Real-Time Embedded Systems

Laurent Pautet

strec.wp.mines-telecom.fr

Laurent.Pautet@enst.fr

Version 3.1

Real-Time Embedded Systems
Examples

Airplane

Cellphone

Automated Subway

Nuclear Plant

?

What do they have in common ?

Embedded Systems
Definition and Requirements

An embedded system is a special-purpose system which software, hardware, mechanical, … components are encapsulated in the device it controls

As opposed to general-purpose systems,
they have specific properties such as
low consumption, small size and weight, limited resources …

A cruise control, a washing machine, factory robot, …

Real-Time Systems
Definition and Requirements

A real-time system consists in one or more sub-systems that have to react under specified time requirements to stimuli produced by the environment

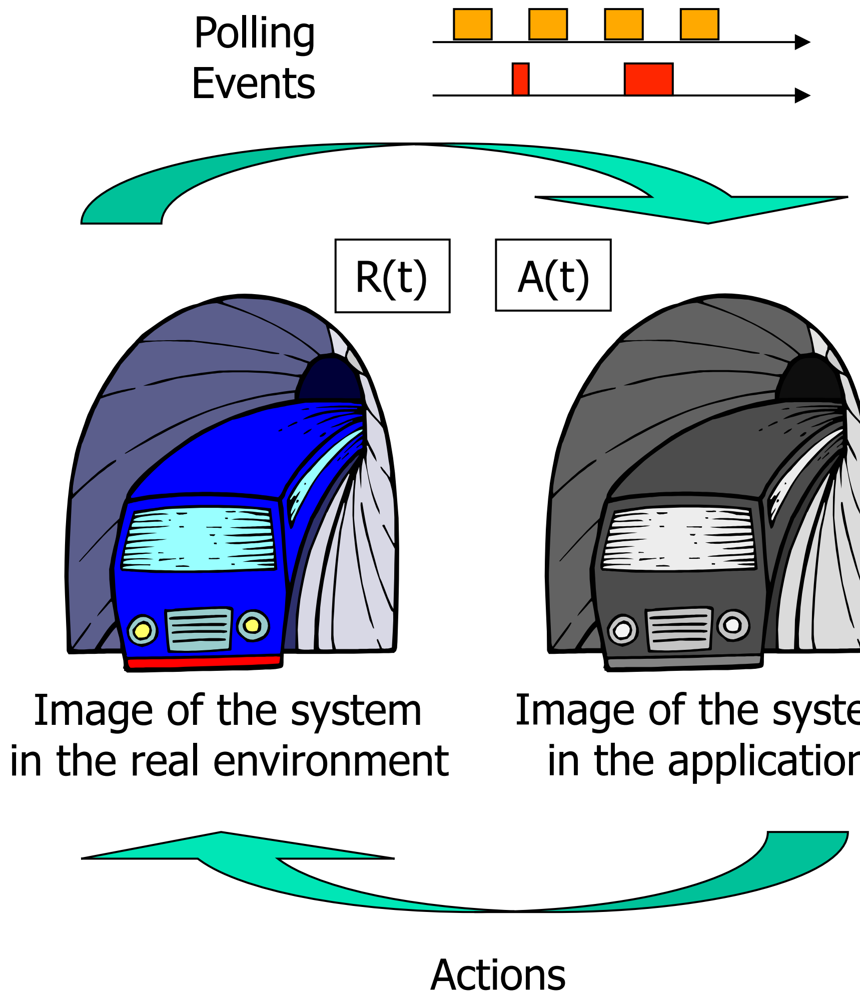
A response after a deadline is invalid

Even if the response is logically correct

A cruise control, a washing machine, factory robot, a nuclear plant, an air traffic control, trading center, …

Most real-time systems are embedded systems

Timing constraints


Polling
Events
R(t)
A(t)
Image of the system in the real environment
Image of the system in the application
Actions

- The application must have a precise and consistent image of the system in its environment at anytime
- The goal of real-time systems is to minimize the difference between the images of the system in reality and in its application ($|R(t)-A(t)|<\varepsilon$)
- To update the image in the application, it reads in particular sensors periodically. The period being a temporal granularity during which the measures evolve significantly)

Non Fonctional Properties

These systems have to be predictible

- Reactivity and temporal consistency
  - Define temporal interval during which data is valid
  - Define time granularity (ship sec, rail msec, airplane usec)
  - Guarantee response time boundaries (known in advance)
- Reliability and Availability
  - Guarantee the correctness of the computed data values
  - Enforce system availability in presence of hostile conditions (fault tolerance, malicious behavior …)

Non-Fonctional Properties -> temporal & structural

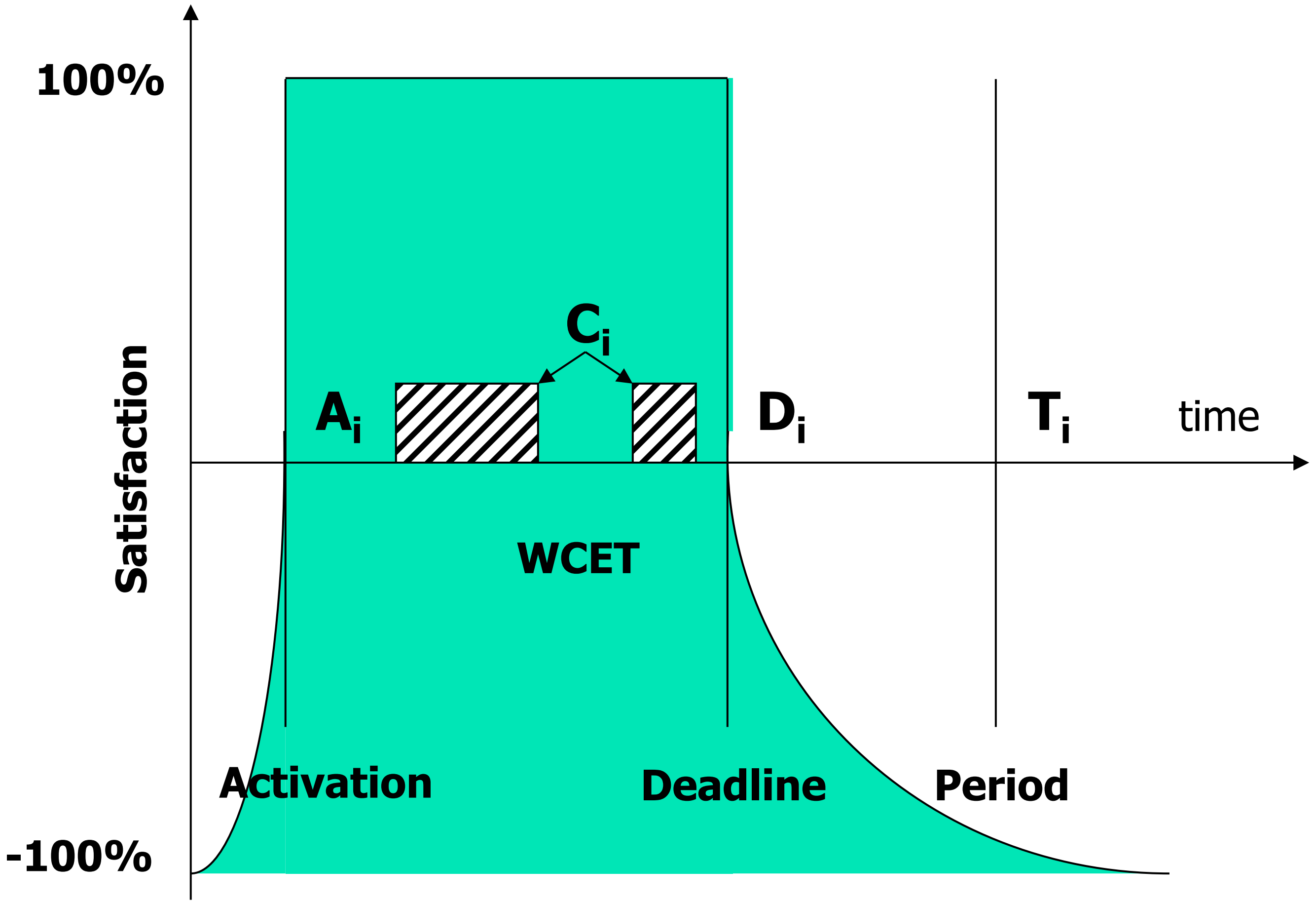
From requirements to technical solutions

- Requirements
  - Reactivity & temporal consistency
  - Reliability & Availability
- Solutions
  - Architectures and frameworks to help the design (Kernels, RT buses and networks, …)
  - Models and methods to enforce predictibility (RT scheduling, Fault tolerance, …)
  - Suitable programming languages (C-Misra, Java-RT, Standard POSIX 1003.1c, Ada, …)
  - Tools to integrate modeling, analysis and synthesis (AADL, Marte, verification, simulation, generation, testing)

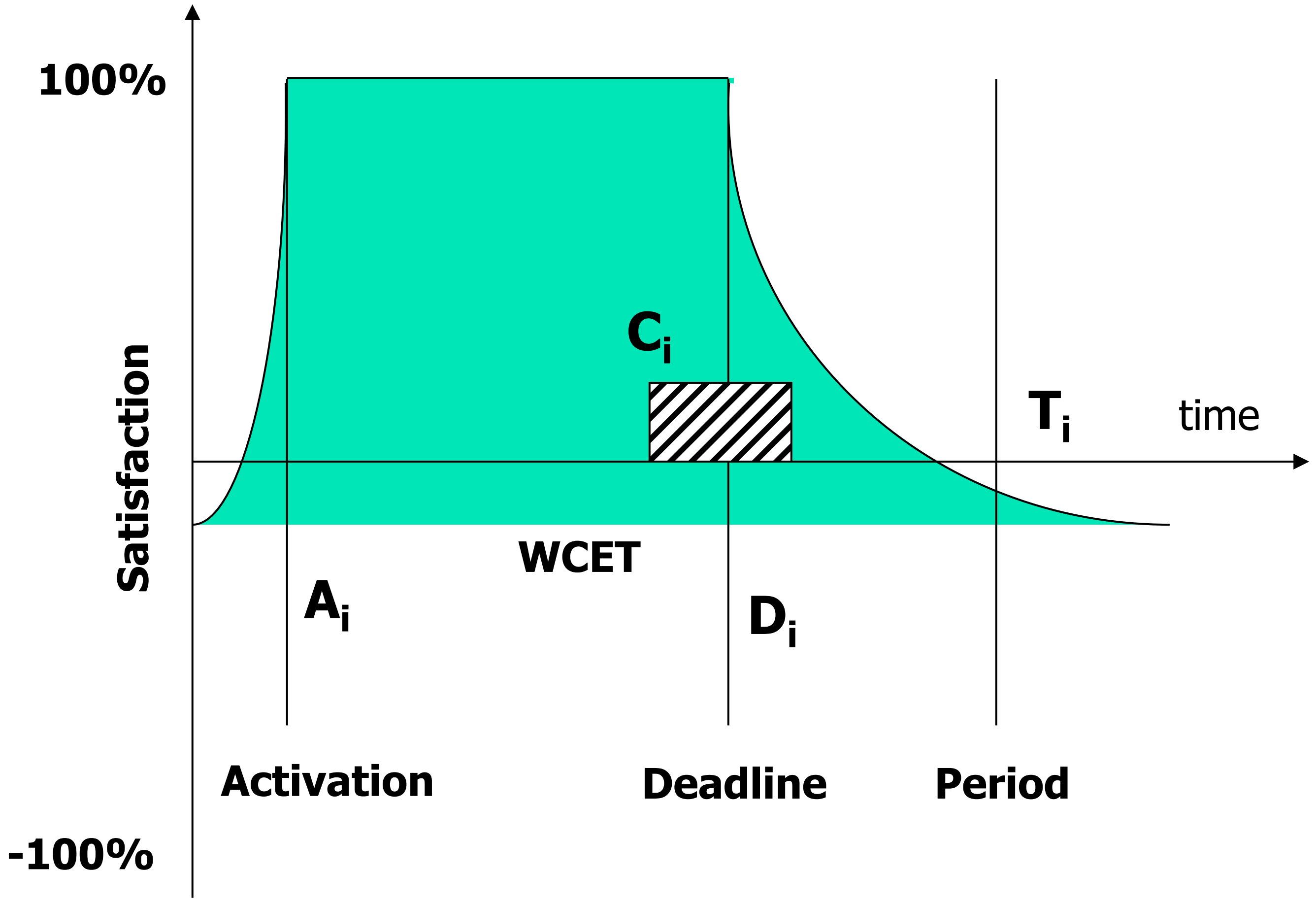
Notations

- Parameters of task t_i
  - C_i : Worst Case Execution Time (WCET) of task t_i
  - A_i : Activation time of task t_i
    - Task must not be activated before S_i
  - D_i : Deadline of task t_i
    - Task must not complete after D_i
  - T_i : Period of task t_i
  - $U_i = C_i / T_i$ = processor utilisation of task t_i
- $A_i + C_i < D_i$ however …
- $D_i < T_i$ is not mandatory
- A_i may be different from 0 (dependency)

Hard Real-Time Task



Soft Real-Time Task
(Different from Best Effort Task that has No Deadline)



Missing deadlines

- For a hard real-time task, deadlines must be fulfilled
  - Enforce a maximal determinism
    - WCET : *Worst Case Execution Time*
  - Reduce non-deterministic behavior
    - Pre-allocated resources
    - System over-dimensioning
- For a soft real-time task, missing deadlines can be tolerated under some circumstances
  - For a given percentage of times
  - For a given number of times
  - For a given frequency
  - And result in a degraded execution mode

Sub-systems of real-time systems

A real-time system is composed of several sub-systems with different real-time properties

Some of these sub-systems may be non real-time, soft real-time or hard real-time sub-systems

- Hard real-time tasks must fulfill their deadlines.
- Soft real-time tasks may fail to fulfill their deadlines. If so, they may execute in a degraded mode.
- Other tasks execute in best-effort mode.

