Real Time Scheduling

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Main goals of the module

- A general overview of how real-time applications can be executed
  - Real-time scheduling
    - Why is it different from non real-time scheduling?
    - What are the features that have to be considered?
    - What are the real-time scheduling algorithms?
    - How can we be sure that it works?
    - ...
  - Real-time operating system
    - Illustration on OSEK

A definition of real-time

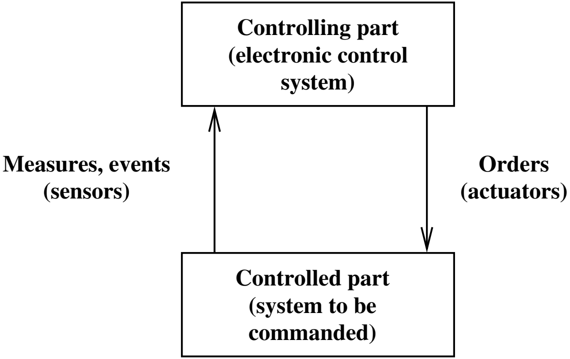
A real-time system is able, first to read all incoming data before they become useless, second to give an appropriate timely reaction

- Temporal correctness : correct result after the deadline = bad (useless) result
- The delay highly depends on the application
- ⇒ real-time is not real fast
- Two main classes of real-time systems :
  - Hard real-time : a missed deadline can have catastrophic consequences ⇒ strict timing constraints
  - Soft real-time : some (not frequent) missed deadlines can be tolerated (⇒ often a predefined rate of allowed missed deadlines)
- Mandatory to guarantee the functionnal behavior as well as the temporal behavior of the system

Application domains

- Factory automation
  - Control/command of a production line
  - Control process
  - ...
- Embedded systems
  - Avionics (flight control, ...)
  - Automotive
  - Space
  - Robotics
  - Home appliance
  - Phones
  - ...

Architecture overview



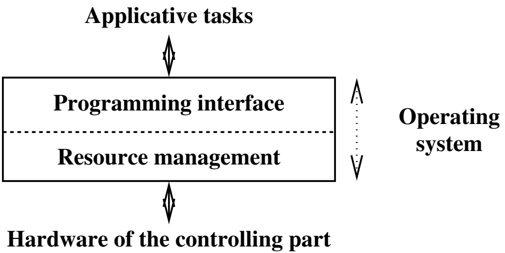
- Inputs and outputs are very important
- Hardware architecture of the controlling part : programmable logic controller (Schneider Electric, Siemens), ad hoc circuit, FPGA, micro-controller, micro-processor
- The controlling part can be centralised or distributed ⇒ industrial networks, fieldbuses (CAN, FIP, ...)

Processing overview

For each event of the controlled part **do**
  Read the data from the controlled part
  Compute the new system state
  Send the orders associated to this state
EndFor

- Synchronous behavior (time driven) : data are read at predefined instants $\Rightarrow$ periodic tasks
- Asynchronous behavior (event driven) : immediate answer to events $\Rightarrow$ non periodic tasks
- Hybrid behavior : mix of periodic and aperiodic tasks

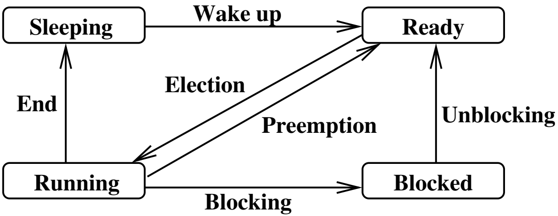
Software architecture



- More or less elaborated operating system, from nothing to a multitask operating system with graphical facilities
- Multitask operating system:
  - Scheduler to manage processor sharing
  - Control access mechanisms in order to share the other resources
  - Synchronisation and communication mechanisms in order to manage global consistency

Scheduler

- State diagram of a task



- Scheduler execution when an interrupt occurs:
  - The context of running task is saved and this task moves to ready state
  - One ready task is elected
  - The context of this elected task is restored
- Scheduling algorithm: activation time of the scheduler + election policy

Operating system

- General purpose operating system:
  - Goals:
    - optimisation of resource utilisation
    - minimisation of average response time
  - Features:
    - round robin scheduler
    - complex memory hierarchy
  - Examples : Linux, Solaris, Windows xx
- Real-time operating system:
  - Goals:
    - predictable delays
    - reliability
  - Features:
    - priority based preemptive scheduling
    - limited and controlled memory hierarchy
    - execution of system primitives in bounded time
  - Examples: Tornado, LynxOS, QNX, RTAI, OSEK, TinyOS

Implementation of a real time system

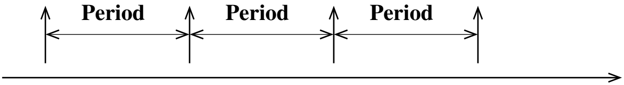
- Cross-development $\Rightarrow$ two machines:
  - host machine:
    - application development and debug
    - code generation for the target machine $\Rightarrow$ cross-compilation
    - this code is loaded on the target machine
    - no host machine at run-time
  - target machine:
    - application execution
- Native development $\Rightarrow$ one single machine:
  - application development and debug
  - application execution
  - Parts of the operating system can be removed at run-timle

A real-time application in this module

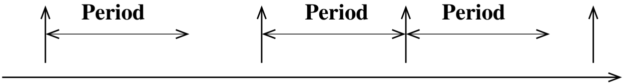
- A set of tasks (pieces of codes)
  - Can be fully independant
  - Can share resources, e.g. variables
  - Can communicate, synchronise, have precedence constraints
- We are only interested in the temporal correctness, not the functionnal one
- Each task is modelled by temporal values
- The set of tasks can be executed on a single core or on a multi-core or a multi-processor

Real-time tasks

- A task: a recurrent execution of a job.
- Request can be
  - Periodic: constant duration between consecutive releases



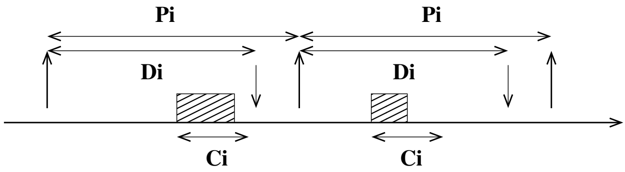
  - Sporadic: variable duration between consecutive releases, with a known minimum



  - Aperiodic: variable duration between consecutive releases.

Non concrete real-time task

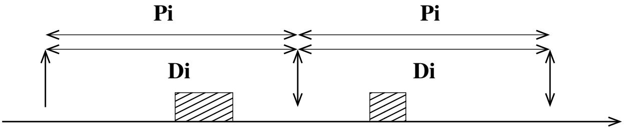
- Defined by the following features
  - A Worst-Case Execution Time (WCET): C_i
    - Safe upper bound on the execution time of one job of the task
  - A release period: P_i
    - (Minimum) duration between consecutive job releases of the task
  - A relative deadline D_i
    - Maximum allowed response time for each job of the task



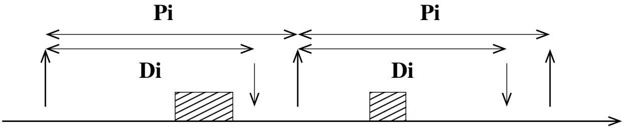
- The first release time of the task is unknown $\Rightarrow$ non concrete task

Non concrete real-time task

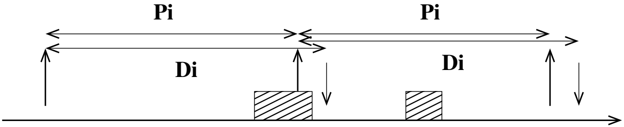
- Relationship between deadline and period
  - Implicit deadline ($D_i = P_i$): the simplest case



  - Constrained deadline ($D_i \leq P_i$): the intermediate case

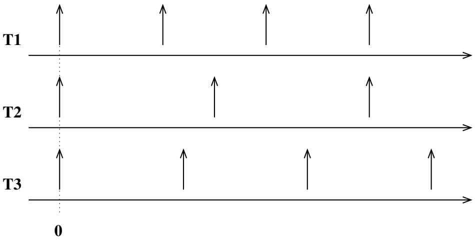


  - Arbitrary deadline (D_i can be greater than P_i): the most complex case

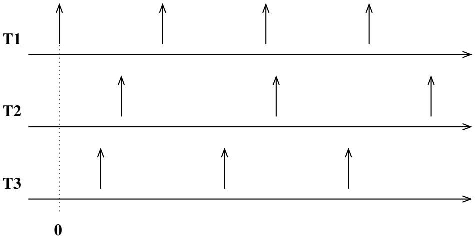


Concrete real-time task

- The first release time r_i of the task is known
- Synchronous system: all the tasks have the same first release time (0)

