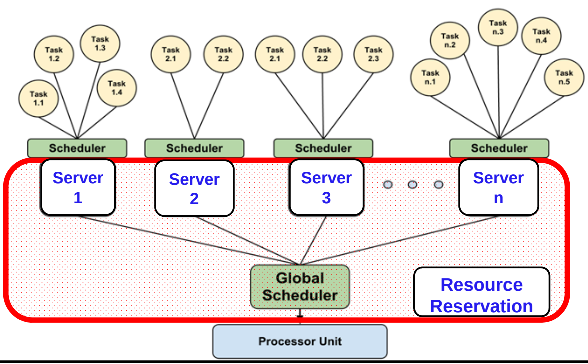
**Integration**

## Introduction

- This lesson: we will look at the problem of supporting component-based development from a real-time systems perspective
  - RTOS mechanisms/scheduling algorithms to support temporal isolation among independently developed applications (software components);
  - Real-time analysis to ensure predictability in executing the software components.
- In general, supporting component-based development requires a widespread view including software engineering, system modeling, programming models, component abstraction, etc…

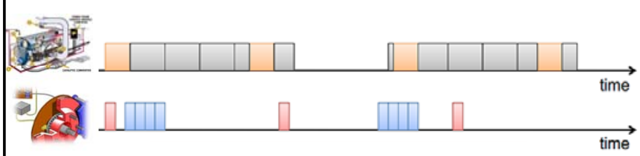
## Introduction

**Hierarchical Scheduling Framework**




## Introduction

**Automotive Example:** Engine Control + ABS



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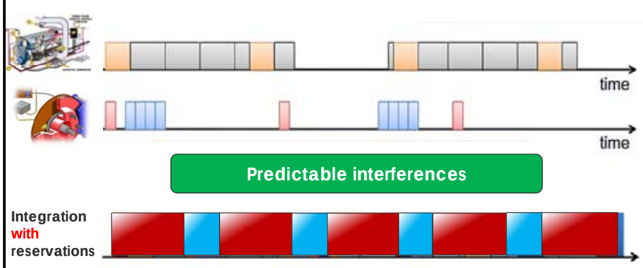


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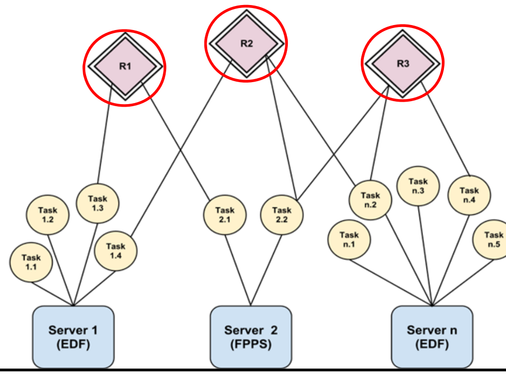
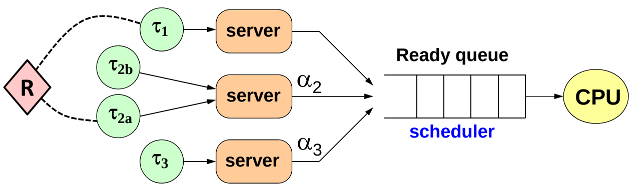



## Shared Resources




Tasks are usually not independent: they share resources!

*Examples:*

*Data Structures, Peripheral Devices, Common Memory Areas*

## HSF

- Scheduling mechanisms needed to implement the Hierarchical Scheduling Framework (HSF)
  - Resource reservation server able to guarantee hard real-time applications;
  - Resource sharing protocol supporting resources shared among tasks running upon different reservation servers.