Real-Time Schedulers

- Allocate (temporal) resources to guarantee safety properties
- In normal mode, respect the time constraints of all tasks
- Otherwise, limit the effects of time overflows and ensure compliance with the constraints of the most critical tasks

In the following, it will be ensured that the time required for the implementation of the scheduling algorithm and that of context change are negligible which implies a low complexity and effective implementation

Definitions
Execution Model

- Dependent or independent tasks
  - Independent tasks sharing only the processor
  - Dependent tasks with shared resources or linked by precedence constraints
- Synchronous task means task of zero activation time
- Periodic task with implicit deadline means periodic task with deadline equals to period
- Task job : instanciation of a task during period
- Worst Case Execution Time : worst computation time
- Response time : time to complete a job while other jobs are also running on the same processor

Definitions

- Preemptive and non-preemptive scheduling
  - A preemptive scheduler can interrupt a task for a higher priority task when a non-preemptive scheduler executes the task until it completes
- Offline or online scheduling
  - A scheduler decides offline or online when and which task to execute
- Optimal scheduling
  - Algorithm that produces a schedule for any set of schedulable tasks (if an algorithm does, it does too)
- Scheduling test
  - A necessary and / or sufficient condition for an algorithm to satisfy the temporal constraints of a set of tasks

Notations

- Characteristics of the task τ_i
  - C_i : worst case computation time of τ_i
  - A_i : activation offset of τ_i
  - D_i : deadline of τ_i
  - T_i : period of τ_i
  - $U_i = C_i / T_i$ = CPU usage for τ_i
- Characteristics of the system
  - N : number of periodic tasks
  - $U = \sum U_i$ = overall CPU usage
- Operators
  - Ceiling $\lceil x \rceil$ (least integer greater than or equal to x)
  - Floor$\lfloor x \rfloor$ (greatest integer less than or equal to x)

Overview of algorithms

- Scheduling periodic tasks
  - Non-preemptive table-based scheduling
  - Preemptive scheduling with static priorities
    - Rate and Deadline Monotonic Scheduling
  - Preemptive scheduling with dynamic priorities
    - Earliest Deadline First and Least Laxity First
- Scheduling aperiodic tasks
  - Background, polling, deferred & sporadic servers
- Sharing resources
  - Priority Inheritance, Priority Ceiling & Highest Locker

Proving schedulability using a scheduling algorithm

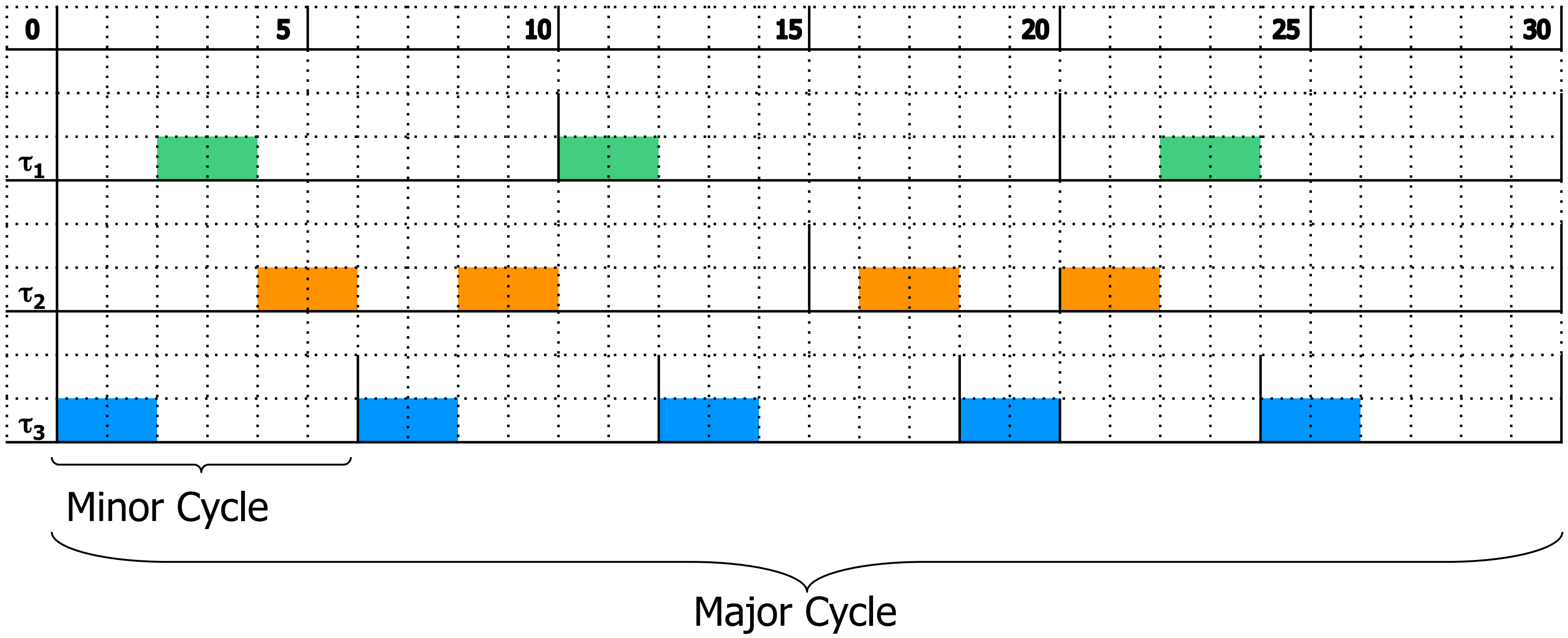
- A set of **periodic** tasks repeats itself after an hyper-period, least common multiple of all task periods
- To prove schedulability of a task set
  - Execute the scheduling algorithm on this task set over an hyper-period
  - Compute a (necessary - sufficient) scheduling test
  - Compute response time & check against deadlines

Table Driven Scheduling
Principles

- Hypotheses
  - Periodic tasks
- Principles
  - Major cycle = LCM of the task periods
  - Minor cycle = non-preemptible block
  - The minor cycle divides the major cycle
  - A cyclic scheduler loops on the major cycle by executing the sequence of minor cycles
  - The minor cycle provides a control point to check the respect of the timing constraints

Table Driven Scheduling
Example

	Period	Deadline	WCET	Usage
τ_1	10	10	2	0,200
τ_2	15	15	4	0.267
τ_3	6	6	2	0.333



Laurent Pautet

Table Driven Scheduling
Advantages and Disadvantages

- Advantages
  - Effective implementation
  - No need for mutual exclusion between tasks
- Disadvantages
  - Not work conserving :
    - the processor may be idle while jobs are not completed
  - Impact of an additional task
  - Execution of aperiodic tasks
  - Difficult construction of the table
    - Allocating slots is a complex problem since it has to take into account time constraints, shared resources & aperiodic tasks.

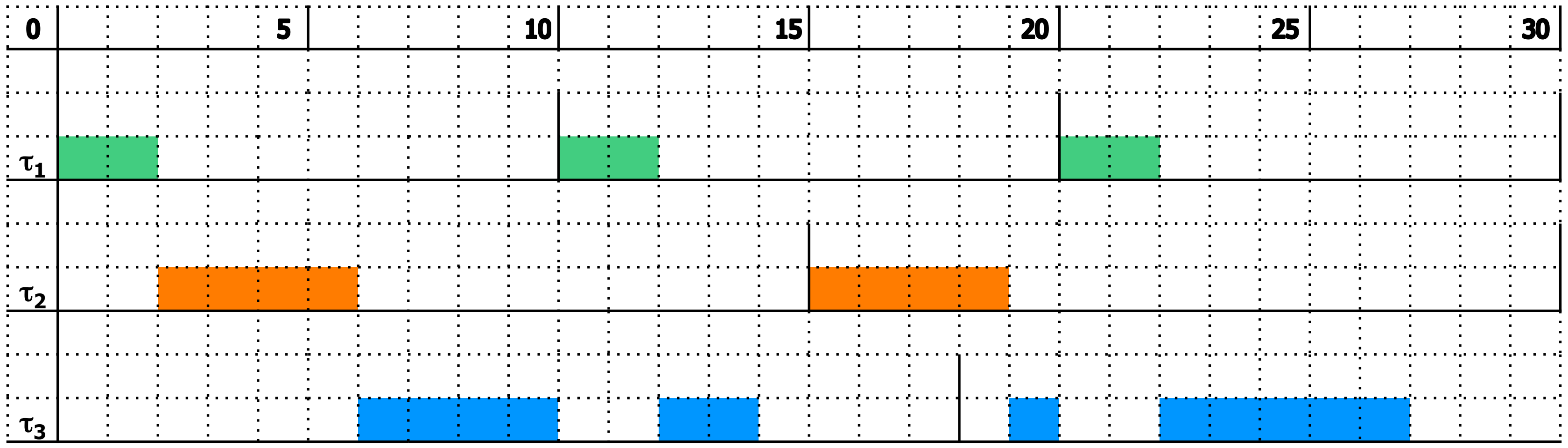
Static Priority Scheduling
Rate Monotonic Scheduling

- Hypotheses
  - Synchronous, deadline implicit & independent tasks
  - Synchronous ($A_i = 0$)
  - Deadline implicit ($D_i = T_i$)
- Principle
  - Task activation or completion wake up the scheduler
  - Select the ready task with the shortest period
- Scheduling test
  - Necessary condition: $U \leq 1$
  - Sufficient condition: $U \leq n\left(2^{1/n} - 1\right)$

$$\lim_{n \to +\infty} n\left(2^{1/n} - 1\right) = \log(2) = 69\%$$

Static Priority Scheduling
Rate Monotonic Scheduling

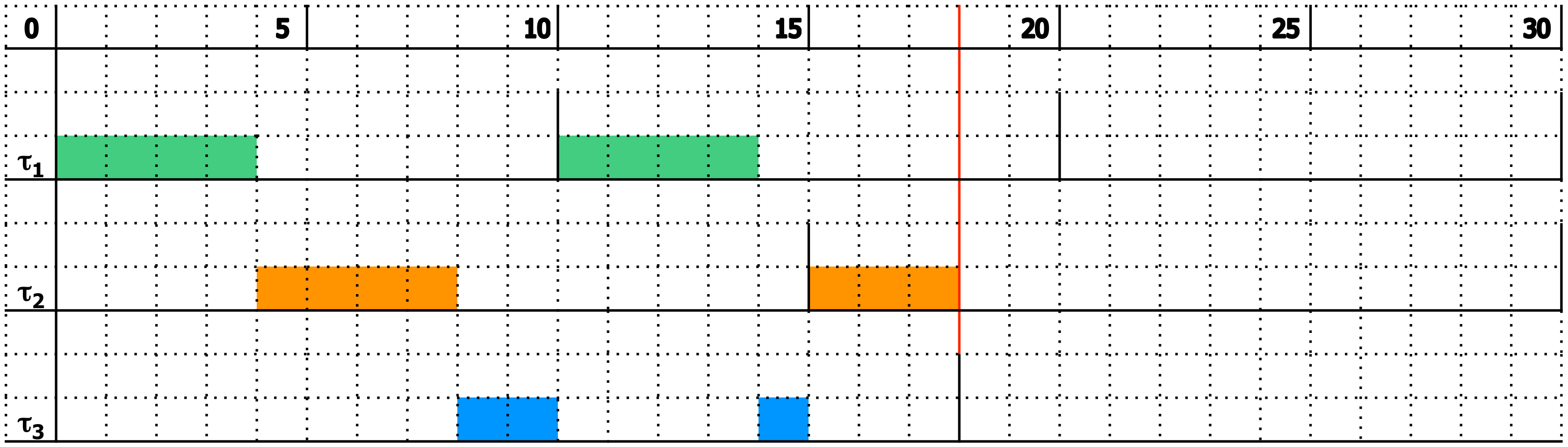
	Period	WCET	Usage
$3\times\left(2^{1/3}-1\right)\approx 0.7$ τ_1	10	2	0.200
τ_2	15	4	0.267
τ_3	18	6	0.333