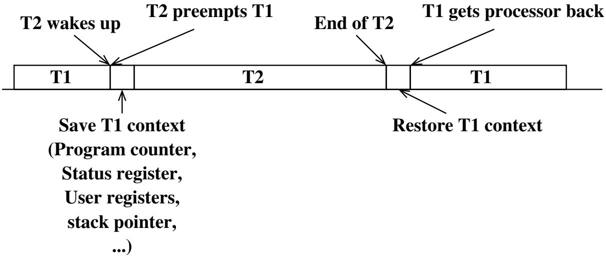


- Asynchronous system: tasks have different release times



Preemptive vs non preemptive tasks

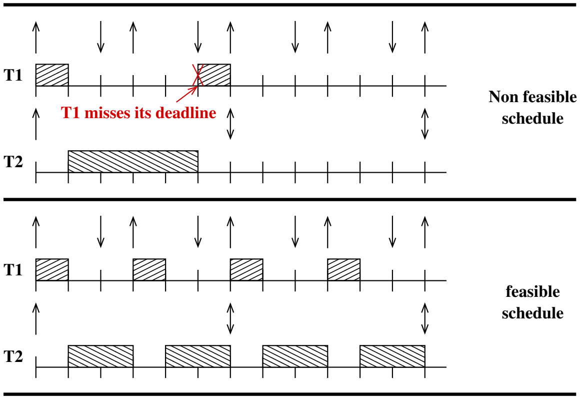
- What is a preemption?
  - the execution of a task is suspended at a point in its execution and will be resumed later at the same point
  - Pros
    - ★ An urgent task can preempt a non-urgent time consuming one
  - Cons
    - ★ context switch overhead



  - Sometimes limited preemption: only possible at given point in the task

Real-time Scheduling

- Multitask system $\Rightarrow$ tasks have to be scheduled
- Real time constraints (especially deadlines) have to be respected.
- Feasible schedule: the worst-case response time of every job of every task is not greater than the task's relative deadline
- Ex: T_1 (r_1: 0, C_1: 1, D_1: 2, P_1: 3), T_2 (r_2: 0, C_2: 4, D_2: 6, P_2: 6)

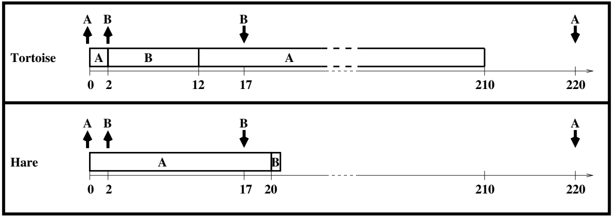


The tortoise and the hare (G. Le Lann)

- Two processors $Pr1$ (hare) et $Pr2$ (tortoise)
  - $Pr1$ 10 times faster than $Pr2$
  - $Pr1$: non preemptive scheduling *First Come First Served*
  - $P2$: preemptive scheduling *Earliest Deadline First*
- Two tasks

	C^{hare}	$C^{tortoise}$	Deadline	Release
A	20	200	220	0
B	1	10	15	2

- B respects its deadline on $P2$ but not on $P1$



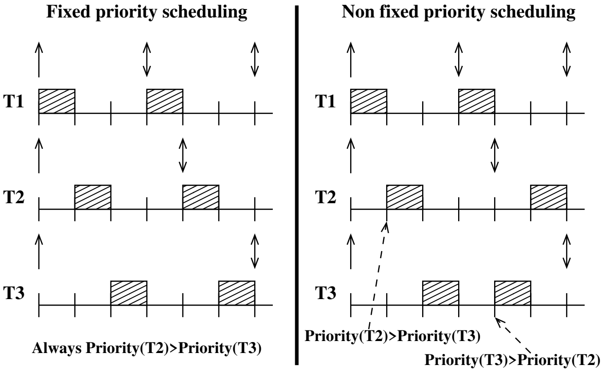
- Choosing the right scheduling policy is essential

Real-Time Scheduling

- Many work has been devoted to real-time scheduling problems
  - Scheduling policies
  - Feasibility tests
  - Complex task models
  - ...
- Feasibility problem is NP-hard, except for basic cases $\Rightarrow$
  - Exact test at exponential cost
  - Pessimistic test at polynomial or pseudo-polynomial cost
- Scheduling algorithms
  - On-line scheduling policies (priority driven)
    - Knowledge of the active jobs only
    - Simple scheduling policy in order to choose the highest priority ready job at specific instants (ends of job execution and/or job releases and/or ...)
  - Off-line scheduling policies (time driven)
    - Knowledge of the past and the future
    - off-line creation of a periodic feasible schedule, using meta-heuristics, branch and bound, ...

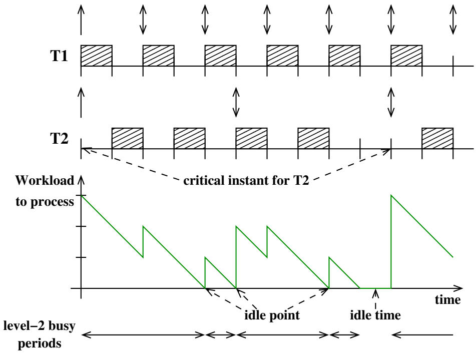
On-line fixed priority scheduling

- We mainly address on-line scheduling in this module
  - At any time, each ready job is assigned the priority of its task
- Task priorities are fixed off-line and don't change dynamically
- Ex: T_1 (r_1: 0, C_1: 1, D_1: 3, P_1: 3), T_2 (r_2: 0, C_2: 1, D_2: 4, P_2: 4), T_3 (r_3: 0, C_3: 2, D_3: 6, P_3: 6)



Critical instant and busy period

- We assume that tasks are ordered by priority level
  - Priority (T_1) $>$ Priority (T_2) $<$ Priority (T_3) $> \dots$
- Crtitical instant for a task T_i: T_i is released simultaneously with all the higher priority tasks
- Level-i busy period: time period where the CPU is kept busy by tasks whose priority is higher or equal to priority of T_i
- Ex: T_1 (r_1: 0, C_1: 1, D_1: 2, P_1: 2), T_2 (r_2: 0, C_2: 2, D_2: 5, P_2: 5)



Results based on critical instant and busy period (1)

- A first theorem: the worst-case response time for a task T_i occurs during the longest level-i busy period
- A second theorem: the longest level-i busy period is initiated by the critical instant for task T_i
- Benefit of these two theorems: the worst-case is known for non concrete and synchronous task systems
  - build the first level-i busy period starting from the critical instant for T_i
  - claim the worst response time of T_i jobs in this busy period as the worst-case response time for T_i
- A busy period always ends iff the processor is not overloaded (its utilization ratio U doesn't exceed 1):

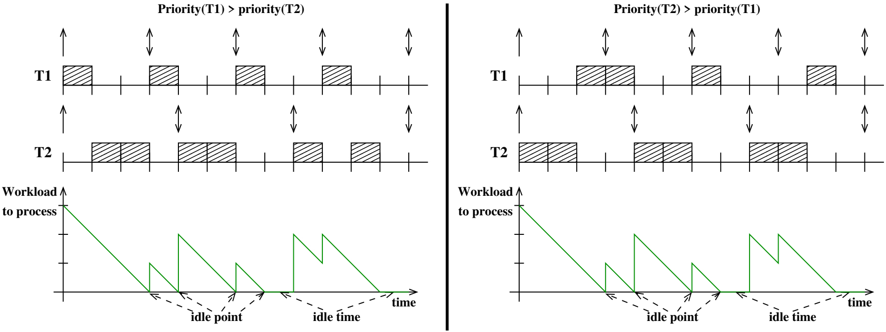
$$U = \sum_{i=1}^{n} \frac{C_i}{P_i} \leq 1$$

  - Synchronous task system $\Rightarrow$ idle time during the least common multiple of the periods ($LCM_{1 \leq i \leq n} T_i$)

$$LCM_{1 \leq i \leq n} T_i \times (1 - U)$$

Results based on critical instant and busy period (2)

- Idle times and instants are the same for any conservative scheduling algorithm



- Problem: building the level-i busy period time unit per time unit is exponential in time
  - When periods are co-prime numbers, we have

$$LCM_{1 \leq i \leq n} T_i = T_1 \times \ldots \times T_n$$

Results based on critical instant and busy period (3)

- Specific case when $D_i \leq P_i$ and preemptive scheduling
  - If there are two jobs of T_i in a level-i busy period, then T_i misses its deadline $\Rightarrow$ pseudo-polynomial test
- Find the smallest fixed point $R_i^{(*)}$ of the equation:

$$\begin{array}{rcl} R_i^{(0)} & = & C_i \\ R_i^{(n+1)} & = & C_i + \sum_{j \in hp(i)} \lceil \frac{R_i^{(n)}}{P_j} \rceil \times C_j \end{array}$$