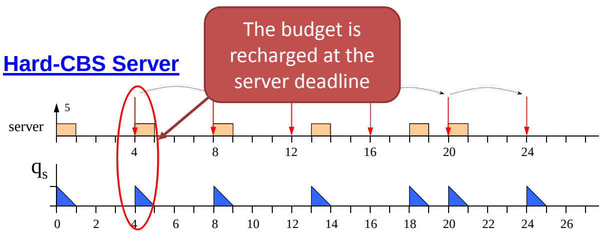
Bounded-Delay Reservation for Open Environment (BROE)

## Resource Reservation

**HARD reservation**

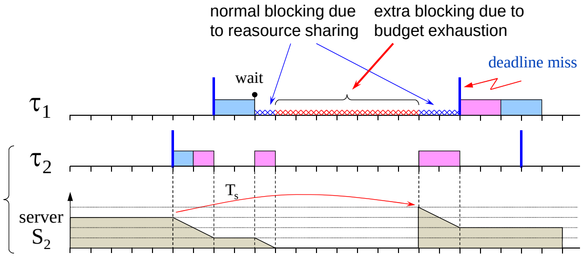
It guarantees that the served application receives at most a budget Q every period P.

**Hard-CBS Server**




## Problems with Reservations

- Resource sharing may break isolation:



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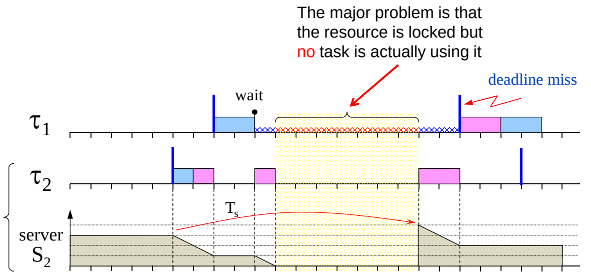
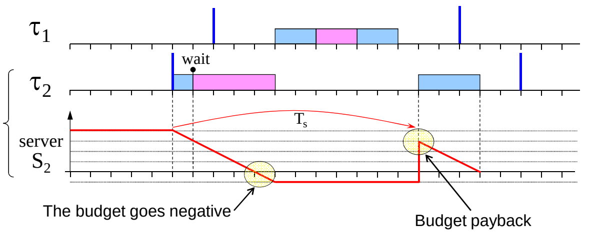



## Overrun W/ Payback

A possible solution: When the budget exhausts inside a critical section, do nothing. Payback at the next budget replenishment.

**Isolation is broken!**

Note that the worst-case bandwidth consumption does not change

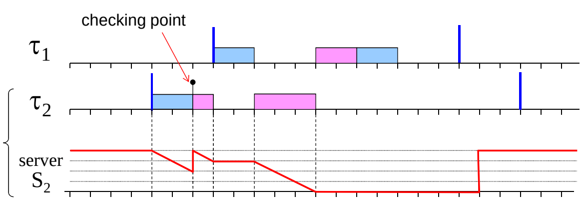



## BROE

**Check and recharge**

If ($q_s \geq \delta_k$) then enter, else recharge the budget at full value and proportionally postpone the server deadline.

Note that off-line we must guarantee that $Q_s \geq \max\{\delta_k\}$.




## BROE

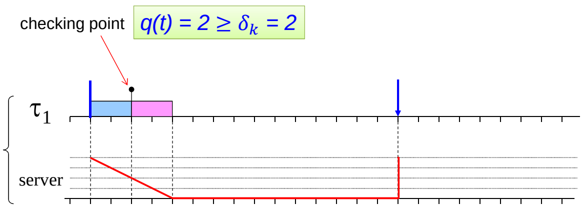
**BROE Design Goals**

Overcome to the problem of budget depletion inside critical sections

- Avoiding budget overruns;
- Ensuring bandwidth isolation (i.e., each server must consume no more than $\alpha = \frac{Q}{P}$ of the processor bandwidth);
- Guaranteeing a bounded-delay partition to the served tasks.