Static Priority Schdeuling

Rate Monotonic Scheduling

$3 \times (2^{1/3} - 1) \approx 0.78$	Period	WCET	Usage
τ_1	10	4	0.400
τ_2	15	4	0.267
τ_3	18	6	0.333

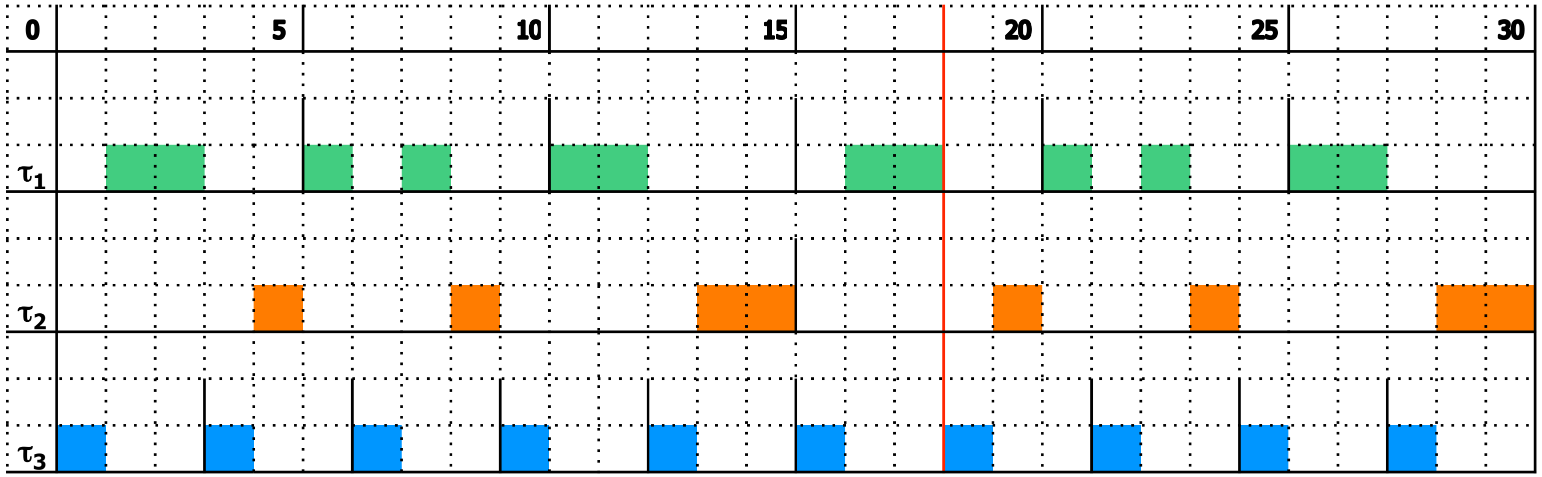


Static Priority Scheduling

Rate Monotonic Scheduling

$3x(2^{1/3}-1)=0.78$	Period	WCET	Usage
τ_1	10	4	0.400
τ_2	15	4	0.267
τ_3	18	6	0.333

$3x(2^{1/3}-1)=0.78$	Period	WCET	Usage
$\tau'_1 = \tau_1 / 2$	**5**	**2**	**0.400**
τ'_2	15	4	0.267
$\tau'_3 = \tau_3 / 6$	**3**	**1**	**0.333**



Static Priority Scheduling
Rate Monotonic Scheduling

- Advantages
  - Easy to implement
  - Optimal for static priority scheduling
  - Frequent in the classic executives
  - Good behavior in case of overload
- Disadvantages
  - Possible oversizing of the system
- Necessary and sufficient condition in *O(n²)*
  - See further OPA algorithm OPA

$$\forall i,\ 1 \le i \le n,\ \min_{(k,l)\in R_i}\left(\sum_{j=1}^{j=i-1}\frac{C_i}{T_j}\frac{T_j}{lT_k}\left\lceil\frac{lT_k}{T_j}\right\rceil + \frac{C_i}{lT_k}\right) \le 1 \ \ avec\ \ R_i = \left\{(k,l)\ \middle|\ 1 \le k \le i,\ l = 1,\ldots,\left\lfloor\frac{T_i}{T_k}\right\rfloor\right\}$$

Static Priority Scheduling

Response Time

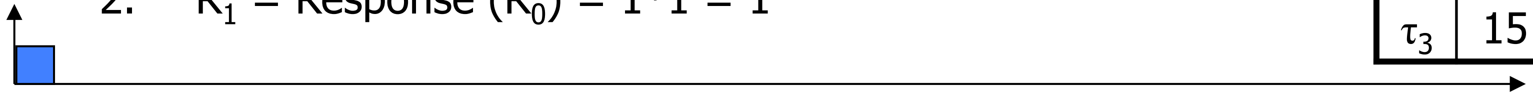
- The *critical instant* for a set of synchronous periodic tasks is when all jobs start at the same time
- For each task, compute time t at which its first activation completes by integrating the execution of highest priority tasks activated in the mean time
  - Start with a first response time $R^i_0 = C_i$
  - Compute $R^i_{n+1} = \Sigma_{j \leq i} C_j * \lceil R^i_n / T_j \rceil$ to integrate the execution of the tasks of highest priority
  - Reiterate until a fixed point is reached
- The task is schedulable if the response time is a fixed value less than or equal to the deadline
- Valid for any static priority scheduling

Response Time

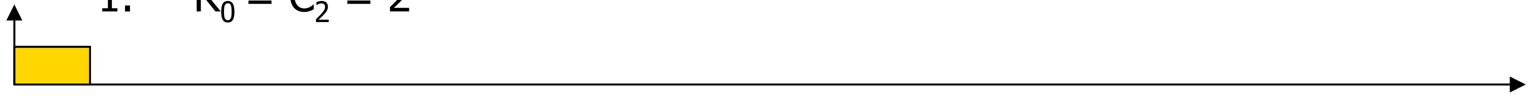
Rate Monotonic Scheduling

	P	C
τ_1	3	1
τ_2	5	2
τ_3	15	4

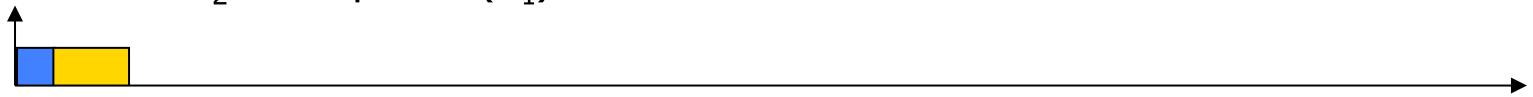
1. Check for τ_1
   1. $R_0 = C_1 = 1$
   2. R_1 = Response (R_0) = 1*1 = 1



2. Check for τ_2 and take into account τ_1
   1. $R_0 = C_2 = 2$



   2. R_1 = Response (R_0) = 1*1+1*2 = 3
   3. R_2 = Response (R_1) = 1*1+1*2 = 3

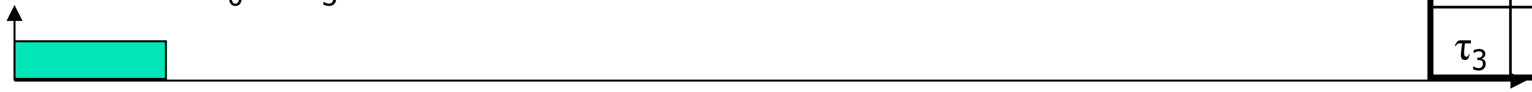


Response Time

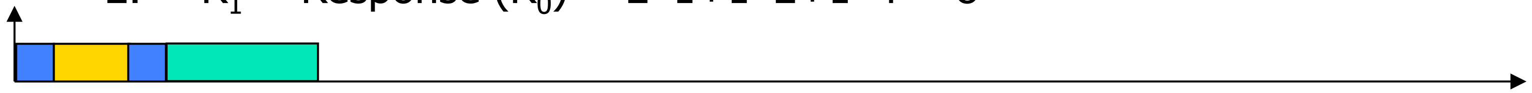
Rate Monotonic Scheduling

	P	C
τ_1	3	1
τ_2	5	2
τ_3	15	4

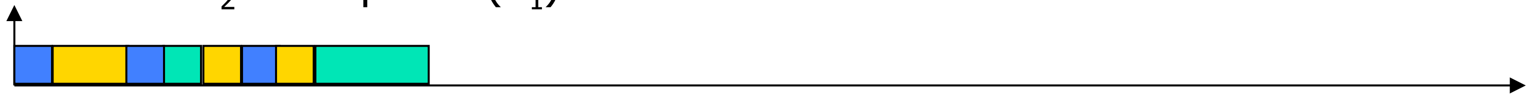
1. Check for τ_3 and take into account τ_1 and τ_2
   1. $R_0 = C_3 = 4$



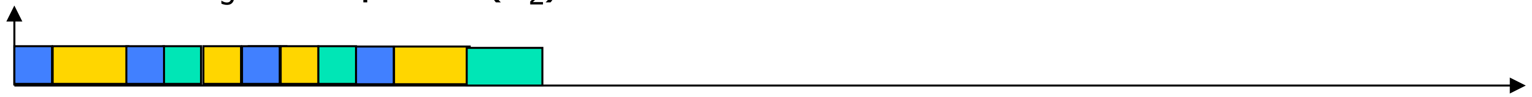
   2. R_1 = Response (R_0) = 2*1+1*2+1*4 = 8



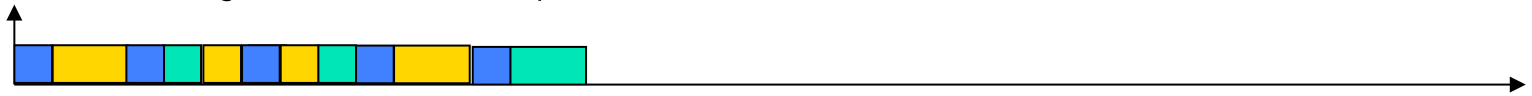
   3. R_2 = Response (R_1) = 3*1+2*2+1*4 = 11



   4. R_3 = Response (R_2) = 4*1+3*2+1*4 = 14



   5. R_4 = Response (R_3) = 5*1+3*2+1*4 = 15
   6. R_5 = Response (R_4) = 5*1+3*2+1*4 = 15



Static Priority Scheduling
OPA – Optimal Priority Assignment

- Let have N fixed priority tasks
- Among these tasks, find a task that can have the lowest priority …
  - Its response time should be less than its deadline when all the others have a higher priority
  - If there is such a task, give it the lowest priority
  - Otherwise, the system is not schedulable
- Repeat with the N-1 remaining tasks

OPA vs RMS

$3x(2^{1/3}-1)=0.78$	Period	WCET	Usage
τ_1	5	2	0.400
τ_2	15	4	0.267
τ_3	3	1	0.333

- τ_1 lowest priority: $R_0= 2$; $R_1=7$; or $R_1>T_1$
- τ_2 lowest priority: $R_0= 4$; $R_1=8$; $R_2=14$; $R_3=15$;
  - τ_1: $R_0= 2$; $R_1=3$; $\tau_2 < \tau_1 < \tau_3$: same as RMS
  - τ_3: $R_0= 1$; $R_1=3$; $\tau_2 < \tau_3 < \tau_1$: different from RMS
- τ_3 lowest priority: $R_0= 1$; $R_1=7$; or $R_1>T_3$

- OPA always finds an assignment if it exists (optimal), in particular the assignment of RMS (also optimal)

Static Priority Scheduling
Deadline Monotonic Scheduling

- Hypotheses
  - Synchronous and independant tasks
  - The deadline is less than the period ($D_i <= T_i$)
- Principle
  - Select the ready task with the shortest deadline
  - When for all tasks $T_i = D_i$, DMS becomes RMS
- Scheduling test
  - The necessary and sufficient condition exists
  - Sufficient condition: $\sum \frac{C_i}{D_i} \leq n\left(2^{1/n} - 1\right)$