- Ex: T_1 (r_1: 0, C_1: 1, D_1: 2, P_1: 2), T_2 (r_2: 0, C_2: 2, D_2: 5, P_2: 5)

$$\begin{array}{rclclcl} R_2^{(0)} & = & C_2 & = & 2 & & \\ R_2^{(1)} & = & C_2 + \lceil \frac{R_2^{(0)}}{P_1} \rceil \times C_1 & = & 2 + \lceil \frac{2}{2} \rceil \times 1 & = & 3 \\ R_2^{(2)} & = & C_2 + \lceil \frac{R_2^{(1)}}{P_1} \rceil \times C_1 & = & 2 + \lceil \frac{3}{2} \rceil \times 1 & = & 4 \\ R_2^{(3)} & = & C_2 + \lceil \frac{R_2^{(2)}}{P_1} \rceil \times C_1 & = & 2 + \lceil \frac{4}{2} \rceil \times 1 & = & 4 \end{array}$$

Results based on critical instant and busy period (4)

- What if $D_i > P_i$?
  - $R_i^{(*)} \leq P_i \Rightarrow$ no difference with $D_i \leq P_i$
  - $R_i^{(*)} > P_i \Rightarrow$ a second job of T_i has been released and the busy period is not over
  - The response time of this job has to be computed
  - General case: k jobs have to be tested, until a job finishes execution before the release of the following job
  - Process: starting with $k = 1$, compute the latest possible ending time $R_i^{(*)}(k)$ of k^{th} job of T_i until $R_i^{(*)}(k) \leq k \times P_i$

$$
\begin{aligned}
R_i^{(0)}(k) &= k \times C_i \\
R_i^{(n+1)}(k) &= k \times C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i^{(n)}(k)}{T_j} \right\rceil \times C_j
\end{aligned}
$$

Ex: $T_1\ (C_1{:}26, D_1 = P_1{:}70), T_2\ (C_2{:}62, D_2{:}118, P_2{:}100)$

T_1: $R_1^{(0)}(1) = C_1 = 26$

T_1: $R_1^{(1)}(1) = C_1 = 26 = R_1^{(*)}(1)$

T_2: $R_2^{(0)}(1) = C_2 = 62$

T_2: $R_2^{(1)}(1) = C_2 + \lceil \frac{R_2^{(0)}(1)}{T_1} \rceil \times C_1 = 62 + \lceil \frac{62}{70} \rceil \times 26 = 88$

T_2: $R_2^{(2)}(1) = C_2 + \lceil \frac{R_2^{(1)}(1)}{T_1} \rceil \times C_1 = 62 + \lceil \frac{88}{70} \rceil \times 26 = 114$

T_2: $R_2^{(3)}(1) = C_2 + \lceil \frac{R_2^{(2)}(1)}{T_1} \rceil \times C_1 = 62 + \lceil \frac{114}{70} \rceil \times 26 = 114 = R_2^{(*)}(1)$

T_2: $R_2^{(0)}(2) = 2 \times C_2 = 124$

...

T_2: $R_2^{(2)}(2) = C_2 + \lceil \frac{R_2^{(1)}(2)}{T_1} \rceil \times C_1 = 124 + \lceil \frac{176}{70} \rceil \times 26 = 202$

T_2: $R_2^{(3)}(2) = C_2 + \lceil \frac{R_2^{(2)}(2)}{T_1} \rceil \times C_1 = 124 + \lceil \frac{202}{70} \rceil \times 26 = 202 = R_2^{(*)}(2)$

$\Rightarrow$ Response time of T_2 second job: 102

Ex: T_1 $(C_1{:}26, D_1 = P_1{:}70), T_2$ $(C_2{:}62, D_2{:}118, P_2{:}100)$

- $R_2^{(*)}(3) = 316$
  $\Rightarrow$ Response time of T_2 second job: 116
- $R_2^{(*)}(4) = 404$
  $\Rightarrow$ Response time of T_2 second job: 104
- $R_2^{(*)}(5) = 518$
  $\Rightarrow$ Response time of T_2 second job: 118
- $R_2^{(*)}(6) = 606$
  $\Rightarrow$ Response time of T_2 second job: 106
- $R_2^{(*)}(7) = 694$
  $\Rightarrow$ Response time of T_2 second job: 94

Rate Monotonic

- Basic algorithm for periodic tasks with implicit deadlines
- The smaller the period of a task, the higher its priority
- Optimal algorithm within the class of fixed priority scheduling algorithms for independant periodic tasks with implicit deadlines
- Sufficient test for the schedulability of a configuration including n tasks:

$$U = \sum_{i=1}^{n} \frac{C_i}{P_i} \leq n \times (2^{\frac{1}{n}} - 1)$$

n	1	2	3	5	10	grand
bound	1	0.83	0.78	0.74	0.72	0.69

- Necessary test for the schedulability of a configuration including n tasks:

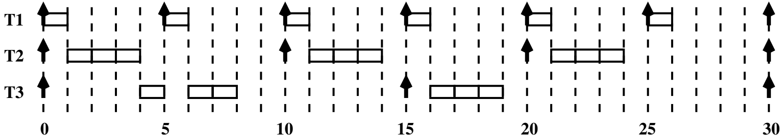
$$U \leq 1$$

Example with Rate Monotonic

- Task features

	WCET	Deadline	Period
T_1	1	5	5
T_2	3	10	10
T_3	3	15	15

- Scheduling sequence in the case of simultaneous releases



Rate Monotonic: worst-case response time computation

- Task features

	WCET	Deadline	Period
T_1	1	5	5
T_2	3	10	10
T_3	3	15	15

- Response time analysis

	T_1	T_2	T_3
t_0	$C_1 = 1$	$C_1 + C_2 = 4$	$C_1 + C_2 + C_3 = 7$
t_1	$C_1 \left\lceil \frac{t_0}{P_1} \right\rceil = 1$	$C_1 \left\lceil \frac{t_0}{P_1} \right\rceil + C_2 \left\lceil \frac{t_0}{P_2} \right\rceil = 4$	$C_1 \left\lceil \frac{t_0}{P_1} \right\rceil + C_2 \left\lceil \frac{t_0}{P_2} \right\rceil + C_3 \left\lceil \frac{t_0}{P_3} \right\rceil = 8$
t_2			$C_1 \left\lceil \frac{t_1}{P_1} \right\rceil + C_2 \left\lceil \frac{t_1}{P_2} \right\rceil + C_3 \left\lceil \frac{t_1}{P_3} \right\rceil = 8$
	OK	OK	OK

Rate Monotonic: Exercice

- Task features

	WCET	Deadline	Period
T_1	2	5	5
T_2	4	10	10
T_3	3	18	18

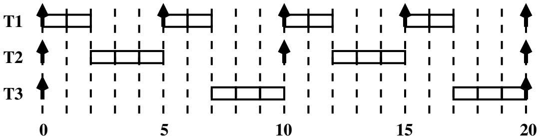
- Response time analysis for T_3?

A specific case: harmonic periods

- The suufficient and necessary condition becomes $U \leq 1$
- Task features

	WCET	Deadline	Period
T_1	2	5	5
T_2	3	10	10
T_3	6	20	20

- Scheduling sequence in the synchronous case

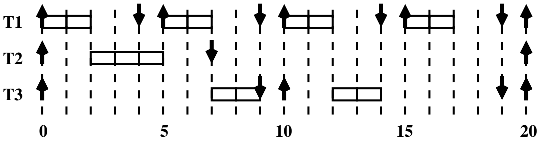


Deadline Monotonic

- In the case of constrained or arbitrary deadlines
- The smaller the deadline of a task, the higher its priority
- Example with the following task features

	WCET	Deadline	Period
T_1	2	4	5
T_2	3	7	20
T_3	2	9	10

- Scheduling case in the synchronous case

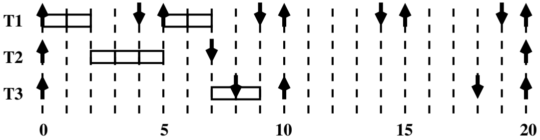


Deadline Monotonic: another example

- Task features

	WCET	Deadline	Period
T_1	2	4	5
T_2	3	7	20
T_3	2	8	10

- Scheduling sequence in the synchronous case

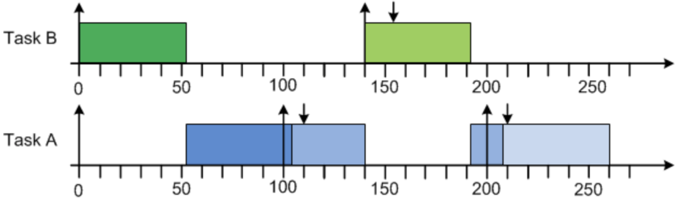


Non optimality of Deadline monotonic

- Deadline Monotonic is not an optimal fixed priority assignment
- Missed deadline if A has the highest priority