## BROE: budget check

- Consider a task $\tau_1$ accessing a resource $R_k$ having $\delta_k = 2$

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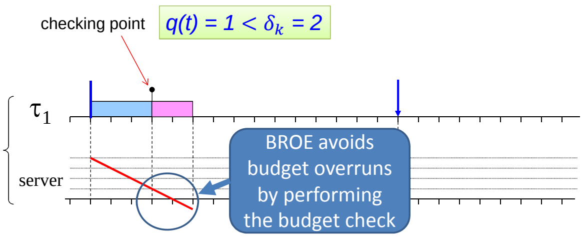

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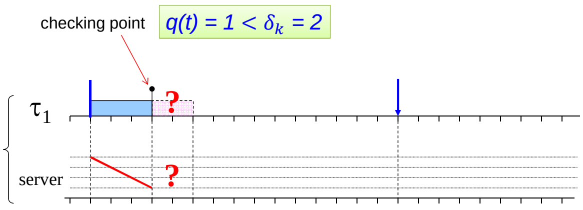


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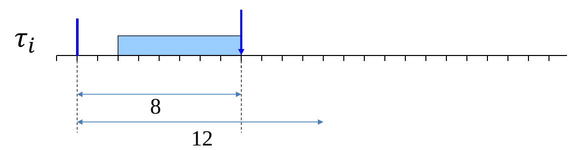
## BROE: bandwidth guarantee

- When the budget is not enough to complete the critical section, BROE performs a full budget replenishment;
- To not violate the server bandwidth, the budget replenishment must be reflected in a proportional deadline postponement

## BROE: bandwidth guarantee

- The idea of proportional deadline comes from a property of EDF scheduling with implicit deadlines;
- Suppose $\tau_i$ be schedulable with bandwidth (utilization) $\alpha_i = 0.5$

$$\alpha_i + \sum_{j \neq i} \alpha_j \leq 1$$

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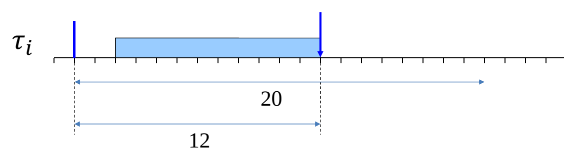
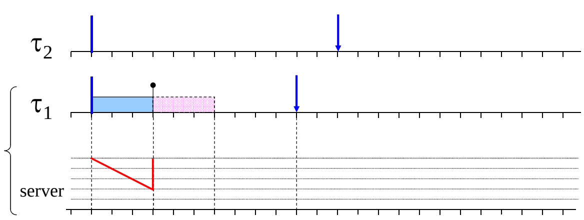



## BROE: bandwidth guarantee

- Consider a task $\tau_1$ accessing a resource $R_k$ having $\delta_k = 3$. Task $\tau_1$ executes on a BROE server configured with Q=5 and P=10



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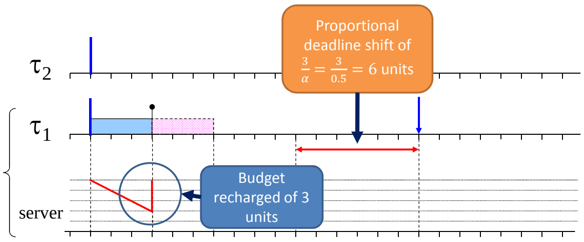


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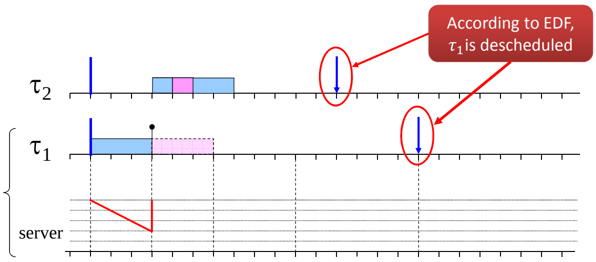


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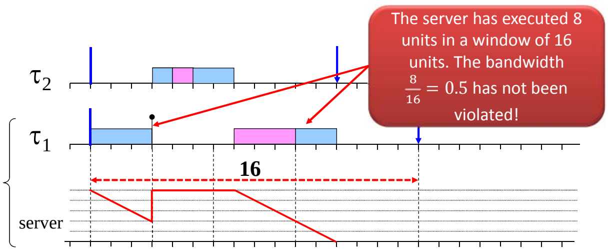