Static Priority Scheduling
Deadline Monotonic Scheduling

- Advantages
  - See RMS
  - RMS penalizes long period but short deadline tasks
  - DMS is better in this case.
- Disadvantages
  - See RMS
  - Do not to be confused with EDF

Dynamic Priority Scheduling

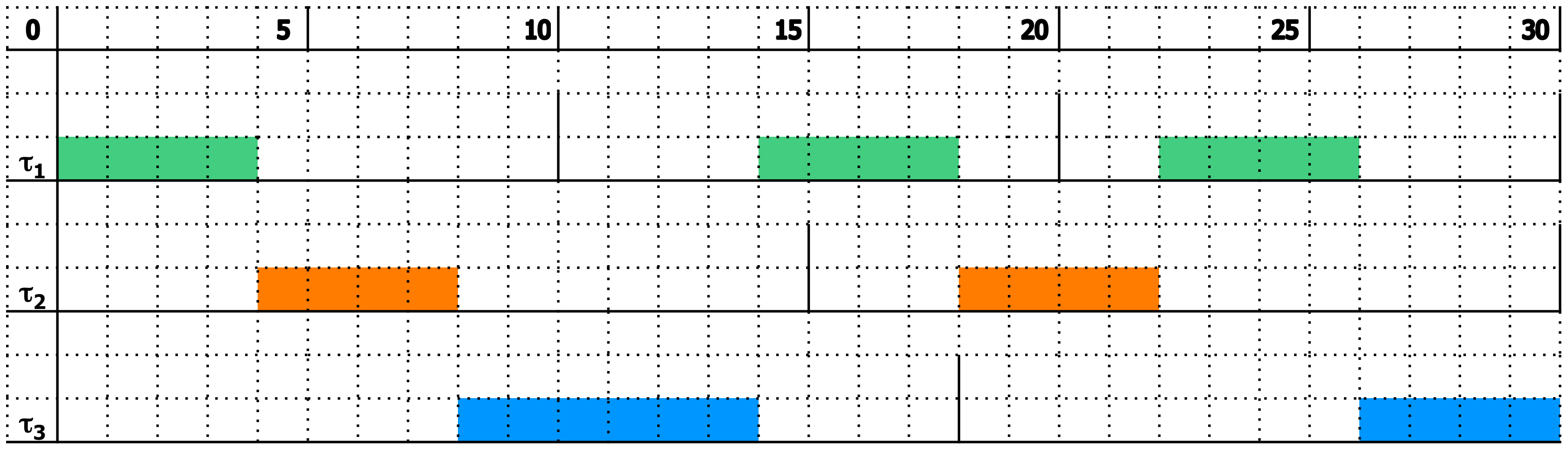
Earliest Deadline First

- Hypotheses
  - Periodic, deadline implicit and independent tasks
  - Deadline implicit ($D_i = T_i$)
  - The deadline is less than the period ($D_i <= T_i$)
- Principle
  - Task activation or completion wake up the scheduler
  - Select the ready task with the earliest deadline
- Scheduling test
  - Necessary and sufficient condition $\sum C_i / T_i \leq 1$

Dynamic Priority Scheduling

Earliest Deadline First

	Period	WCET	Usage
τ_1	10	4	0.400
τ_2	15	4	0.267
τ_3	18	6	0.333



Dynamic Priority Scheduling
Earliest Deadline First

- Advantages
  - Possible use of 100% of the processor
  - Optimal for dynamic priority scheduling if the deadlines are lower than the periods
- Disadvantages
  - Slight complexity of implementation
  - Less common in executives than RMS
  - Bad behavior in case of overload
- Remarks
  - If Di is arbitrary compared to Ti, the necessary and sufficient condition is no longer sufficient $\sum C_i / D_i \leq 1$

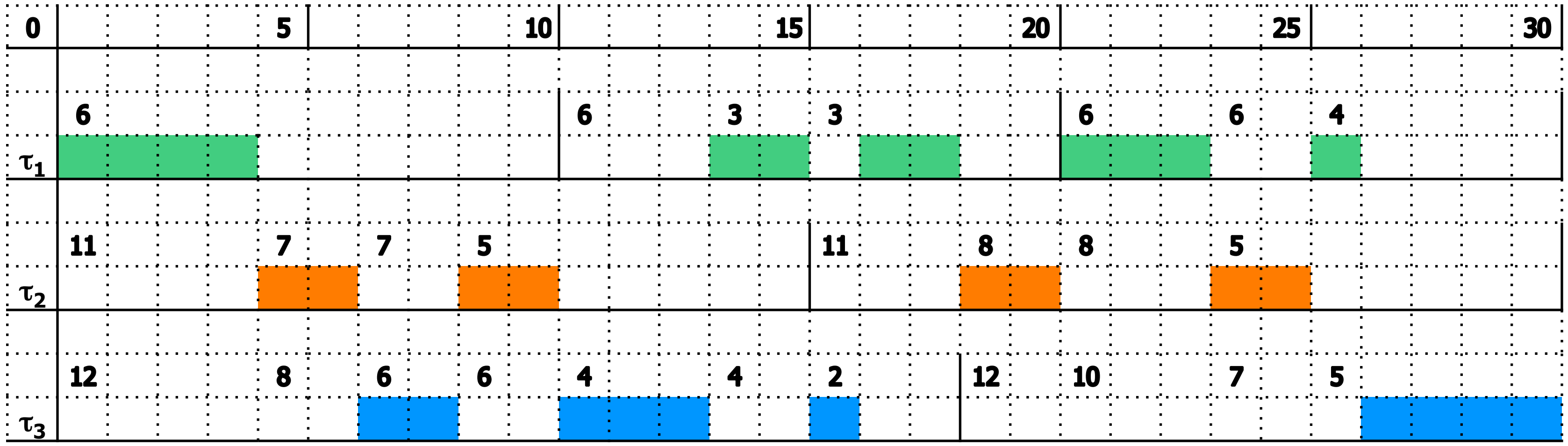
Dynamic Priority Scheduling
Least Laxity First

- Hypotheses
  - Similar to those of EDF
- Principle
  - Task activation or completion wake the scheduler
  - Select the ready task with the lowest margin
  - margin = deadline – remaining comp. time – current time
- Scheduling test
  - Necessary and sufficient condition: $\sum C_i / T_i \leq 1$

Dynamic Priority Scheduling

Least Laxity First

	Period	WCET	Usage
τ_1	10	4	0.400
τ_2	15	4	0.267
τ_3	18	6	0.333



Laurent Pautet

Dynamic Priority Scheduling

Least Laxity First

- Advantages
  - Better than EDF in the case of multi-processor
- Disadvantages
  - High complexity of implementation
  - Complex to compute remaining execution time
  - Bad behavior in case of overload
  - High number of preemptions
  - LLF oscillates in case of tied-laxities tasks

Aperiodic Task Scheduling

- Definitions
  - Aperiodic tasks are activated at arbitrary instants
  - Sporadic tasks are aperiodic tasks activated with a minimum delay between two activations
  - Sporadic tasks are almost periodic as they are activated with a variable but minimal period
  - Aperiodic tasks must respect their deadlines
- Principles
  - Aperiodic tasks must be integrated into the scheduling of periodic tasks

Aperiodic tasks with periodic tasks

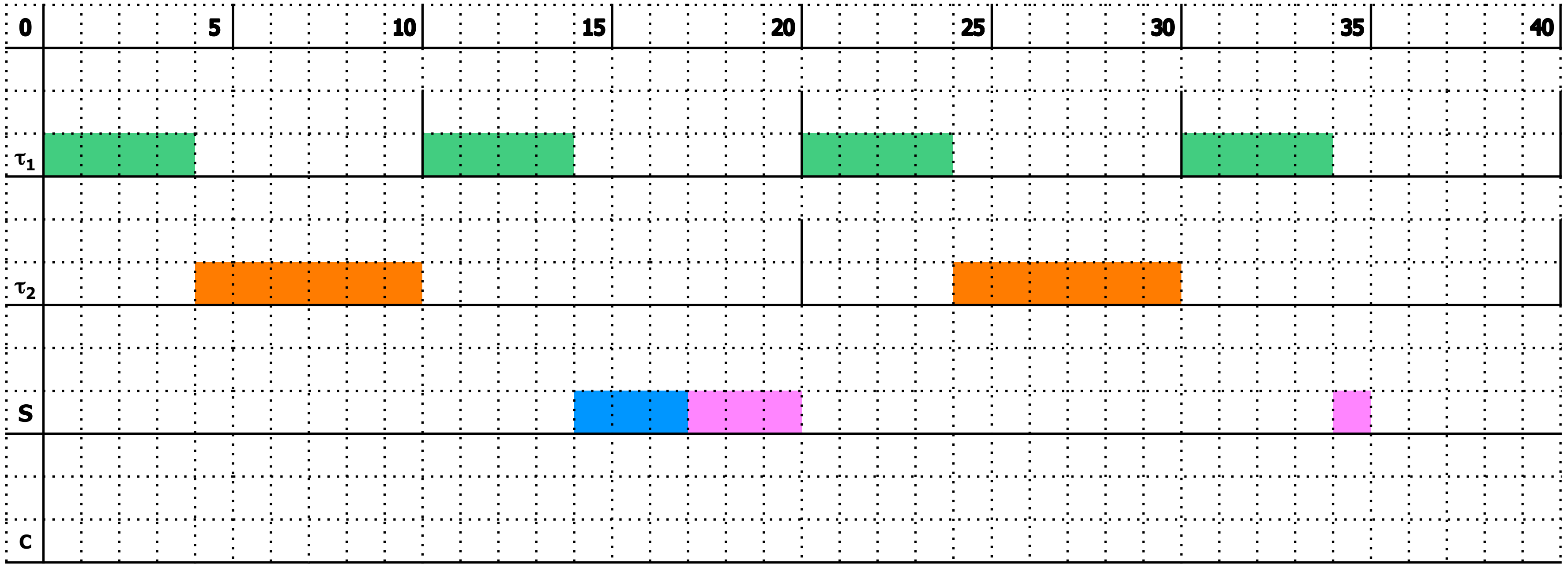
- First solution for sporadic tasks
  - Handle sporadic tasks as periodic tasks when scheduling algorithm **allows** it
  - Ie the scheduling algorithm accepts tasks that are not activated at fixed time
- Second solution (more general)
  - Handle aperiodic tasks with a periodic server
  - The periodic server when it is active handles the aperiodic tasks as long as it is allowed
- Reuse schedulability tests for periodic tasks

Scheduling aperiodic tasks
Background server

- The aperiodic tasks are processed sequentially by a low priority server
- The server has no associated budget (since it has the lowest priority)
- The lack of budget comes from the fact that the server fills the holes in the scheduling

Scheduling aperiodic tasks
Background server

	Period/Release	Budget	Priority	Utilization/Response
Aperiodic task ε_1	7	3		17-7=10
Aperiodic task ε_2	11	4		35-11=24
Periodic task τ_1	10	4	3	0,400
Periodic task τ_2	20	6	2	0,300
Background Server	*	*	1	*



Laurent Pautet

Scheduling aperiodic tasks
Background server

- Advantages
  - Simplicity of implementation
- Disadvantages
  - Difficult to predict response time of aperiodic tasks
  - … although aperiodic tasks can be critical
  - Bad response time under heavy workload