- Tasks with arbitrary deadlines

Task	Execution Time	Deadline	Period
A	52	110	100
B	52	154	140



Dynamic priority algorithms

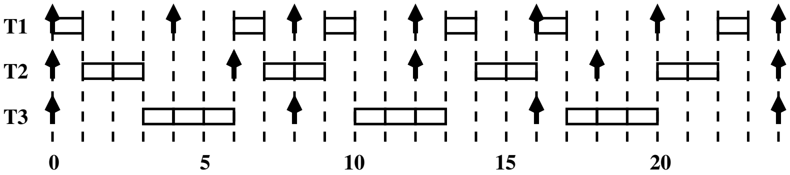
- The priority of a given task is not always the same
- Two classes of solutions
  - The priority of a job is fixed ⇒ job-level fixed priority scheduling
    - Earliest Deadline first
  - The priority of a job may vary with time ⇒ job-level dynamic priority scheduling
    - Least-Laxity First
    - p-fair
  - Focus on Earliest Deadline First
    - The most important (and analysed) dynamic priority algorithm
    - The priority of a job is inversely proportional to its absolute deadline
    - Two jobs with the same absolute deadline ⇒ random choice (doesn't matter

Earliest Deadline First: example

- Task features

	WCET	Deadline	Period
T_1	1	4	4
T_2	2	6	6
T_3	3	8	8

- Scheduling sequence in the synchronous case



Earliest Deadline First vs Fixed Priority

- Some advantages of EDF
  - EDF can schedule all task sets that can be scheduled by Fixed Priority, but not vice versa
  - There is no need to define priorities in EDF
    - Assuming Fixed Priority, basic priority assignment (e.g. Deadline Monotonic) are not optimal
  - EDF often has less preemptions
- Some disadvantages of EDF
  - EDF is not provided in many commercial RTOS
  - More implementation overhead with EDF
  - EDF is less controllable
    - Reduce the response time of a task with Fixed Priority $\Rightarrow$ increase its priority, nothing can be done with EDF

Schedulability analysis with EDF

- Task set with implicit deadlines for all the tasks
  - Necessary and sufficient condition

$$U = \sum_{i=1}^{N} \frac{C_i}{T_i} \leq 1$$

  - $\Rightarrow$ In this situation, EDF is obviously optimal
- Task sets with constrained or arbitrary deadlines
  - EDF is still optimal
  - The schedulability analysis becomes more complex
  - Based on the demand function (df)
    - ★ The demand function for a task T_i is a function of an interval $[t_1, t_2]$ that gives the amount of T_i computation that must be completed in $[t_1, t_2]$ for T_i to be schedulable

$$df_i(t_1, t_2) = \sum_{a_{ij} \geq t_1, d_{ij} \leq t_2} C_{ij}$$

    - ★ For the entire task set

$$df(t_1, t_2) = \sum_{i=1}^{N} df_i(t_1, t_2)$$

Schedulability analysis with EDF

- For a set of synchronous periodic tasks, the worst case demand is found for intervals starting at 0

$$\forall t_1, t_2 > t_1 \; df(t_1, t_2) \leq df(0, t_2 - t_1)$$

- Demand bound function

$$dbf(L) = \max_t (df(t, t+L) = df(0, L)$$

- Impossible to compute the dbf for all possible values of L
- For a set of synchronous periodic tasks, only consider one hyperperiod H and only consider task deadlines within H
  - A synchronous periodic task set TS is schedulable by EDF iff

$$\forall L \in dead(TS) \; dbf(L) \leq L$$

    Where $dead(TS)$ is the set of deadlines in $[0, H]$

- The synchronous case is a worst-case of any asynchronous one

Schedulability analysis with EDF

- Example with the following task features

	WCET	Deadline	Period
T_1	1	4	4
T_2	2	6	6
T_3	3	8	8

- $H = 24$
- deadline set: 4, 6, 8, 12, 16, 18, 20, 24
- $dbf(4) = 1$
- $dbf(6) = 3$
- $dbf(8) = 7$
- $dbf(12) = 10$
- $dbf(16) = 14$
- $dbf(18) = 16$
- $dbf(20) = 17$
- $dbf(24) = 23$

Earliest Deadline First: exercice

- Task features

	WCET	Deadline	Period
T_1	2	4	5
T_2	3	7	20
T_3	2	8	10

- Is it schedulable with EDF?

Rate Monotonic / Earliest Deadline First: Mixed solution

- Trade-off between Fixed Priority simplicity and EDF better schedulability
- Rate Monotonic for tasks with shortest periods
- Other tasks with dynamic lower priorities
- Task features

	WCET	Deasline	Period
T_1	1	4	4
T_2	1	5	5
T_3	2	6	6
T_4	2	10	10

Adding aperiodic tasks

- Up to now, only tasks with a known minimum duration between any two consecutive occurreneces (the period)
- What if this minimum duration is unknown (i.e. aperiodic tasks)?
- Two cases have to be considered
  - Aperiodic jobs don't have deadlines
    - Try to minimize their response time while ensuring that periodic tasks never miss deadlines
  - Aperiodic jobs do have deadlines
    - Acceptance test: can it be executed before its deadline without jeopardising periodic jobs and already accepted aperiodic ones?
    - If not, one solution is to reject the aperiodic job
    - Another solution is to kill the least important job
    - Approaches are classically based on Earliest Deadline First
- Presentation of some simple scheduling algorithms for the case without deadline

Background execution of aperiodic jobs without deadlines

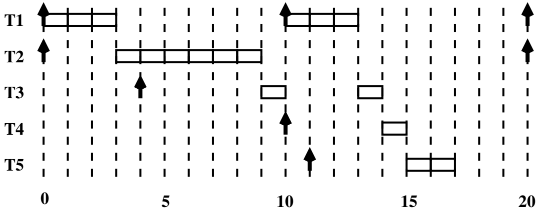
- The simplest solution
- Periodic tasks are scheduled using one of the previously presented algorithms (rate monotonic, deadline monotonic, earliest deadline first, ...)
- Aperiodic jobs are scheduled when there are no pending periodic ones
- Aperiodic jobs are scheduled following a "First Come First Served" policy
- Straightforward implementation
  - Periodic tasks are assigned priorities, based on the scheduling policy
  - All aperiodic jobs are assigned the same lowest priority
- This solution makes nothing to minimise the response time of aperiodic jobs

An example of the background execution approach

- Task features

	(first) occurence	WCET	Deadline	Period
T_1	0	3	10	10
T_2	0	6	20	20
T_3	4	2		
T_4	10	1		
T_5	11	2		

- Task scheduling, assuming rate monotonic



Polling server for aperiodic jobs without deadlines

- Server: periodic task with a budget for the execution of pending aperiodic jobs
- Short period for the server $\Rightarrow$ high priority task (consider for instance rate monotonic)
- Every time the server gets the processor

  Budget $\leftarrow$ Cs;
  Next_Activation $\leftarrow$ t_current + Ps;
  While Pending aperiodic jobs **and** Budget $>$ 0 **do**
      Execute one time unit of oldest pending aperiodic job;
      Budget $\leftarrow$ Budget - 1;
  EndWhile;
  Budget $\leftarrow$ 0;

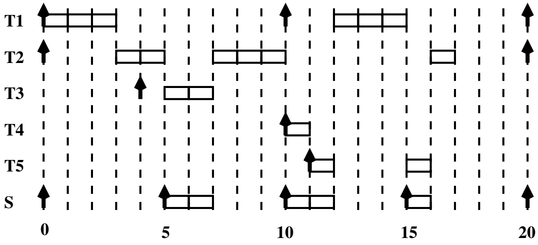
- Aperiodic request after the server dropped its budget $\Rightarrow$ it has to wait for the next server activation

An example of the polling server approach

- Task features

	(first) occurrence	WCET	Deadline	Period
T_1	0	3	10	10
T_2	0	6	20	20
S	0	2	5	5
T_3	4	2		
T_4	10	1		
T_5	11	2		

- Task scheduling assuming rate monotonic



Deferable server for aperiodic jobs without deadlines

- The budget is not reset to 0 when there are no (more) pending aperiodic jobs
- Every time the server is activated

  Budget $\leftarrow$ Cs;
  Next_Activation $\leftarrow$ t_current + Ps;
  While pending aperiodic jobs **and** Budget $>$ 0 **do**
      Execute one time unit of oldest pending aperiodic job;
      Budget $\leftarrow$ Budget - 1;
  EndWhile;

- Aperiodic request while server is not executing, but has some remaining budget

  While pending aperiodic jobs **and** Budget $>$ 0 **do**
      Execute one time unit of new pending aperiodic job;
      Budget $\leftarrow$ Budget - 1;
  EndWhile;

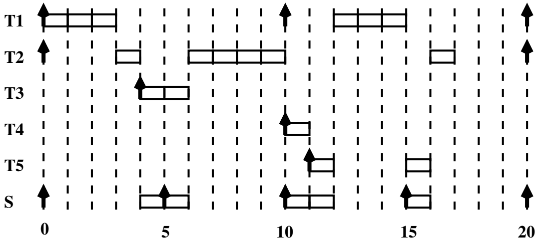
- Can lead to missed deadlines for periodic jobs!!!

