# EINDHOVEN UNIVERSITY OF TECHNOLOGY

**Department of Mathematics and Computer Science**

*Examination of Real-time Systems (2IMN20)*
*on Tuesday, April* $18^{th}$ *2017, 8.00h-12.00h.*

First read the entire examination. There are 7 exercises in total. Grades are included between parentheses at all parts and sum up to 10 points. *Motivate all your answers.* Good luck!

1. *Reference model*

   (a) (0.5) The activation times of a strictly periodic task $\tau_i$ are given by $a_{i,k} = \phi_i + k \times T_i$. Define the activation times for sporadic tasks and elastic tasks.

   (b) (0.5) Give a motivation for sporadic tasks.

   (c) (0.5) Give a motivation for elastic tasks.

   **Answer**: See slides `RTS.B3-Reference Model`.

2. *Cyclic executives*

   (a) (0.5) Describe two advantages of a cyclic executive based on a *single-rate time-driven AFAP* compared to single-rate AFAP.
   **Answer**: See slides `RTS.B3-Cyclic-Executive`.

   (b) (0.5) Consider a real-time application consisting of three non-preemptive periodic tasks; see the following table providing their characteristics. Provide prototypical code for a *multi-rate periodic* cyclic executive to schedule the task set.

| | $T$ | $D$ | $WC$ |
|---|---|---|---|
| $\tau_1$ | 10 | 3 | 2 |
| $\tau_2$ | 10 | 5 | 3 |
| $\tau_3$ | 20 | 15 | 5 |

   **Answer**: See slides `RTS.B3-Cyclic-Executive`.

3. Consider three tasks that are scheduled by means of FPPS, where $\tau_1$ has highest and $\tau_3$ has lowest priority, with arbitrary phasing and characteristics as given below.

| | $WT = BT$ | $WD$ | $BD$ | $AJ$ | $WC$ | $BC$ |
|---|---|---|---|---|---|---|
| $\tau_1$ | 5 | 3 | 1 | 1 | 2 | 2 |
| $\tau_2$ | 8 | 8 | 3 | 0 | 3 | 3 |
| $\tau_3$ | 25 | 24 | 8 | 0 | 5 | 4 |

   (a) (0.5) Determine the worst-case response time of $\tau_3$ by means of the following recursive equation.

$$x = B_i + WC_i + \sum_{1 \leq j < i} \left\lceil \frac{x + AJ_j}{WT_j} \right\rceil WC_j. \quad (1)$$

   **Answer**: Note that the *lowest* priority task is *never* blocked. Hence, $B_3 = 0$ irrespective of potential resource sharing. Using an iterative procedure, we find $WR_3 = 24$.

   (b) Determine the best-case response time of task $\tau_3$

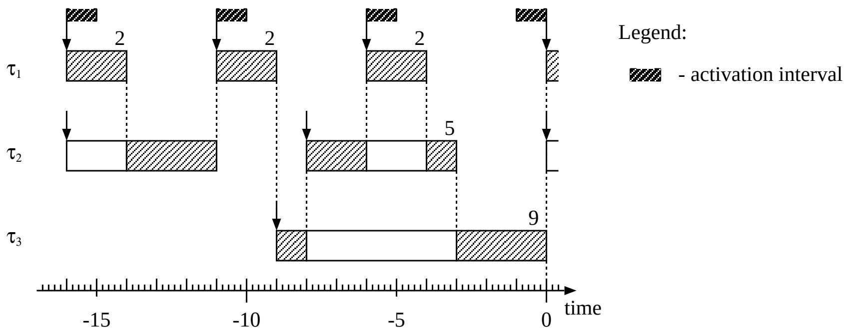


Figure 1: Timeline with an optimal instant for task $\tau_3$.

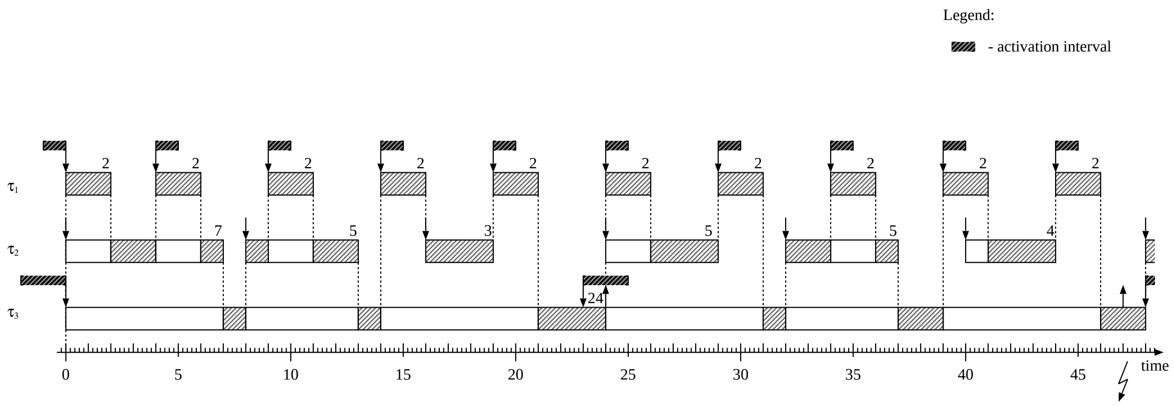


Figure 2: Timeline with a critical instant for task $\tau_3$.