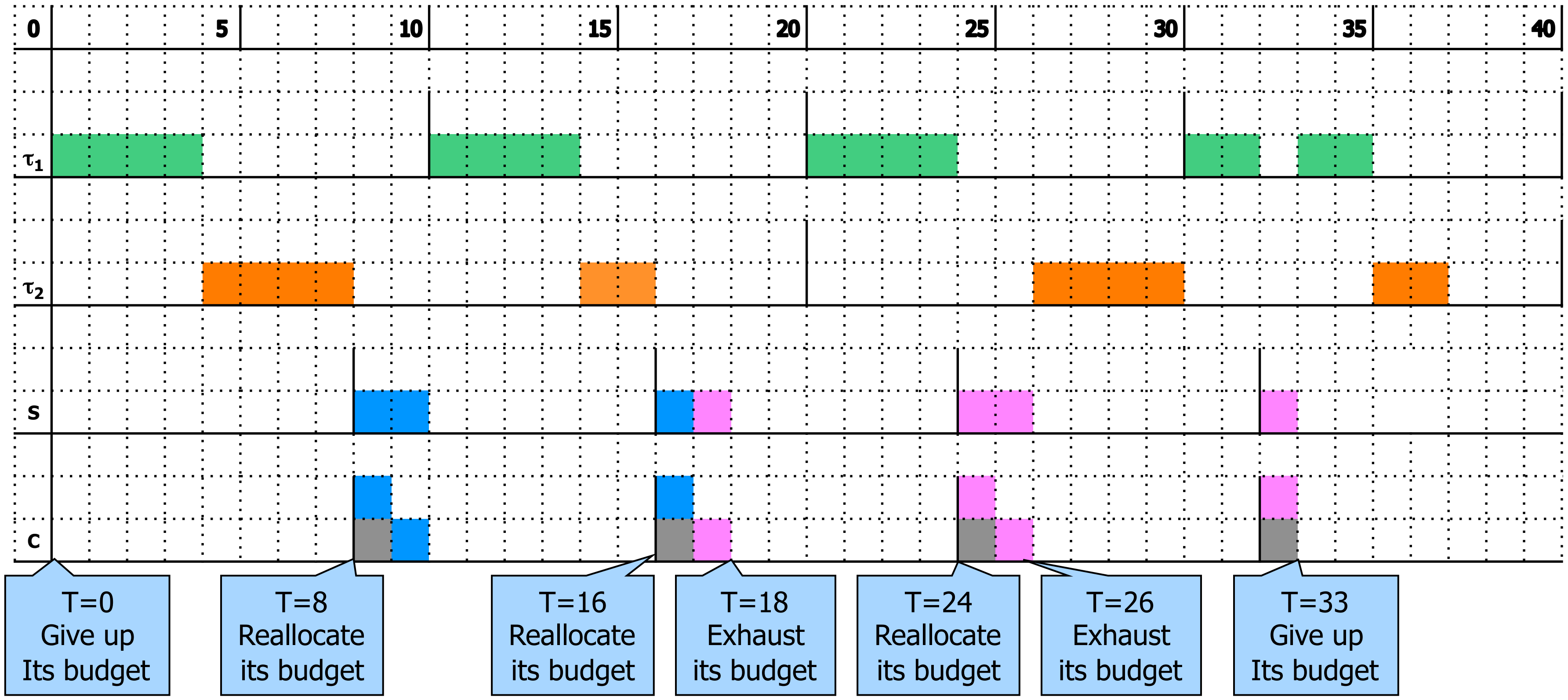
Scheduling aperiodic tasks
Polling server

- Aperiodic tasks are processed sequentially by a high priority server
- The server has a budget and a period
- The budget is reallocated every period
- The time consumed to process an aperiodic task is debited on its budget
- The server executes aperiodic tasks within its budget
- The server becomes inactive when there is no task to execute and gives up its budget until next period

Scheduling aperiodic tasks

Polling server

	Period/Release	Budget	Priority	Utilisation/Response	
Aperiodic task ε_1	7	3			10
Aperiodic task ε_2	11	4			22
Periodic task τ_1	10	4	2	0,400	6
Periodic task τ_2	20	6	1	0,300	20
Polling Server	8	2	3	0,250	2



Scheduling aperiodic tasks
Polling server

- Advantages
  - Simplicity of implementation
- Disadvantages
  - By giving up its budget, the server exhausts the processing time allocated to future tasks
  - Bad response time even when aperiodic tasks are released just after server activations

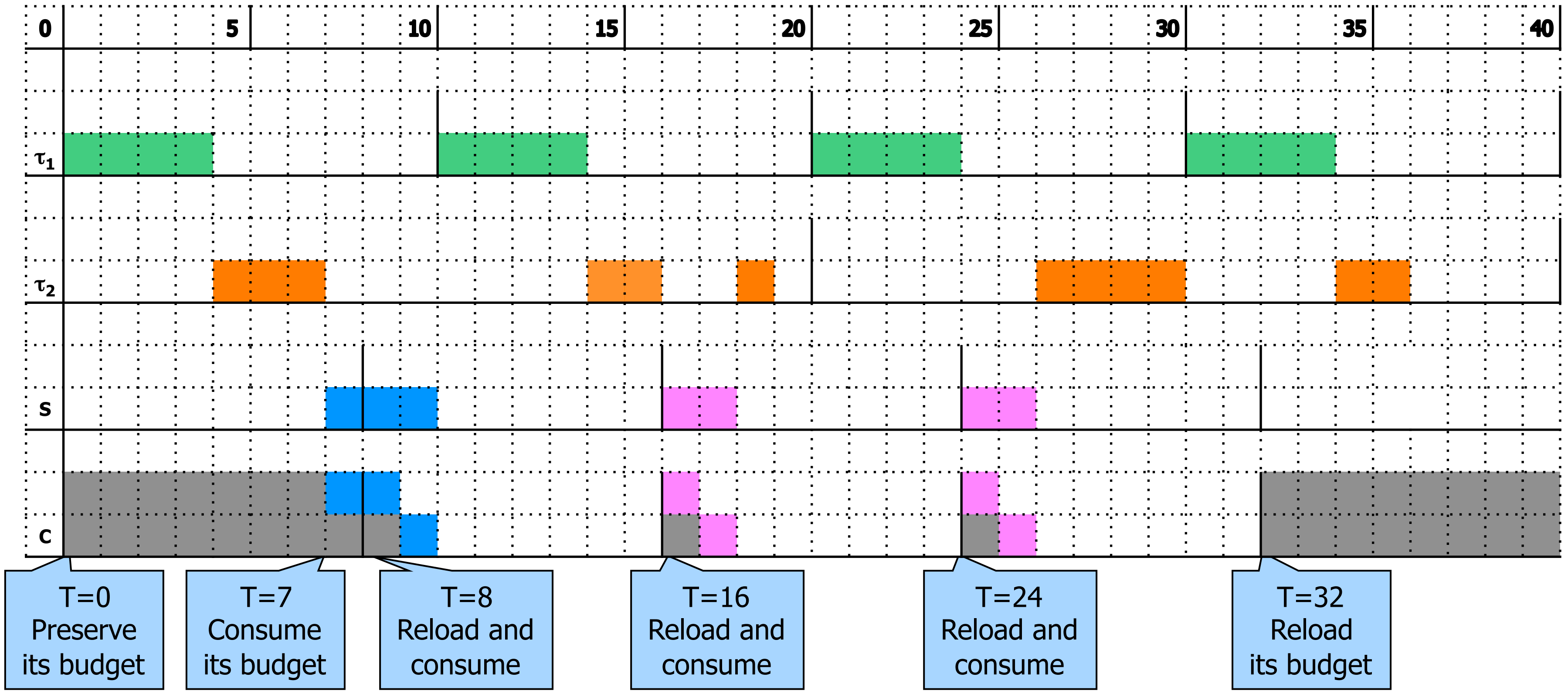
Scheduling aperiodic tasks
Deferred server

- The aperiodic tasks are processed sequentially by a high priority server
- The server has a budget and a period
- The budget is reallocated every period
- The time consumed to process an aperiodic task is debited on its budget
- The server becomes active only when an aperiodic task is to be processed and its budget is not yet exhausted

Scheduling aperiodic tasks

Deferred server

	Period / Release	Budget	Priority	Usage / Response
Aperiodic task ε_1	7	3		3
Aperiodic task ε_2	11	4		15
Periodic task τ_1	10	4	2	0,400
Periodic task τ_2	20	6	1	0,300
Deferred server S	8	2	3	0,250



Scheduling aperiodic tasks
Deferred server

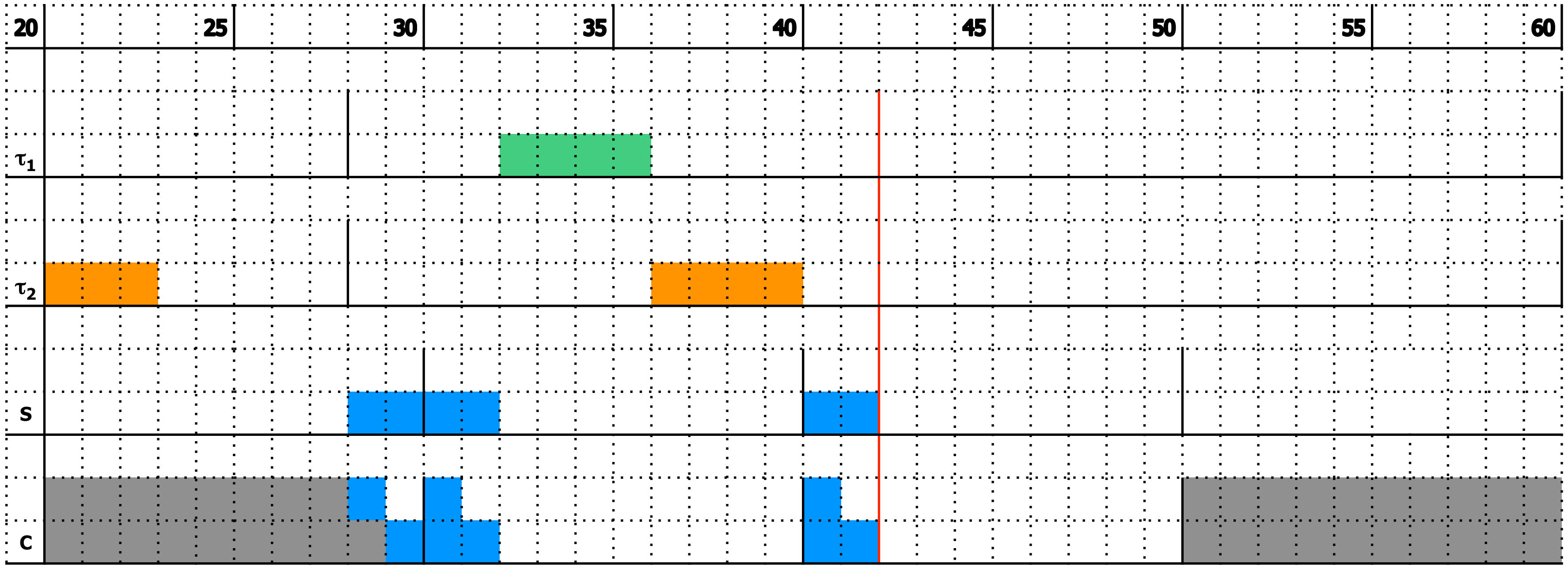
- Advantages
  - It preserves its budget for future tasks
- Disadvantages
  - By not immediately consuming its budget, a deferred server violates the scheduling hypotheses of a periodic task because it does not execute while it can.
  - A scheduling analysis can claim that the scheduling is correct while the server causes a deadline miss of a low priority task by delaying its execution

Scheduling aperiodic tasks

Issue with deferred server

	Period / Release	Budget	Priority	Utilisation/Response	
Aperiodic task ε_1	28	6			12
Periodic task τ_1	14	4	1	0,285	13
Periodic task τ_2	14	5	2	0,357	9
Deferred Server S	10	2	3	0,200	2

Tasks S, τ_1 et $\tau_2$sont ordonnançables par RMS



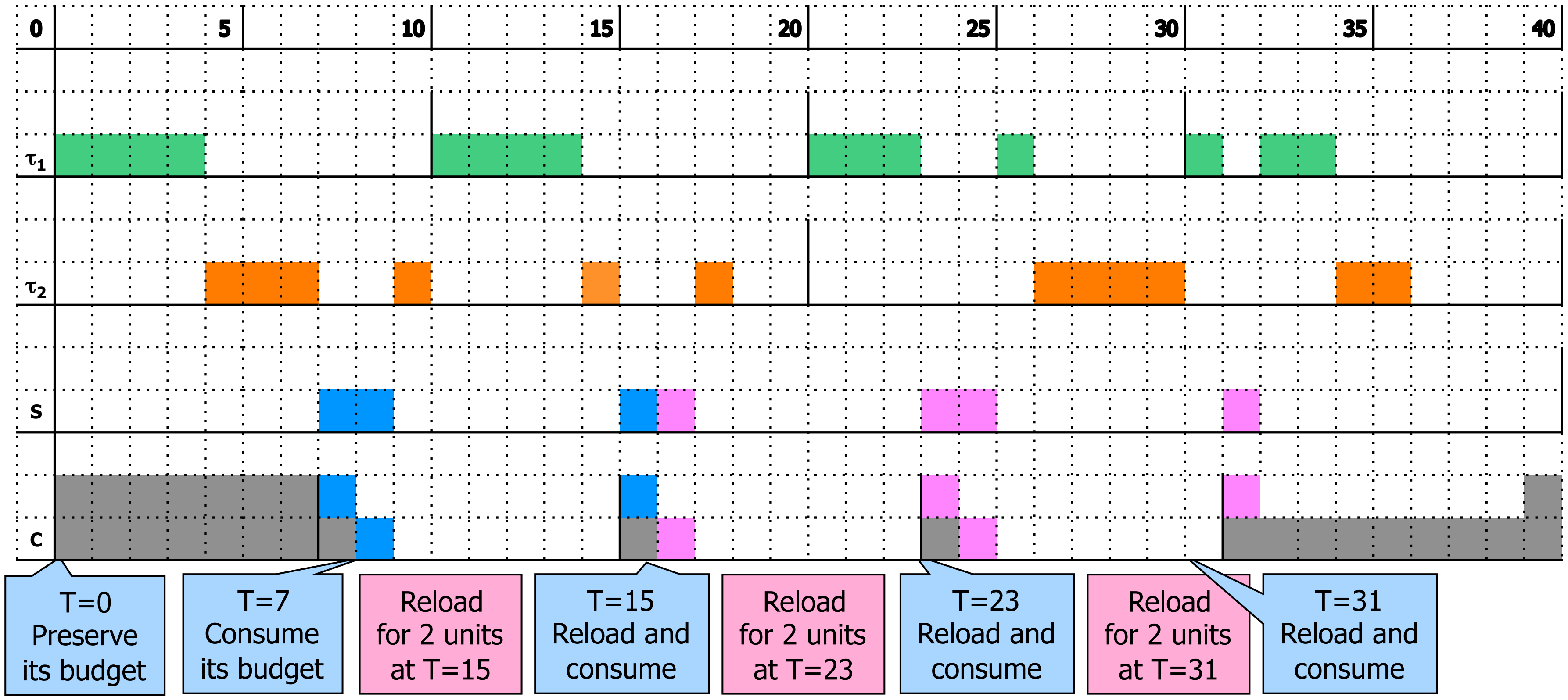
Scheduling aperiodic tasks
Sporadic server