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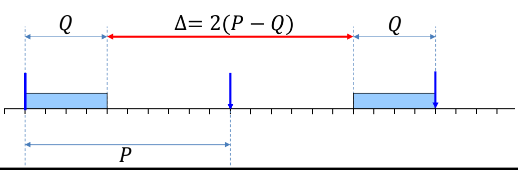
## BROE: bounded-delay

- To guarantee real-time workload executing upon a reservation server, the server must ensure a bounded-delay service

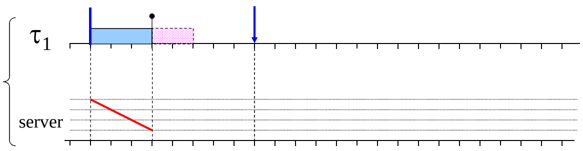



## BROE: bounded-delay

- The budget replenishment and the corresponding deadline postponement can easily result in a violation of the worst-case delay $\Delta = 2(P - Q)$, if not properly handled

## BROE: bounded-delay

- Consider a BROE server with Q=4 and P=8
- $\tau_1$ accesses a resource having $\delta = 2$

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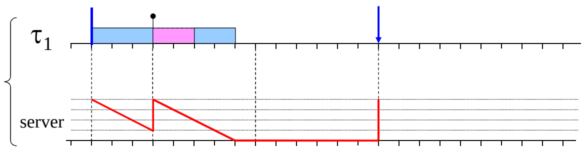
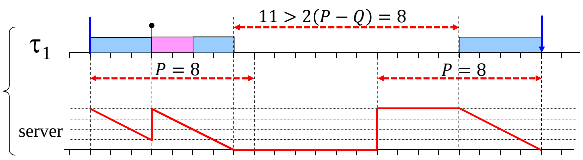



## BROE: bounded-delay

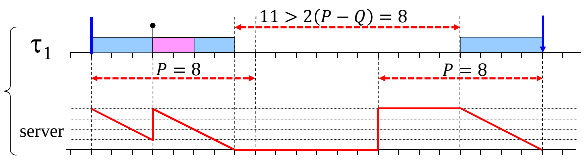
- Consider a BROE server with Q=4 and P=8
- $\tau_1$ accesses a resource having $\delta = 2$
- The worst-case delay $\Delta = 2(P - Q)$ is violated!

This is only an example, in the worst-case the delay can be potentially unbounded!




## BROE: bounded-delay

- How to solve this problem?
- The idea is to avoid to let the server execute "*too much earlier*" with respect to its deadline, after a budget replenishment

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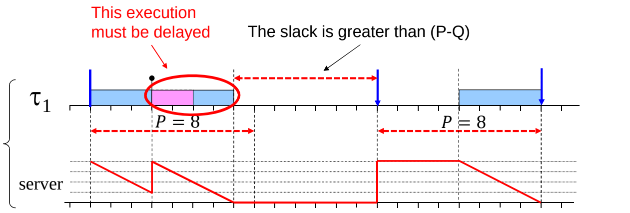
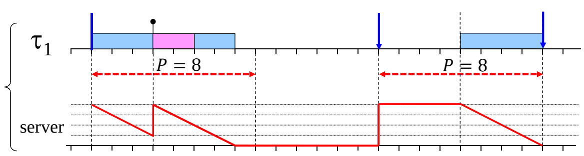



## BROE: bounded-delay

- To guarantee a bounded-delay of $\Delta = 2(P - Q)$, BROE imposes an explicit server suspension



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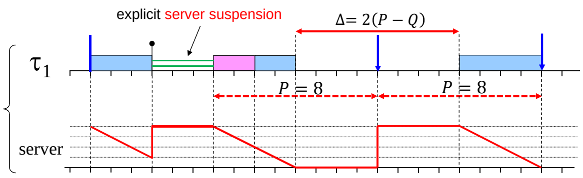
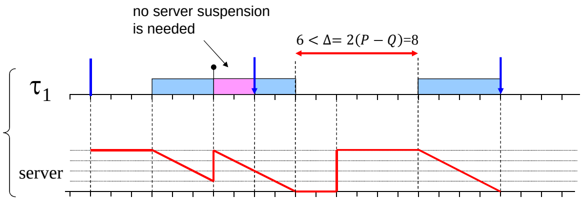