An example of the deferable server approach

- Task features

	(first) occurrence	WCET	Deadline	Period
T_1	0	3	10	10
T_2	0	6	20	20
S	0	2	5	5
T_3	4	2		
T_4	10	1		
T_5	11	2		

- Task scheduling assuming rate monotonic

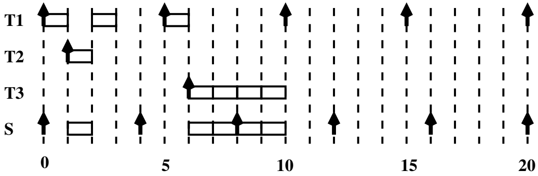


Another example of the deferable server approach

- Task features

	(first) occurrence	WCET	Deadline	Period
T_1	0	2	5	5
S	0	2	4	4
T_2	1	1		
T_3	6	4		

- Task scheduling assuming rate monotonic



Sporadic server for aperiodic jobs without deadlines

- No budget reset, the period starts when the server consumes budget
- Every time the server is activated

  Budget $\leftarrow$ Cs;
  If pending aperiodic jobs **then**
      Next_Activation $\leftarrow$ t_current + Ps;
      While pending aperiodic jobs **and** Budget $>$ 0 **do**
          Execute one time unit of oldest pending aperiodic job;
          Budget $\leftarrow$ Budget - 1;
      EndWhile;
  EndIf;

- Aperiodic request while server is not executing, but has some remaining budget

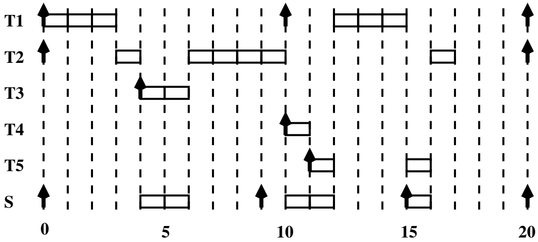
  If Budget $=$ Cs **Then** Next_Activation $\leftarrow$ t_current + Ps;
  While pending aperiodic jobs **and** Budget $>$ 0 **do**
      Execute one time unit of oldest pending aperiodic job;
      Budget $\leftarrow$ Budget - 1;
  EndWhile;

An example of the sporadic server approach

- Task features

	(first) occurrence	WCET	Deadline	Period
T_1	0	3	10	10
T_2	0	6	20	20
S	0	2	5	5
T_3	4	2		
T_4	10	1		
T_5	11	2		

- Task scheduling assuming rate monotonic

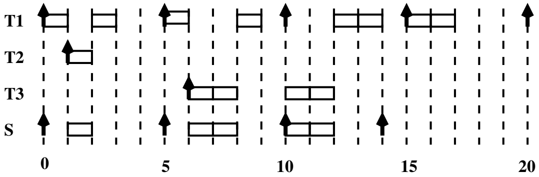


Another example of the sporadic server approach

- Task features

	(first) occurrence)	WCET	Délai critique	Période
T_1	0	2	5	5
S	0	2	4	4
T_2	1	1		
T_3	6	4		

- Task scheduling assuming rate monotonic



Exercise

- Task features, periodic tasks scheduled with rate monotonic

	(first) occurrence	WCET	D	P
T_1	0	1	6	6
T_2	0	4	12	12
T_3	0	6	24	24
T_4	1	2		
T_5	11	1		
T_6	13	2		

1. Response time of T_4, T_5 and T_6 with the background approach
2. Same question with a polling server with budget 1 and period 4
3. Same question with a deferable server with budget 1 and period 4
4. Same question with a sporadic server with budget 1 and period 4

Precedence constraints with rate monotonic

- Precedence constraints between periodic tasks $\Rightarrow$ defines an execution order
- one precedence constraint: n^{th} job of task T_i has to execute before n^{th} job of task T_j

$$T_i \rightarrow T_j$$

- Precedence constraints of a configuration are modelled by a precedence graph
- Tasks sharing precedence constraints typically have the same period
- Rate monotonic solution $\Rightarrow$ precedence constraints are integrated in task features offline
  - Activation dates and deadlines are modified offline for each task T_j

$$\begin{array}{rcll} r_j^* & = & max(r_j, r_i^*) & \quad \text{for every } T_i \rightarrow T_j \\ D_j^* & = & D_j - (r_j^* - r_j) & \end{array}$$

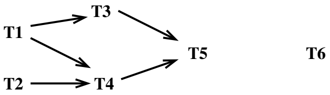
  - Different priorites for tasks with the same period: T_i has a higher priority than T_j if $T_i \rightarrow T_j$

Example with precedence constraints and rate monotonic

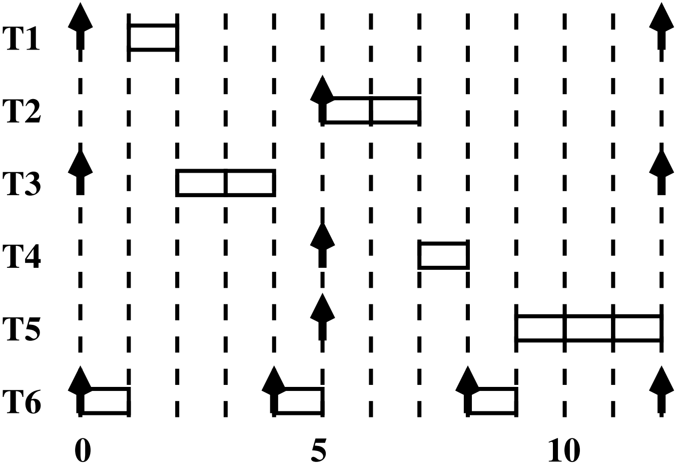
- Task features

	first occurrence		WCET	Deadline		Period
	r	r^*		D	D^*	
T_1	0	0	1	12	12	12
T_2	5	5	2	7	7	12
T_3	0	0	2	12	12	12
T_4	0	5	1	12	7	12
T_5	0	5	3	12	7	12
T_6	0	0	1	4	4	4

- Precedence constraints



Example with precedence constraints and rate monotonic



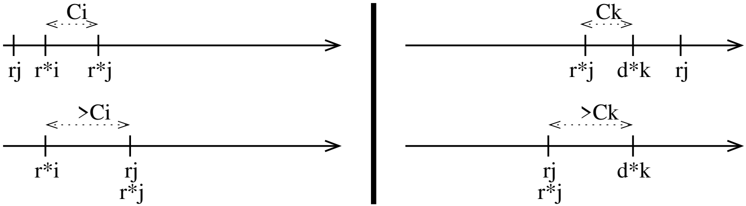
Precedence constraints with Earliest Deadline First

- Similar principle as with rate monotonic ⇒ off-line integration of constraints in task features
  - Modification of the activation date of T_j

$$r_j^* \quad = \quad max(r_j, max(r_i^* + C_i)) \quad \text{for all } T_i \rightarrow T_j$$

  - Modification of the deadline of T_j

$$d_j^* \quad = \quad min(d_j, min(d_k^* - C_k)) \quad \text{for all } T_j \rightarrow T_k$$

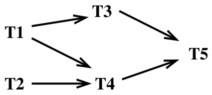


Example with precedence constraints and EDF

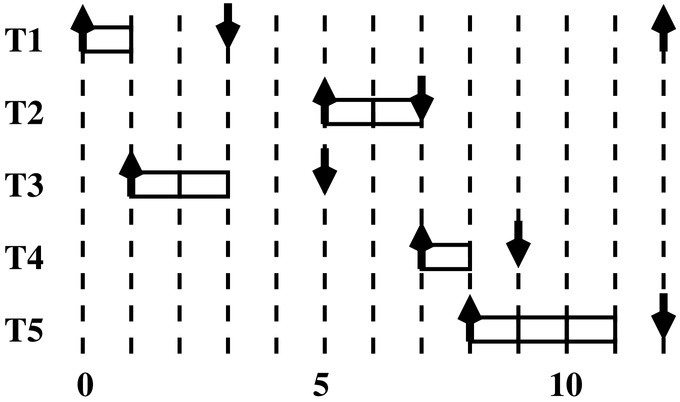
- Task features

	first occurrence		WCET	Deadline		Period
	r	r^*		d	d^*	
T_1	0	0	1	5	3	12
T_2	5	5	2	7	7	12
T_3	0	1	2	5	5	12
T_4	0	7	1	10	9	12
T_5	0	8	3	12	12	12