- The aperiodic tasks are processed sequentially by a high priority server
- The server has a budget and a period
- The time consumed to process an aperiodic task is debited on its budget
- The amount of time consumed is credited after a delay of one period
- The server becomes active when an aperiodic task is to be processed and its budget is not exhausted

Scheduling aperiodic tasks

Sporadic server

	Period/Release	Budget	Priority	Utilisation/Response
Aperiodic Task ε_1	7	3		9
Aperiodic Task ε_2	11	4		21
Aperiodic Task τ_1	10	4	2	0,400
Aperiodic Task τ_2	20	6	1	0,300
Sporadic Server S	8	2	3	0,250

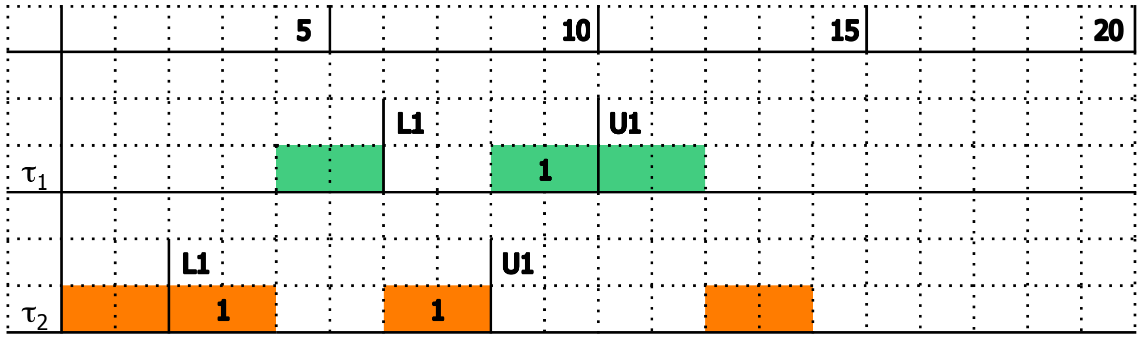


Scheduling aperiodic tasks
Sporadic server

- Advantages
  - Better properties than previous servers
- Disadvantages
  - High complexity compared to the deferred server
- Variant
  - An alternative is to transform the sporadic server into a background server (low priority) when its budget is exhausted in order to take advantage the unused processing time

Sharing resources

Blocking Time (BT) and Scheduling



BT = 2u
Max BT= 4u

- Analogy with the previous scenario (independant tasks)
  - Let B_i be the longest duration of potential blocking of task t_i by a task of lower priority
  - Analogy with a scenario where for the task t_i, the computation time C_i would become $C_i + B_i$
- The goal is to reduce B_i by introducing adequate resource sharing policies

Sharing resources

Including blocking time in scheduling test

- A high priority task can be blocked **directly** by a low priority task because they share a common resource
- A middle priority task can be blocked **indirectly** by a low priority task without sharing a resource because the latter is blocking a high priority task (see priority inheritance later on)
- Condition suffisante d'ordonnancement avec RMS

$$\forall i, 1 \le i \le n, \sum_{j=1}^{j=i} \frac{C_j}{T_j} + \frac{B_i}{T_i} \le n\left(2^{\frac{1}{n}} - 1\right)$$

- Le théorème de la zone critique devient

$$\forall i, 1 \le i \le n, \ \exists\, t \le D_i, W_i(t) = \sum_{j=i}^{i} C_j \left\lceil \frac{t}{T_j} \right\rceil + B_i \le t$$

- Condition suffisante d'ordonnancement avec EDF

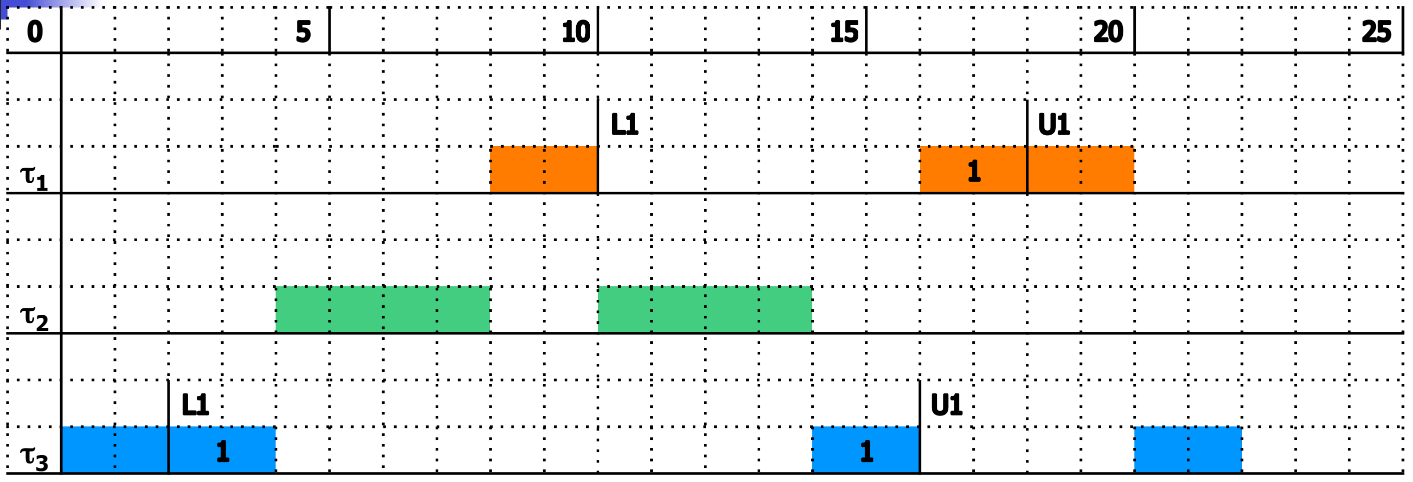
$$\forall i, 1 \le i \le n, \Sigma_{j \le i} C_j / T_j + B_i / T_i \le 1$$

Sharing resources
Priority Inheritance Protocol

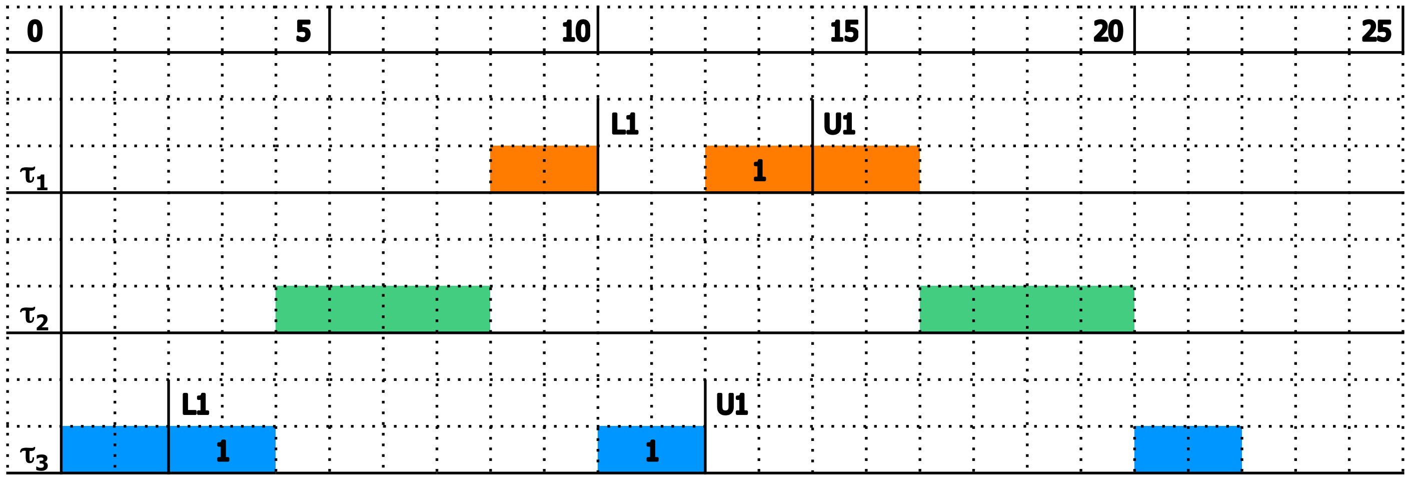
- Problems
  - Preemptive scheduling with fixed priority can lead to a situation of priority inversion
  - A low priority task blocks a high priority task for a time longer than that of its mutual exclusion
  - Difficult to estimate the upper bound of this time
- Solution
  - Priority inheritance raises the priority of the blocking task to the blocked one
  - Once the semaphore is released, the blocking task returns to its initial priority

Priority Inheritance Protocol

Blocking time longer than the expected one



Without PIP
BT = 6u
Max BT = 12



With PIP
BT = 2u
Max BT = 4u

Compute the maximum blocking time (BT) on this example

Priority Inheritance Protocol
Advantages and disadvantages

- Advantages
  - The blocking time is reduced to the use of semaphore by the low priority task
- Disadvantages
  - N resources : N blocking times & priority elevations
  - Deadlocks are possible
  - A low priority task blocks a priority task **only once**
  - A high priority task blocks on a resource **only once**
  - A low task can **indirectly** block a task **without sharing** a resource because of priority inheritance

Priority Inheritance Protocol

Blocking Time Analysis

- τ_3 can be actually blocked by the 3 resources
- Although τ_3 uses only S3, it can be indirectly blocked by τ_4 or τ_5 when they block τ_1 or τ_2 using S1 et S2 because of priority inheritance (τ_4 inherits τ_1 priority)
- A low priority task blocks a priority task **only once**
- A high priority task blocks on a resource **only once**
- The worst case occurs when
  - τ_4 blocks on S1
  - τ_5 blocks on S2
- B3 = max(3+2,3+1,1+2,1+1) = 5

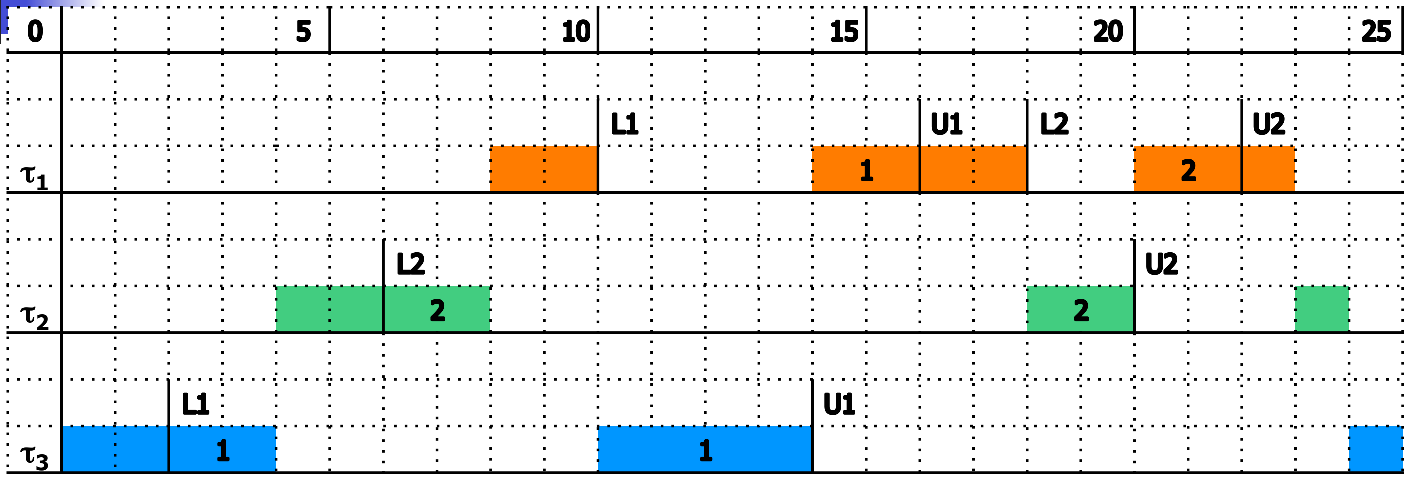
	S1	S2	S3	B
τ_1	2	.	.	3
τ_2	.	1	.	5
τ_3	.	.	2	5
τ_4	3	3	1	2
τ_5	1	2	1	0