i. (1.0) by drawing a time line with an optimal instant for $\tau_3$.
**Answer**: See Figure 1. Note that $BR_3 = 9$.

ii. (0.5) by means of the following recursive equation.

$$x = BC_i + \sum_{1 \le j < i} \left( \left\lceil \frac{x - AJ_j}{BT_j} \right\rceil - 1 \right)^+ BC_j \tag{2}$$

**Answer**: Using $WR_3 = 24$ as initial value for the iterative procedure to determine the best-case response time $BR_3$, we find $BR_3 = 9$.

(c) (0.5) Let $AJ_3 = 2$. Does this have an influence on the worst-case response time of task $\tau_3$?
**Answer**: First, observe that $WD_3 + AJ_3 = 26 > T_3 = 25$, hence using (1) is not appropriate in general. Next, because $WR_3 + AJ_3 = 26 > T_3 = 25$, using (1) does not necessarily yield $WR_3$, i.e. a next job of $\tau_3$ may have a larger response time than the first job due to additional interference of its previous jobs. By drawing a time-line (see Figure 2), we find that the second job has a response time of 25, which is larger than $WD_3$. From the timeline, we also derive that the level-3 active period ends at the finalization of the second job, hence $WR_3 = 25 > WD_3 = 24$. Hence, the value found by means of (1) is not the worst-case response time of task $\tau_3$ for $AJ_3 = 2$.

4. *Servers*: Consider a (fixed-priority) deferrable server, characterized by a period $T_{SS}$, a capacity $C_{SS}$, and a phasing $\phi_{SS}$.

(a) (0.5) Describe how the server shall be incorporated in the worst-case and best-case response time analysis.
**Answer**: See `RTS.B4-Polices-2-FP-servers` exercise 3.

(b) (0.5) Let the server be scheduled at the highest priority in a system. Suppose an aperiodic request $A$ of $2 \times C_{\text{SS}}$ arrives at time $a_A$. What is the best-case and worst-case response time of that aperiodic request when it is handled by the server, assuming no pending load of aperiodic requests at time $a_A$?

**Answer**: The best-case occurs when the aperiodic request arrives at $a_A = \phi_{\text{SS}} + k \times T_{\text{SS}} - C_{\text{SS}}$, i.e. *before* an activation of the server, and the entire capacity of the deferrable server is still available at time $a_A$. The best-case response time $BR_A$ of the request is subsequently identical to $2 \times C_{\text{SS}}$.

The worst-case happens when the aperiodic request arrives at $a_A = \phi_{\text{SS}} + k \times T_{\text{SS}} + C_{\text{SS}}$, i.e. *after* an activation of the server, and the entire capacity of the deferrable server has been consumed at time $a_A$. The worst-case response time $WR_A$ of the request is now identical to $2 \times T_{\text{SS}}$.

5. *Expected reading*

(a) (0.5) *Mars Rover Pathfinder*: Explain in your own words what happened on the Mars Rover Pathfinder, in particular *the problem* and *its correction*.

(b) (0.5) *Conformance testing of priority inheritance protocols*: This paper by Polock and Zoebel identifies an error in the informal description of the PIP protocol by Sha, Rajkumar, and Lehoczky. Describe *what* was wrong and *why* it is wrong.

**Answer**: See papers.

6. *Practical factors*

(a) (0.5) *Context switches*: For fixed-priority pre-emptive scheduling (FPPS) and independent tasks, a job of a task can preempt at most 1 running task. How many times can a job pre-empt a running task in case of resource sharing? Explicitly consider PIP and SRP.

(b) (0.5) *Clock interrupt*: Extend the recursive equation (1) to determine the worst-case response time for FPPS including clock interrupts.

(c) (1.0) *External interrupts*: Extend the recursive equation to determine the worst-case response time for FPPS including external interrupts, where $T_k$ denotes the minimum inter-arrival time of the interrupt corresponding with the sporadic task $\tau_k$, $\mathcal{T}_{\text{S}}$ denotes the set of sporadic tasks, and $IH_k$ denotes the cost of handling the interrupt for $\tau_k$.

**Answer**: See slides `RTS.B5-Analysis-9-practical factors`.

7. (1.0) This question concerns the guest-lecture of Prof. Hentschel. System control can be simplified by shifting control issues to an SVA. Describe the principle of SVAs with priority processing in your own words.
**Answer**: See slides `SVA Lectures 2008-02`.