- Precedence constaints



Example with precedence constraints and EDF



Dealing with shared resources

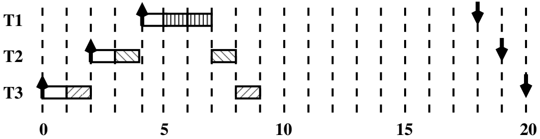
- Tasks often have to access to shared resources (i.e. shared variables) in mutual exclusion
- Critical sections are used to implement the access to these shared resources.
- A given task T_i cannot enter a critical section if the corresponding resource is not free
- Two potential problems
  - The deadlock: non cycle-free resource demands at a given time
  - Priority inversion: a task T_i waits for a resource earned by a lowe priority task T_j
- A deadlock should never occur in a critical real-time system
  - One solution: implement tasks such that they a deadlock can never occur (e.g. always take resources in the same order)
  - Another solution: provide a resource allocation mechanism that prevents deadlock (i.e. gives a resource only if it cannot lead to a deadlock)
- Priority inversion cannot be avoided, but should be upper bounded
  - Thanks to the resource allocation mechanism

Example of a deadlock

- Task features

	First release	WCET	Deadline	Period	Resource utilisation				
T_1	4	5	14	20		R_3	R_3	$R_1 R_3$	
T_2	2	5	17	20		R_2	R_2	$R_2 R_3$	
T_3	0	5	20	20		R_1	R_1	$R_1 R_2$	

- Sscheduling result



- Deadlock at $t = 9$

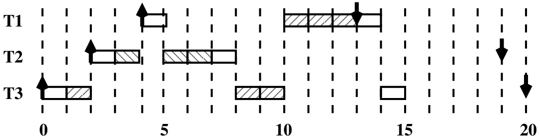
Example of a priority inversion

- Task features

	First release	WCET	Deadline	Period
T_1	4	5	9	20
T_2	2	5	17	20
T_3	0	5	20	20

Resource utilisation				
	R_1	R_1	R_1	
	R_2	R_2	R_2	
	R_1	R_1	R_1	

- Sscheduling result



- Priority inversion between $t = 5$ and $t = 10$

The "super priority" approach

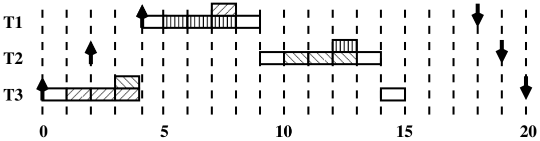
- The simplest solution to prevent deadlock and upper bound priority inversion
- A tasks asks for a resource $\Rightarrow$ it gets it immediately
- Every task which owns a resource gets the highest priority in the system $\Rightarrow$ no preemption within a critical section $\Rightarrow$ at most one task in critical section at any time
- A deadlock cannot occur
- the duration of a priority inversion is upper bounded by the longest critical section
- No need to know resource utilisation by tasks beforehand
- Doesn't take into account which resource is used $\Rightarrow$ can generate additionnal priority inversions

A first example of the super priority approach

- Task features

	First release	WCET	Deadline	Period	Resource utilisation				
T_1	4	5	14	20		R_3	R_3	$R_1 R_3$	
T_2	2	5	17	20		R_2	R_2	$R_2 R_3$	
T_3	0	5	20	20		R_1	R_1	$R_1 R_2$	

- Scheduling result



- No more deadlock

A second example of the super priority approach

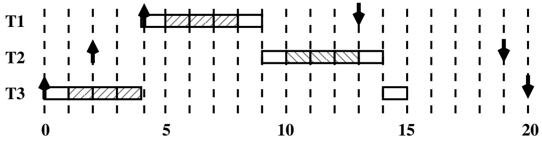
- Task features

	First release	WCET	Deadline	Period
T_1	4	5	9	20
T_2	2	5	17	20
T_3	0	5	20	20

Resource utilisation

	R_1	R_1	R_1	
	R_2	R_2	R_2	
	R_1	R_1	R_1	

- Scheduling result



A third example of the super priority approach

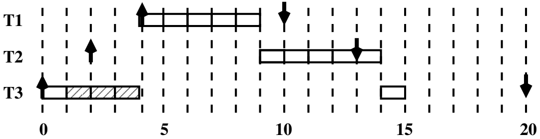
- Task features

	First release	WCET	Deadline	Period
T_1	4	5	9	20
T_2	2	5	17	20
T_3	0	5	20	20

Resource utilisation

	R_1	R_1	R_1	

- Scheduling result



The priority inheritance protocol

- Doesn't prevent deadlock, but upper bound priority inversion duration
- When a task T_i asks for an unavailable resource, the task T_j which owns the resource inherits the priority of blocked task T_i
- This rule is transitively applied
- No need to know resource utilisation by tasks beforehand

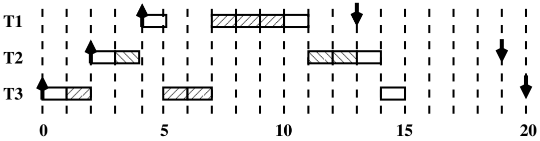
An example of the priority inheritance protocol

- Task features

	First release	WCET	Deadline	Period
T_1	4	5	9	20
T_2	2	5	17	20
T_3	0	5	20	20

Resource utilisation				
	R_1	R_1	R_1	
	R_2	R_2	R_2	
	R_1	R_1	R_1	

- Scheduling result



The "stack-based protocol"

- Based on the ceiling priority notion
  - The ceiling priority of a resource is the highest priority among the tasks which use this resource
  - Task requests in tems of resources have to be known beforehand
- A task owning no resource executes at its initial priority
- A task owning resources executes at the highest ceiling priority of these resources
- Every task asking for a resource gets it immediately
- It prevents deadlocks
- It upper bounds priority inversion duration

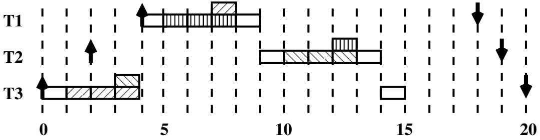
A first example of the “stack-based protocol”

- Task features

	First release	WCET	Deadline	Period
T_1	4	5	14	20
T_2	2	5	17	20
T_3	0	5	20	20

Resource utilisation				
	R_3	R_3	$R_1 R_3$	
	R_2	R_2	$R_2 R_3$	
	R_1	R_1	$R_1 R_2$	

- Scheduling result



A second example of the "stack-based protocol"

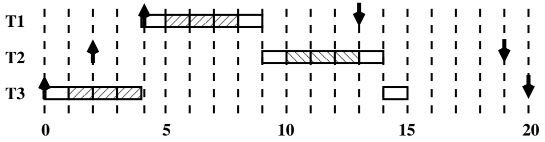
- Task features

	First release	WCET	Deadline	Period
T_1	4	5	9	20
T_2	2	5	17	20
T_3	0	5	20	20

Resource utilisation

	R_1	R_1	R_1	
	R_2	R_2	R_2	
	R_1	R_1	R_1	

- Scheduling result



A third example of the “stack-based protocol”

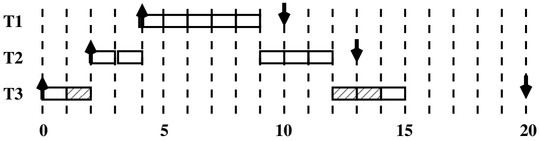
- Task features

	First release	WCET	Deadline	Period
T_1	4	5	9	20
T_2	2	5	17	20
T_3	0	5	20	20

Resource utilisation

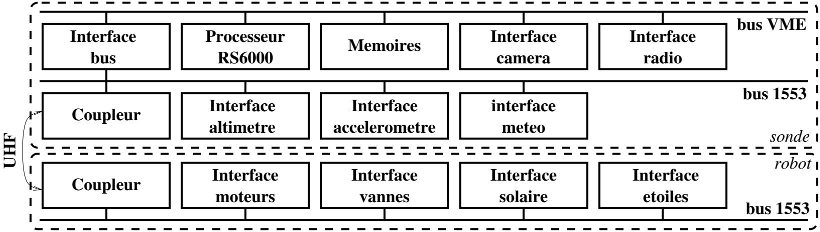
	R_1	R_1	R_1	

- Scheduling sequence



A real example: the Pathfinder mission

- NASA mission (Jet Propulsion Laboratory) in order to charaterise Mars environment
- Launched: 4 december, 1996
  - Lander: 264 Kg
  - Rover 11.5 Kg with six wheels, powered by solar panels and lithium batteries



- Landing on Mars: 4 juillet, 1997
- Some days without any problem, then the embedded computer resets several times ⇒ lots of data lost
- Remote detection and correction of the problem