## BROE: bounded-delay

- If the server is "not executing too earlier", it is not possible to violate the worst-case delay $\Delta$

Depending on the execution state, BROE decides to suspend the server or not

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## BROE

**BROE Resource Access Policy**

Consider a BROE server having period P and budget Q. The current budget at time t is denoted as q(t).

When a task wishes to access a resource $R_k$ at time t:

- If $q(t) \geq \delta_k$, then enter the critical section (there is enough budget)
- Else, compute a recharging time $t_r = d - \frac{q(t)}{\alpha}$
  - If $t < t_r$, the server is suspended until time $t_r$, the budget is replenished to Q and the deadline is shifted to $d = t_r + P$
  - Otherwise, the budget is immediately replenished to Q and $d = t_r + P$

## BROE: constraints

- The BROE resource access policy can work **only with EDF** scheduling due to the proportional deadline shift. The support for FP scheduling of the servers is currently an open problem;
- In order to perform the budget check, BROE requires the specification of a **worst-case holding time** for the shared resources;
- BROE is intrinsically designed for the worst-case: the budget check can cause a scheduling decision that could be unnecessary.

## BROE: recap

- The BROE server is a scheduling mechanism providing resource reservation including the support for shared resources
  - Hard reservation implementing the Hard-CBS algorithm;
  - Resource access protocol that guarantees both bandwidth isolation and bounded-delay to the served application.

## Resource Holding Time

- In general, the BROE budget check has to be performed using the Resource Holding Time (RHT) of a shared resource;
- **RHT** = *budget consumed from the lock of a resource until its unlock*

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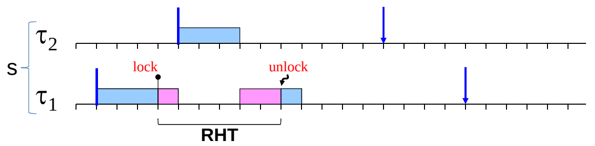
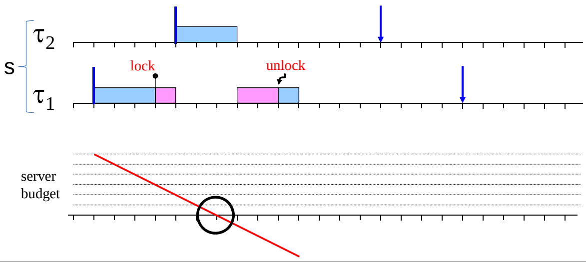


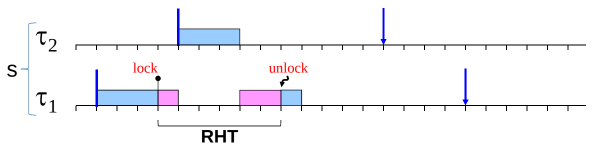

## Resource Holding Time

- Interference from high-priority task has to be accounted in the budget consumed when a resource is locked



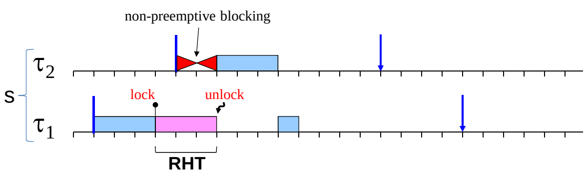

## Resource Holding Time

- **RHT** = *Critical Section WCET* + *Worst-case Interference*
- The interference is caused by the task preemptions