Sharing resources
Priority Ceiling Protocol

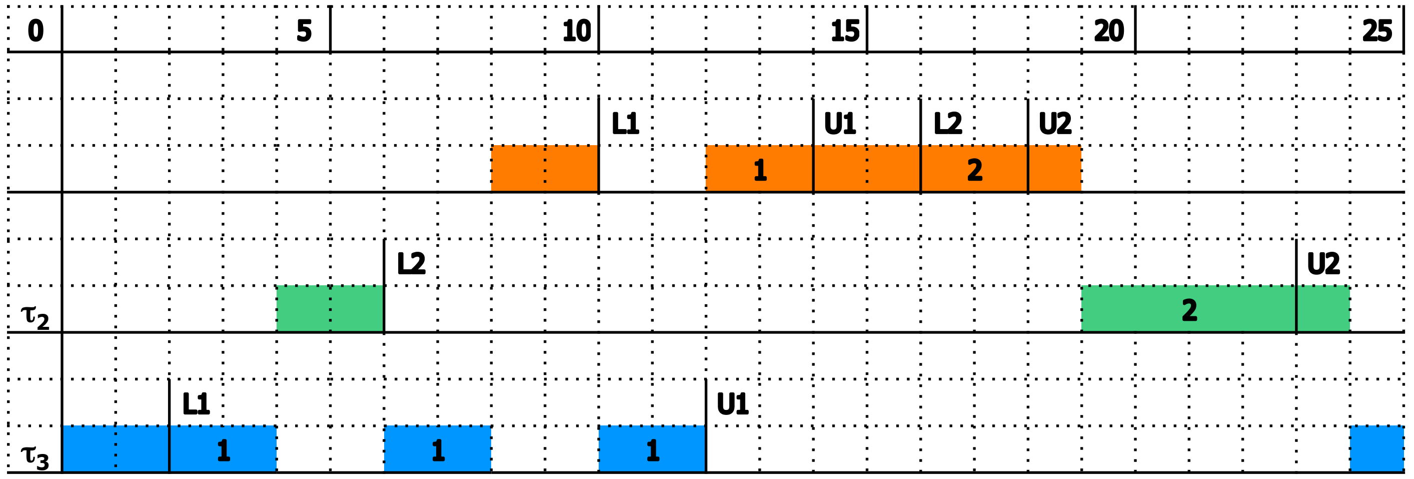
- Problems
  - N resources : N blocking times & priority elevations
  - Deadlocks are possible
- Solution (fixed priorities)
  - The (static) priority ceiling represents the maximum priority of tasks using the resource
  - A task gets access to a resource when its priority is strictly greater than all the priority ceiling of the used resources
  - The blocking task inherits the priority of the highest priority blocked task

Priority Ceiling Protocol

Chained blocking



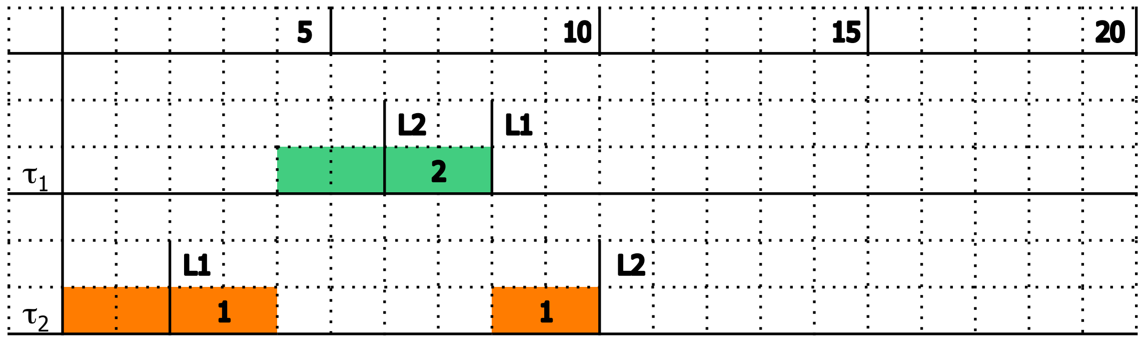
Without PCP
BT = 6u
Max BT = 10u



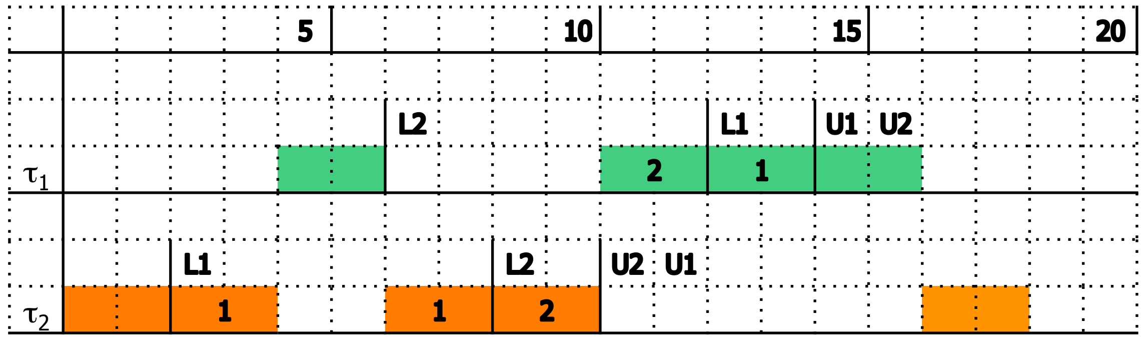
With PCP
BT = 2u
Max BT = 6u

Compute the maximum blocking time (BT) on this example

Priority Ceiling Protocol
Deadlock



Without PCP



With PCP

Priority Ceiling Protocol
Advantages and disadvantages

- Advantages
  - No chained blocking time
  - The task is blocked almost once whatever the number of shared resources
  - No deadlock
- Disadvantages
  - Implementation complexity
  - Multiple priority elevations

Priority Ceiling Protocol
Analysis of blocking time

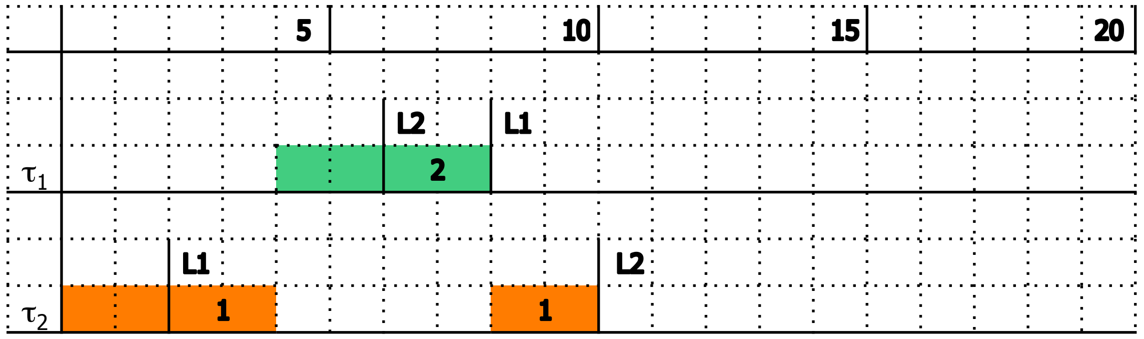
- A low priority task blocks a priority task **only once**
- A high priority task blocks on a resource **only once**
- A low task can **indirectly** block a task **without sharing** a resource because of priority inheritance
- With PCP, a task can be blocked by a lower priority task only once and on a single resource

	S1	S2	S3	B
τ_1	2	.	.	3
τ_2	.	1	.	3
τ_3	.	.	2	3
τ_4	3	3	1	2
τ_5	1	2	1	0

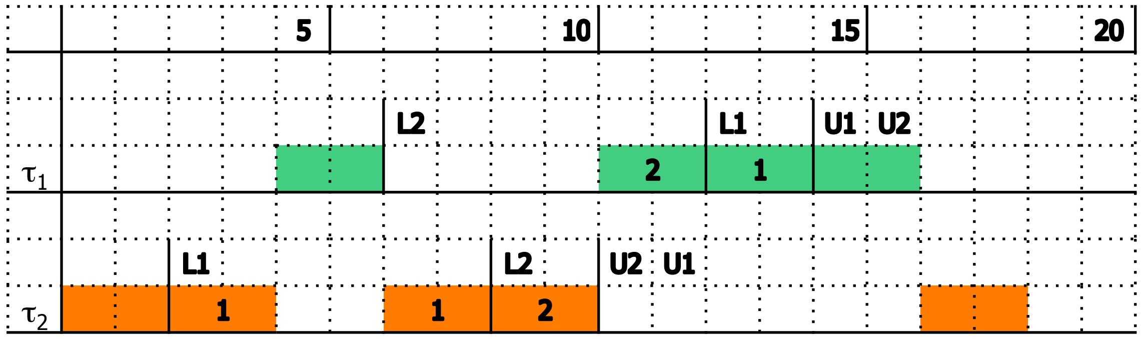
Sharing resources
Immediate Priority Ceiling Protocol

- Problems
  - PCP implementation complexity
  - PCP multiple priority changes
- Solution
  - The (static) priority ceiling represents the maximum priority of the tasks that use it
  - When a task gets access to a resource, it inherits (immediately) a priority strictly greater than the priority ceiling

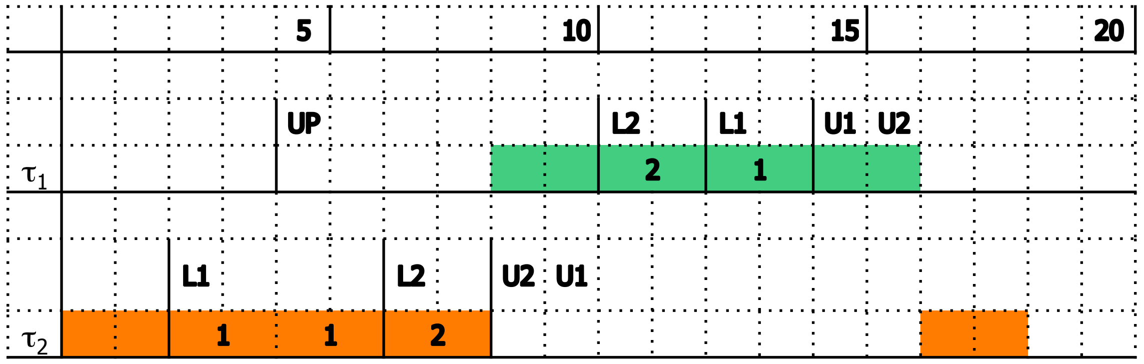
Immediate Priority Ceiling Protocol
Deadlock



PIP



PCP



IPCP

Immediate Priority Ceiling Protocol
Advantages and disadvantages

- Avantages
  - Less complex than PCP
- Disadvantages
  - IPCP (and PCP) relies on fixed priority scheduling

Sharing Resources
Stack Resource Protocol

- Problem
  - IPCP or PCP rely on fixed priorities
- Solution
  - Preemption level replaces priority
  - The preemption level of a task is for RMS its priority, for EDF the opposite of its deadline
  - The preemption level of a resource is the maximum preemption level of tasks using it
  - The preemption level of the system is the maximum preemption level of the resources used

Stack Resource Protocol
Description

- A task runs if it is ready with the highest priority and its preemption level higher than the system
- SRP with RMS behaves like IPCP
- A task is blocked at most once
- Blocking time is the maximum blocking time of critical sections of resources used by the task