A real example: the Pathfinder mission

- Multitask software using VxWorks RTOS (Wind River System)
- More than 25 periodic and aperiodic taks
  - Mode management (fly, approach, landing, exploration)
  - Surface pointing
  - Fault analysis
  - Weather forecast management
  - 1553 bus control
  - Star analysis
  - ...
- Different phases in the mission (fly, approach, landing, exploration) $\Rightarrow$ a subset of the task are executing in each phase
- The mode management task put each task in the right state (asleep, awake)
- An internal real-time clock for the activation of periodic tasks
- Problem occurs during the execution phase

A real example: the Pathfinder mission

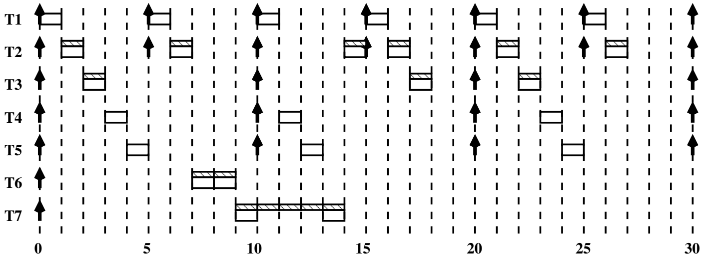
- Task features for the exploration phase

Task name	WCET	Period	Priority
Bus_scheduling (T1)	25 μs	125 μs	1
Data_distribution (T2)	25 μs	125 μs	2
Guiding (T3)	25 μs	250 μs	3
Radio (T4)	25 μs	250 μs	4
Camera (T5)	25 μs	250 μs	5
Measures (T6)	50 μs	5000 μs	6
Weather (T7)	$50; 75$ μs	5000 μs	7

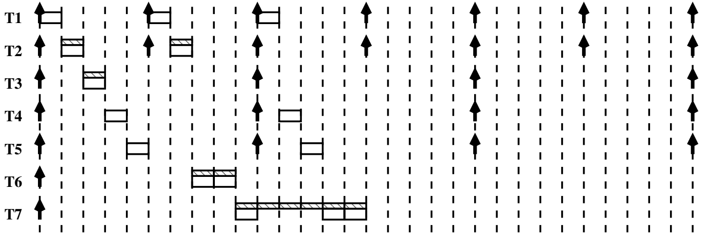
- One time unit: 25 μs
- T2, T3, T6 and T7 share a resource *data_buffer*
- Each task asks for the resource at the begining of its execution and gives it back at the end
- The inheritance priority protocol is not used

A real example: the Pathfinder mission

- Worst-case when the execution time for Weather task is 50 μs $\Rightarrow$ ok

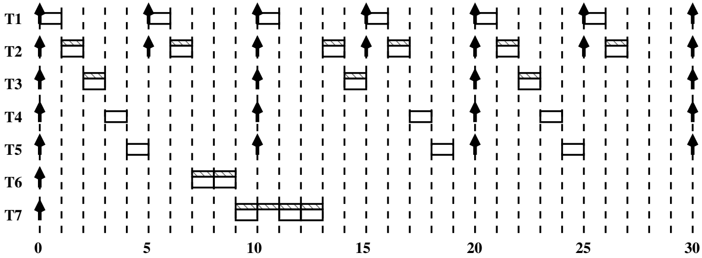


- Worst-case when the execution time for Weather task is 75 μs $\Rightarrow$ T2 misses a deadline



A real example: the Pathfinder mission

- Problem: too long priority inversion (between $t = 11$ et $t = 15$)
- Solution: Utilisation of the priority inheritance protocol
- Worst-case when the execution time for Weather task is 75 $\mu s \Rightarrow$ ok

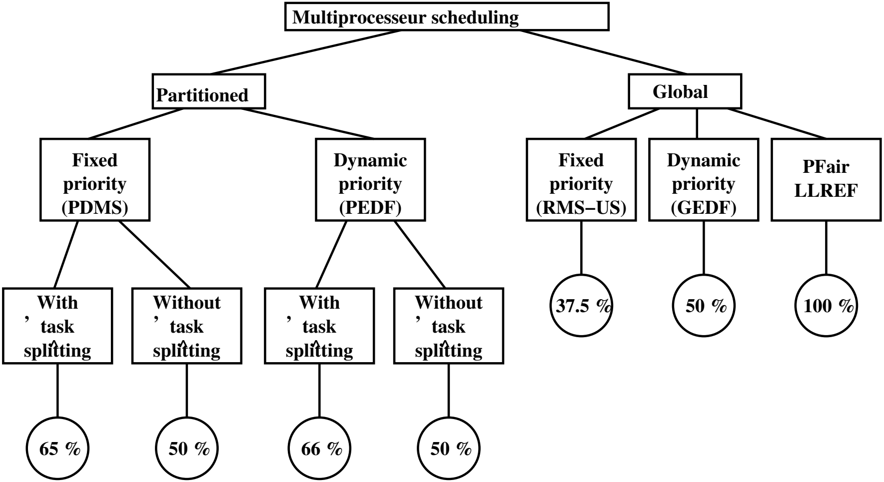


- Correction of the problem by uploading the modified code

Multiprocessor scheduling

- Problem definition
  - Scheduling of a set of n periodic tasks on m processors
  - Each processor executes at most one task at any instant
  - Each task is executed by at most one processor at any instant
- Different criteria to classify the solutions
  - To which extent task migrations are allowed
    - Partitioned scheduling No migrations: tasks statically distributed on processors
    - Global scheduling
      Task level migration: no migration of a job during its execution
      Job level migration
  - Priorities assigned to tasks
    - Task level fixed priorities (Rate Monotonic, ...)
    - Job level fixed priorities (Earliest Deadline First, ...)
    - Fully dynamic priorities (least laxity, PFAIR, DP-FAIR, ...)

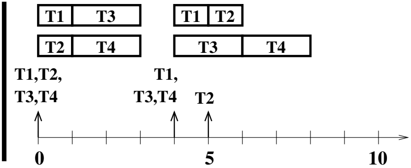
Overview of the different solutions



Some scheduling anomalies

- The synchronous case doesn't always lead to the worst-case respense time

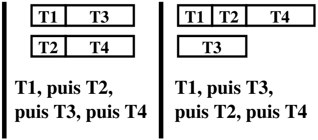
	C	D	P
T1	1	1	4
T2	1	1	5
T3	2	3	4
T4	2	3	4



⇒ The second job of T4 misses its deadline

- The response time of a task might depend on the priority order of higher priority tasks

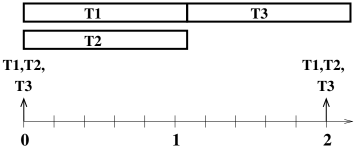
	C	D	P
T1	1	3	5
T2	1	3	5
T3	2	3	5
T4	2	3	5



⇒ T4 misses its deadline in the second case

Partitioned scheduling

- Tasks are statically distributed on the available processors
  - Optimal allocation: non polynomial problem (*bin packing*)
- Each processor executes independantly its allocated task set
  - Benefit from the monoprocessor scheduling theory
- The bound on the utilisation factor for each processor can be quite low
  - $m + 1$ periodic tasks with implicit deadlines
    - ⋆ Worst-case execution time of one job: $1 + \epsilon$
    - ⋆ Period of a task: 2
  - not schedulable on m processors with a partitioned approach $\Rightarrow$ on such a configuration we cannot exceed $U = \frac{m+1}{2}$ on m processors



Distribution of the tasks on the processors

- Divide the task set into m subsets such that each subset is schedulable on one processor
- One possible algorithm: Rate Monotonic First Fit
  - Tasks are sorted by increasing periods
  - Each task is allocated to the first processor which remains schedulable with this additionnal task
- Example of task distribution with RM first fit

(P_i, C_i)	U_i	(P_i, C_i)	U_i	(P_i, C_i)	U_i
$(2, 1)$	0.500	$(4.5, 0.1)$	0.022	$(8, 1)$	0.125
$(2.5, 0.1)$	0.040	$(5, 1)$	0.200	$(8.5, 0.1)$	0.012
$(3, 1)$	0.333	$(6, 1)$	0.167	$(9, 1)$	0.111
$(4, 1)$	0.250	$(7, 1)$	0.143		

P_1 : $(2, 1)$, $(2.5, 0.1)$, $(4.5, 0.1)$, $(6, 1)$, $(8.5, 0.1)$
P_2 : $(3, 1)$, $(4, 1)$, $(7, 1)$
P_3 : $(5, 1)$, $(8, 1)$, $(9, 1)$