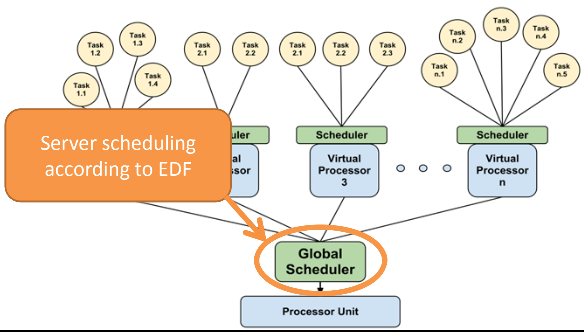

## Resource Holding Time

- If resources are accessed in a non-preemptive manner, the RHT is equal to the worst-case critical section length;
- Trade-off: lower threshold for the budget check, but greater task blocking due to non-preemptive blocking




## Implementation Issues

- **Goal**: Implementation of a two-level Hierarchical Scheduling Framework using the BROE algorithm.



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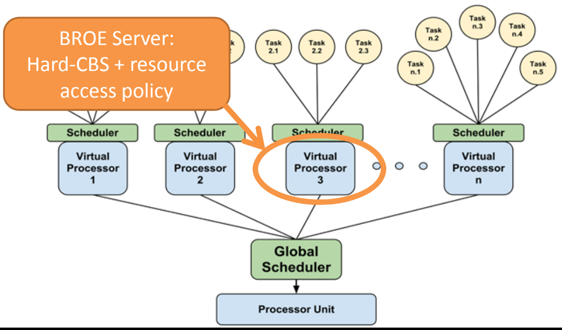


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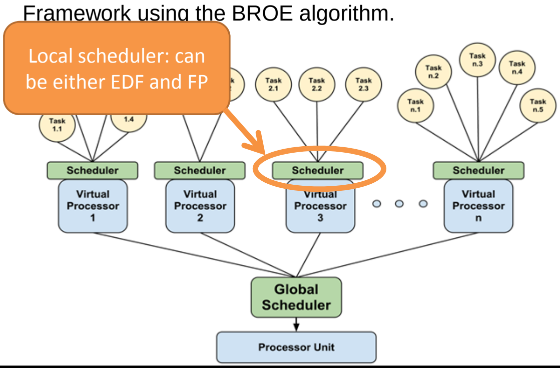
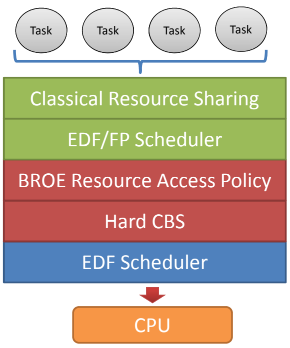


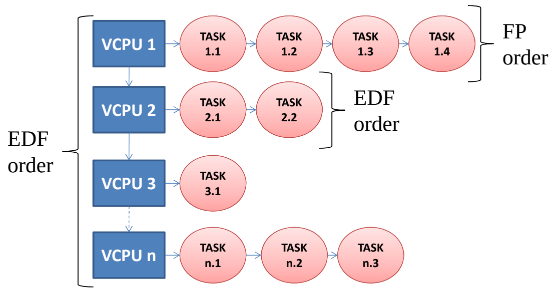

## Implementation Issues

- Multi-layer scheduling infrastructure




## Implementation Issues

- Ready queue structure




## Implementation Issues

- OS with tick: the kernel comes into operation periodically, even if there are no scheduling events to be handled;
- OS tick-less: the kernel come into operation only when is needed, i.e., in correspondence of scheduling events.
- *Example*: budget management for reservation

- We look at tick-less RTOS implementation on small microcontrollers.

## Implementation Issues

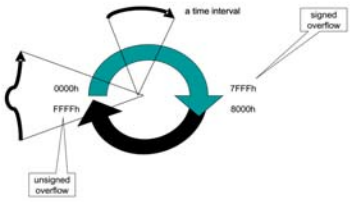
- EDF scheduling implementation: need for a timing reference having both
  - High-resolution;
  - Long life-time (to handle absolute deadlines).

Require 64 bit data structure for time representation

- Deal with 64 bit data structures in small microcontrollers imposes a significant overhead in the scheduler implementation.