Sharing Resources

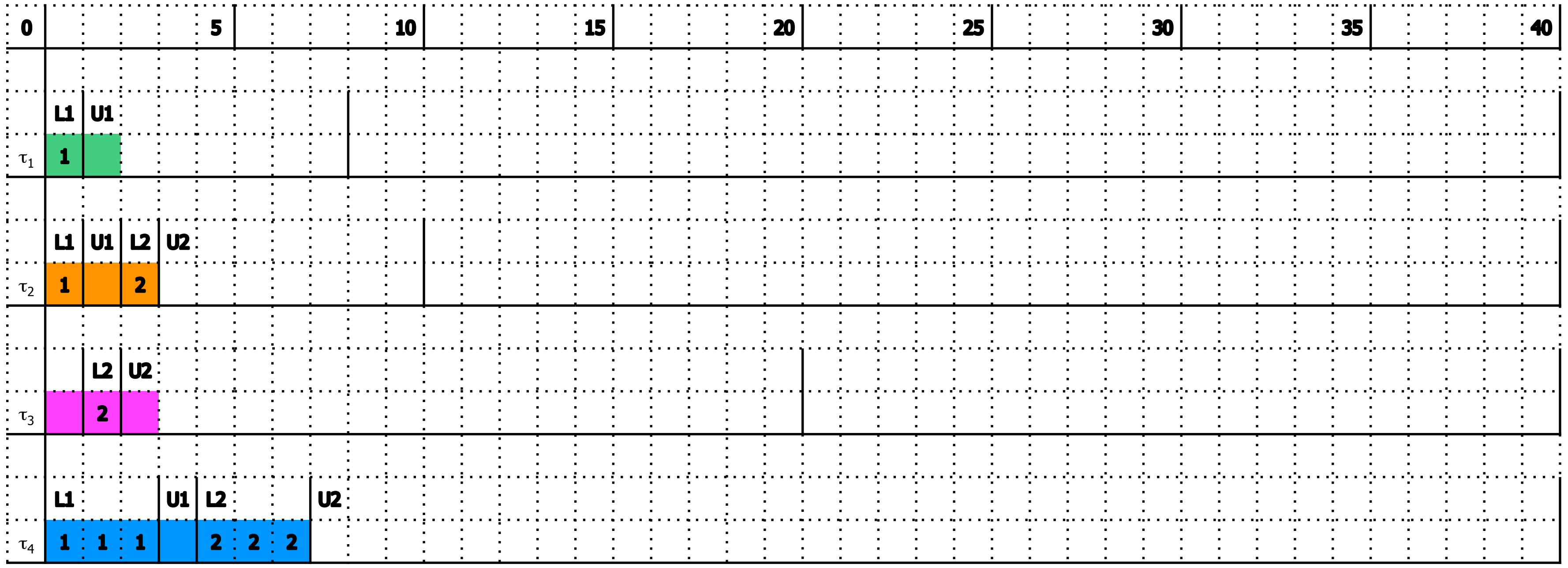
Stack Resource Protocol

- Advantages
  - Less complexity compared to PCP
  - SRP reduces the number of pre-emptions compared to PCP
  - No need for priority inheritance
- Disadvantages
  - Blocking time is the longest blocking time that PCP would have produced

Comparaison PIP-EDF et SRP-EDF

Example of scenario

- Let schedule the previously described task set with a sequence of critical sections as follows



Laurent Pautet

Comparison PIP-EDF and SRP-EDF

Schedulability analysis with PIP-EDF

	C	**T**	**U**	**R1**	**R2**	**B**
τ_1	2	8	0.25	1	0	3
τ_2	3	10	0.3	2	1	4
τ_3	3	20	0.15	0	1	3
τ_4	7	40	0.175	3	3	0

We check the sufficient schedulability condition for EDF schedulability
$\Sigma_{j \leq i} C_j/T_j + B_i/T_i \leq 1$ for each subset of tasks 1 .. i

$C_1/T_1 + B_1/T_1 = 2/8 + 3/8 = 25/40 \leq 1$

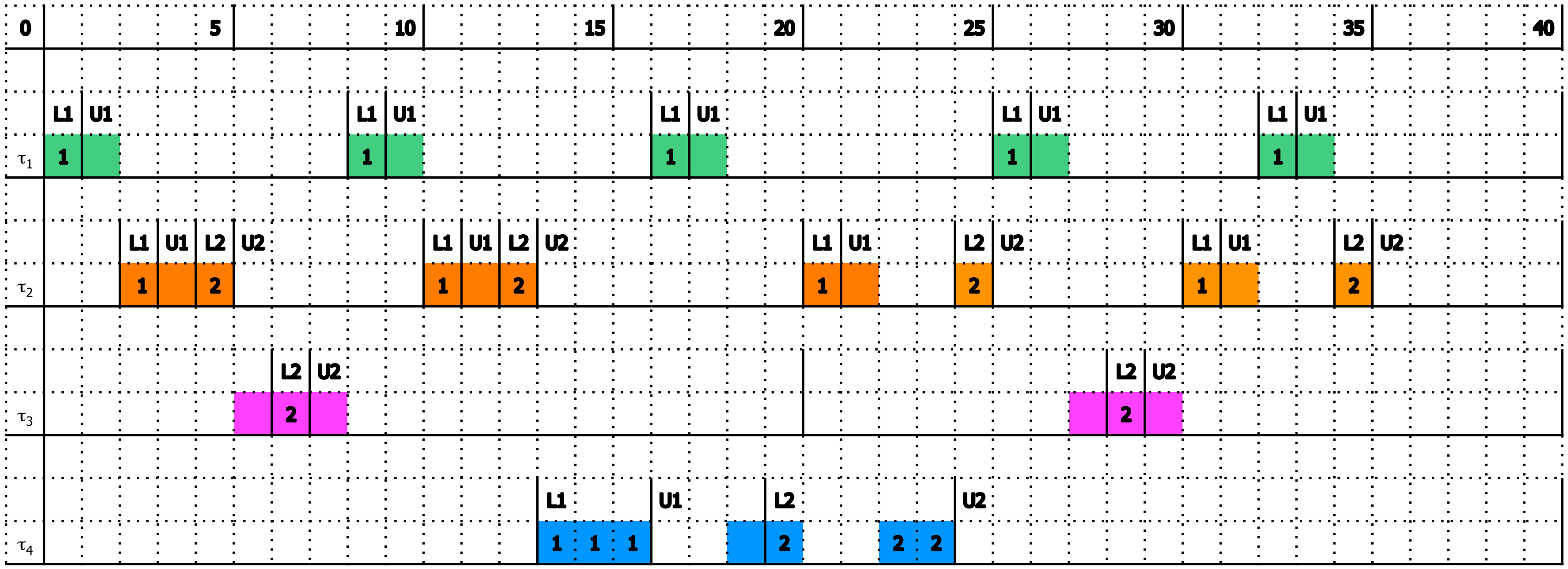
$C_1/T_1 + C_2/T_2 + B_2/T_2 = 2/8 + 3/10 + 4/10 = 38/40 \leq 1$

$C_1/T_1 + C_2/T_2 + C_3/T_3 + B_3/T_3 = 2/8 + 3/10 + 3/20 + 3/20 = 34/40 \leq 1$

$C_1/T_1 + C_2/T_2 + C_3/T_3 + C_4/T_4 + B_4/T_4 = 2/8 + 3/10 + 3/20 + 7/40 = 35/40 \leq 1$

Comparison PIP-EDF and SRP-EDF

Possible scheduling with PIP-EDF



Comparison PIP-EDF and SRP-EDF

Schedulability analysis with SRP-EDF

	C	T	U	R1	R2	B	π
τ_1	2	8	0.25	1	0	3	4
τ_2	3	10	0.3	2	1	3	3
τ_3	3	20	0.15	0	1	3	2
τ_4	7	40	0.175	3	3	0	1

We check the sufficient schedulability condition for EDF schedulability
$\Sigma_{j \leq i} C_j/T_j + B_i/T_i \leq 1$ for each subset of tasks 1 .. i

$C_1/T_1 + B_1/T_1 = 2/8 + 3/8 = 25/40 \leq 1$

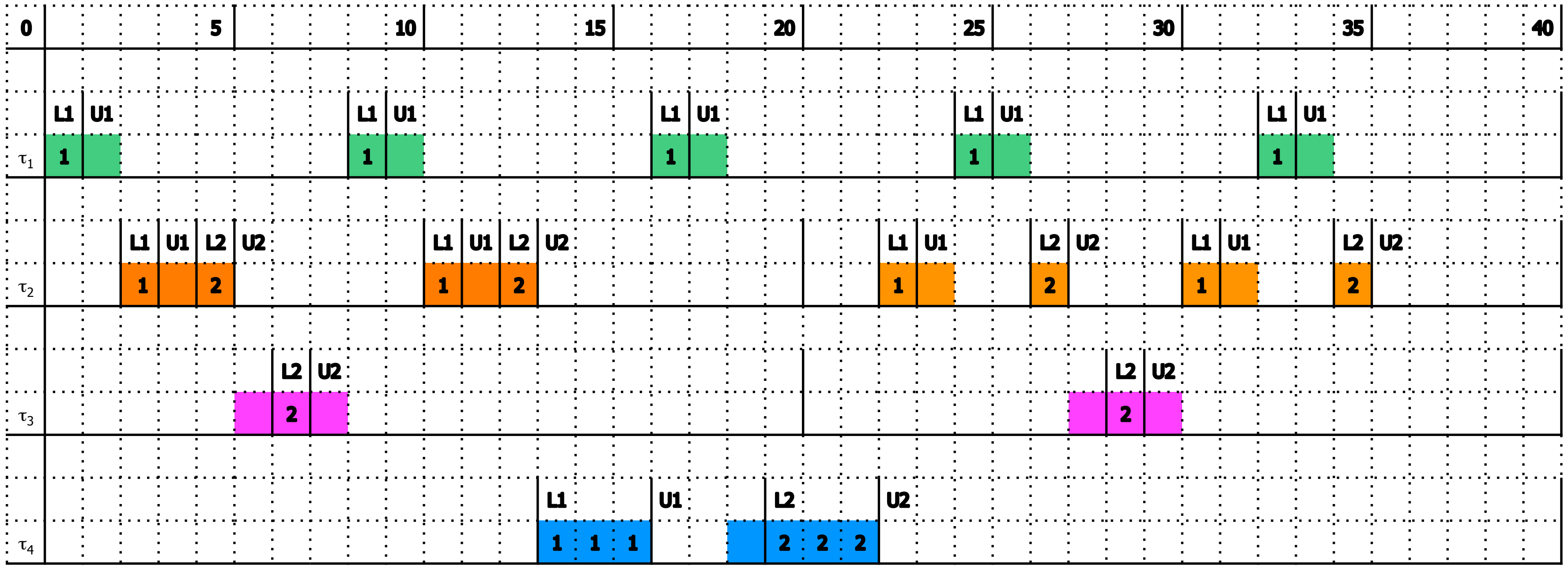
$C_1/T_1 + C_2/T_2 + B_2/T_2 = 2/8 + 3/10 + 3/10 = 34/40 \leq 1$

$C_1/T_1 + C_2/T_2 + C_3/T_3 + B_3/T_3 = 2/8 + 3/10 + 3/20 + 3/20 = 34/40 \leq 1$

$C_1/T_1 + C_2/T_2 + C_3/T_3 + C_4/T_4 + B_4/T_4 = 2/8 + 3/10 + 3/20 + 7/40 = 35/40 \leq 1$

Comparison PIP-EDF and SRP-EDF

Possible scheduling with SRP-EDF



Conclusions

- To satisfy the time constraints in hard real time systems, the first concern must be the predetermination of the system behavior.
- Offline static scheduling is most often the only practical way to achieve predictable behavior in a complex system

Lectures

- G. Buttazzo. Hard Real-Time Computing Systems: Predictable Scheduling Algorithms and Applications Kluwer academic Publishers, Boston, 1997.
- C. Liu and J. Layland. Scheduling Algorithms for Multiprogramming in a Hard Real-time Environment. Journal of the ACM, 20(1):46--61, Jan. 1973.
- L. Sha, R. Rajkumar and J. Lehoczky, "*Priority Inheritance Protocol*": An Approach to real-time synchronisation," IEEE Transaction on Computers 39(9), pp.1175-1185, 1993.
- Min-Ih Chen and Kwei-Jay Lin. Dynamic priority ceilings: A concurrency control protocol for real-time systems. Journal of Real-Time Systems, 2:325--346, 1990.
- T. Baker. Stack-based scheduling of real-time processes. Real-Time Systems, 3(1):67--99, March 1991.
- B. Sprunt, L. Sha, and J. P. Lehoczky, "Aperiodic scheduling for hard real-time system". The Journal of Real-Time Systems, 1, pp. 27-60, 1989.