Task splitting to improve the partitioning

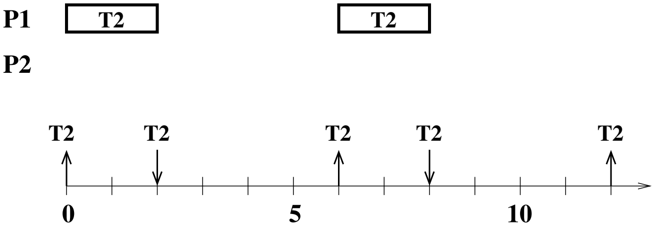
- Comes to allow some task migrations
- Example: PDMS-HPTS-DS algorithm
  - Deadline Monotonic scheduling on each processor
  - Tasks are allocated by decreasing load
  - As soon as the task set allocated on the current processor is no more schedulable, a portion of the highest priority task is removed such that the task set is just schedulable
  - This portion is allocated to the next processor
- At most $m - 1$ splitted tasks for m processors
- The two portions of the splitted task must not execute simultaneously
  - The release time of the second portion must not be before the latest possible end of the first portion
  - Splitting the highest priority task minimises this latest possible end

Task splitting to improve the partitioning

- Example with five tasks on two processors

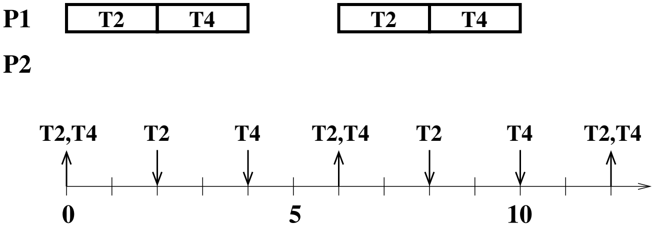
	(P_i, D_i, C_i)	U_i	CH_i		(P_i, D_i, C_i)	U_i	CH_i
T_1	$(4, 3, 1)$	0.25	0.33	T_2	$(6, 2, 2)$	0.33	1
T_3	$(4, 4, 1)$	0.25	0.25	T_4	$(6, 4, 2)$	0.33	0.5
T_5	$(6, 5, 1)$	0.16	0.2				

- Allocation of the task with the highest load, i.e. T_2 on processor $P1$: OK

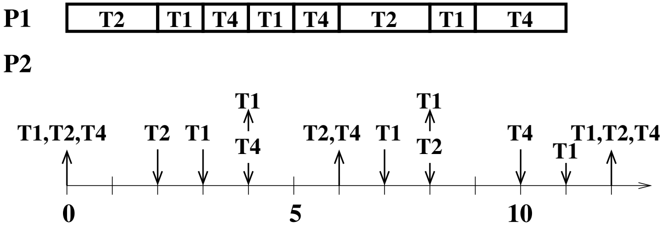


Task splitting to improve the partitioning

- Allocation of the remaining task with the highest load, i.e. T_4 on processor $P1$: OK

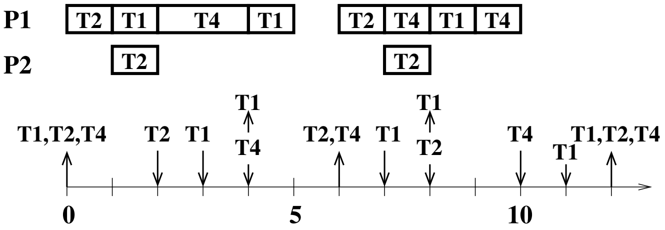


- Allocation of the remaining task with the highest load, i.e. T_1 on processor $P1$: KO ($T4$ at 4 and 10)

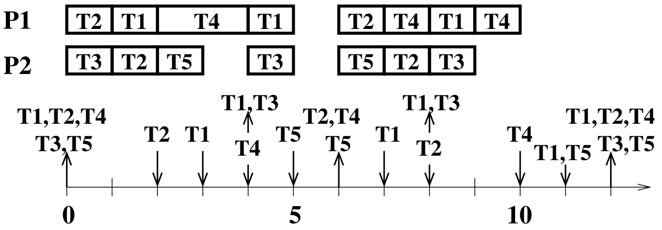


Task splitting to improve the partitioning

- Splitting of the highest priority task (T_2) such that the subset allocated to $P1$ becomes schedulable

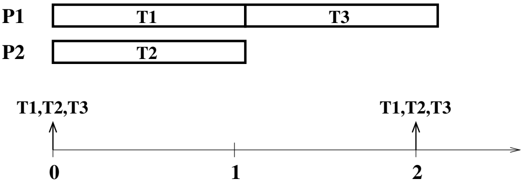


- Allocation of the two remaining tasks (T_3 and T_5) on processor $P2$

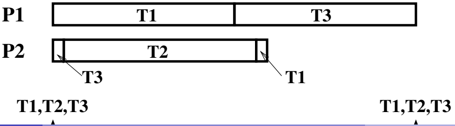


Global approaches without job migrations

- At any time, the m pending tasks with the highest priority are executed
- A job starts execution on a processor and never migrates
- Leads to a load balancing between processors
- Cannot schedule on m processors $m+1$ periodic tasks avec a WCET of $1+\epsilon$ and a period of 2
  - Example: three tasks on two processors



  - Schedulable configuration if job migration is allowed migration des occurrences



Global approaches with job migrations

- A job can migrate on a different processor during its execution
- An ideal algortithm for tasks with implicit deadlines
  - At any time, every task gets the percentage of the processor equal to its utilisation factor (fluid model)
  - Example: a task T_i with $C_i = 8$ and $P_i = 11$ always gets $\frac{8}{11} = 72.73$ % of the processor
  - Cannot be implemented like that
- An approximation: Pfair (Proportionate-fair)
  - The processor is allocated by discrete time units
  - The difference with the fluid model must never exceed one time unit

$$-1 < difference(T_i, t) < 1 \; for \; t \in N^*$$

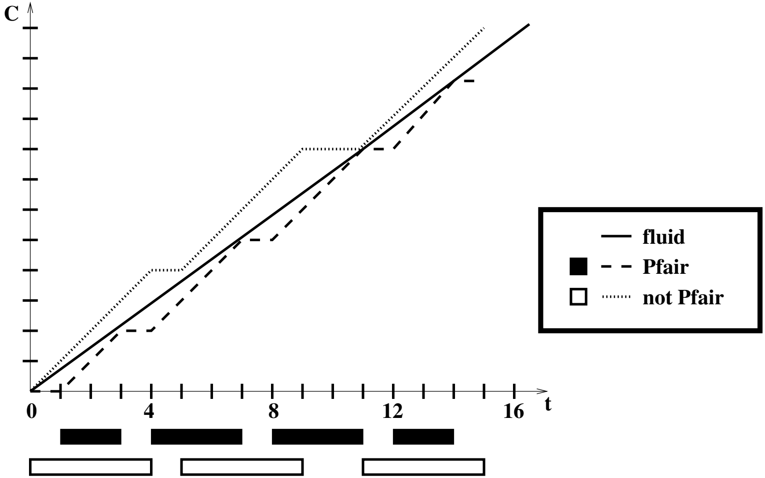
with

$$difference(T_i, t) = U_i \times t - \sum_{x=0}^{t-1} S(T_i, x)$$

et

$S(T_i, x) = 1$ if T_i is executing during time unit x
0 otherwise

Illustration of Pfair for $C_i = 8$ and $P_i = 11$



- Optimal algorithm
- Typically leads to a very high number of preemptions and migrations
  $\Rightarrow$ very large overhead

Can a greedy algorithm be optimal?

- Modeling of the urgency of a task by a single value
  - *Earliest deadline first*
  - *Least laxity first*
- Fails for schedulable task configurations
- Example: *least laxity first* on two processors processeurs

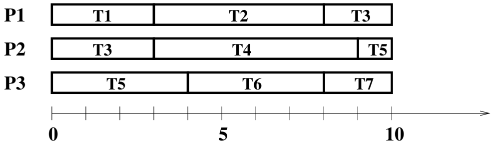
	C	P
T_1	9	10
T_2	9	10
T_3	8	40

- Utilisation factor of 2 for the configuration $\Rightarrow$ no idle time on any processor for any valid scheduling sequence
- One idle time at $t = 9$ with *least laxity first* $\Rightarrow$ fails
- No known greedy algorithm successfully schedules this configuration

Specific case: all the tasks have the same deadline

- Each task gets a slot equal to its WCET
- For m processors and a duration d_{dead} until the deadline
  - Building of a sequence with length $m \times d_{dead}$ with a slot of length its WCET for each task
  - Splitting of the sequence in m parts with the same length
- An example with three processors and seven tasks

	C	P		C	P
T_1	3	10	T_5	5	10
T_2	5	10	T_6	4	10
T_3	5	10	T_7	2	10
T_4	6	10			



DP-Fair : Deadline Partitionning

- Segmentation of the time, based on task deadlines
- In each portion, each task gets a slot corresponding to its utilisation factor
- The algorithm of the previous slide is applied in each portion
- Much less preemptions and migrations than with Pfair
- Example with three tasks on two processors

	C	P
T_1	9	10
T_2	9	10
T_3	8	40