## Implementation Issues

- Circular timer: avoid an absolute timing reference. The notion of time is relative with respect to a free running timer.
- Let T the lifetime of the free running timer.
- It is possible to handle temporal events having a maximum spread of T/2.




## Implementation Issues

- Consider two events $e_1$ and $e_2$.
- Let $t(e_1)$ be the absolute time of an event, and $r(e_1)$ its relative representation by using the circular timer.
- To compare two events having $|t(e_1) - t(e_2)| < T/2$
  - If $(r(e_1) - r(e_2)) > 0$ then $t(e_1) > t(e_2)$
  - If $(r(e_1) - r(e_2)) < 0$ then $t(e_1) < t(e_2)$
  - If $(r(e_1) - r(e_2)) == 0$ then $t(e_1) = t(e_2)$

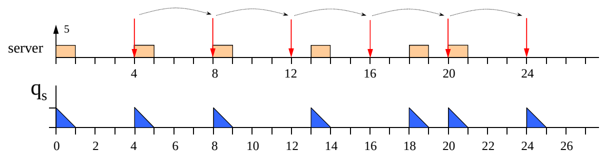
## Implementation Issues

- Warning: a relative representation becomes inconsistent after T/2!
- Inactive servers: It is necessary to perform a periodic check of inconsistent deadlines;
- A special timer has to be reserved for that job.

The implementation of EDF requires 2 timers:
- Free running timer
- Periodic timer for deadline consistency

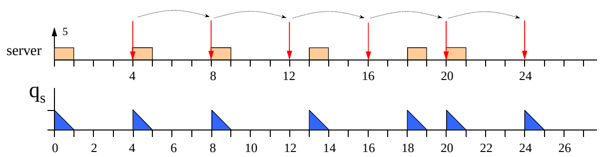
## Implementation Issues

- **Hard-CBS Server**: its implementation requires to manage two main operations
  - Budget enforcement;
  - Budget recharge.



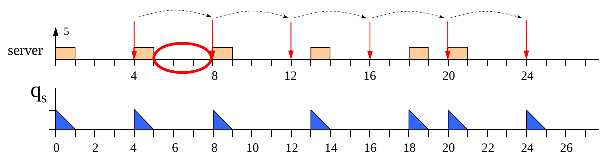

## Implementation Issues

- **Budget enforcement**: when then server starts to execute at time $t$, set up an one-shot timer with the current budget $q(t)$.
- If a preemption occurs, the timer is reconfigured; otherwise, it will fire to notify a budget exhaustion.




## Implementation Issues

- **Budget recharge**: when a server exhaust its budget, it has to be *suspended* until its deadline, where the budget will be recharged.
- A deadline-ordered queue of suspended server has to be provided. Another one-shot timer triggers the budget recharge event for the first server in the queue.



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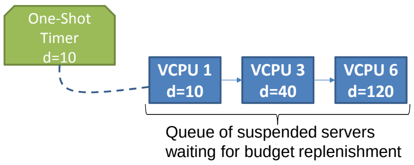


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  - Budget enforcement;
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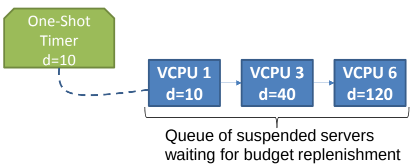
The implementation of the Hard CBS requires 2 timers:
- One-shot timer for budget enforcement
- One-shot timer for budget recharge

## Implementation Issues

- **BROE server suspension**: can be implemented exploiting the budget recharge queue
  - *"If $t < t_r$, the server is suspended until time $t_r$"*

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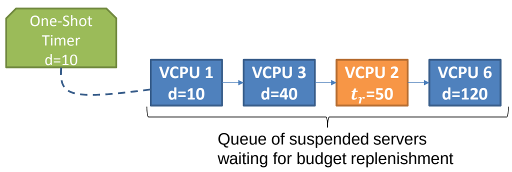


# Thank you!


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