

# Aperiodic Scheduling

Earliest Deadline Due, Latest Deadline First, Earliest Deadline First

Exercise class 4

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*Based on the lecture of:*  
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# Gliederung

Organisation

Overview Aperiodic Task Scheduling

Task 1

Task 2

Task 3

Task 4

Task 5



# Organisation



# Organisation I

► feedback for me: <https://forms.gle/f3YN8EFrZ1vsfPoC6>

Questions **Responses 1** Settings

1 response + ⋮

Accepting responses ☒

Summary **Question** Individual

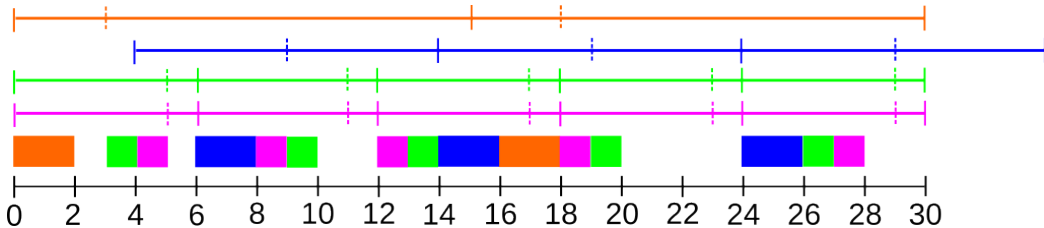
Is there something that could be improved?

1 response

It would be good, if the questions which are asked during the session would be repeated for the live stream and the recording.  
Sometimes it is hard to understand them in the live stream an the uploaded recording.

# Organisation I

- Question: Periodic schedule for framesize  $f = 2$  for task 3 of sheet 2



# Overview Aperiodic Task Scheduling



# Overview Aperiodic Task Scheduling

	Equal arrival times non preemptive	Arbitrary arrival times preemptive
Independent tasks	EDD (Jackson)	EDF (Horn)
Dependent tasks	LDF (Lawler)	EDF* (Chetto)

# Overview Aperiodic Task Scheduling

- ▶ **Lateness:**  $L_i = f_i - d_i$
- ▶ **Maximum lateness:**  $L_{\max} = \max_i (f_i - d_i)$ 
  - ▶ this a a metric to compare schedules



# Task 1

# Task 1

## Earliest Deadline Due

### Task 1.1:

	$J_1$	$J_2$	$J_3$	$J_4$
$C_i$	3	6	2	4
$D_i$	8	15	3	11

$(\forall J_i \in J : a_i = 0)$

### Requirements 1.1:

- ▶ *non-preemptive*
- ▶ tasks have *same arrival times* (synchronous arrivals)
- ▶ tasks are *independent*
- ▶  $\min(D_i)$  for all remaining  $J_i$  ( $d_i$  if  $\forall J_i \in J : a_i = c \wedge c \neq 0$ )
- ▶ *minimizing the maximum lateness*

# Task 1

## Earliest Deadline Due

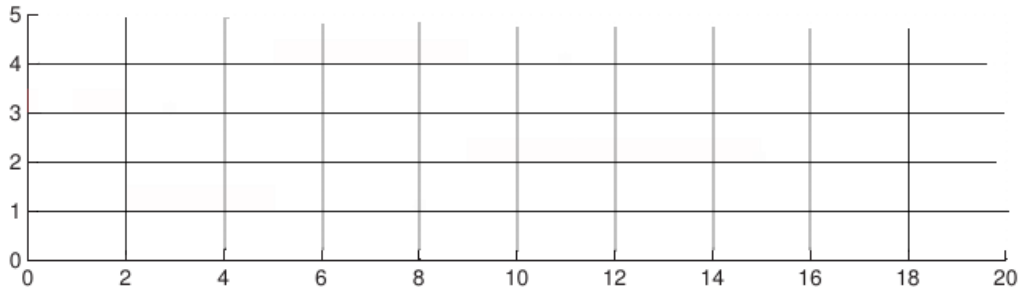


Figure 1: EDD schedule.

# Task 1

## Earliest Deadline Due

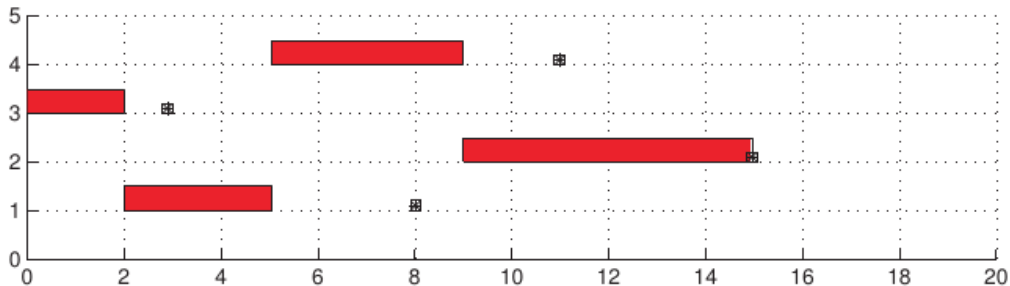


Figure 1: EDD schedule.

# Task 2



# Task 2

## Latest Deadline First

### Task 2.1:

	$J_1$	$J_2$	$J_3$	$J_4$	$J_5$	$J_6$	$J_7$	$J_8$
$C_i$	3	4	2	3	3	2	2	1
$D_i$	5	8	11	15	12	18	19	20

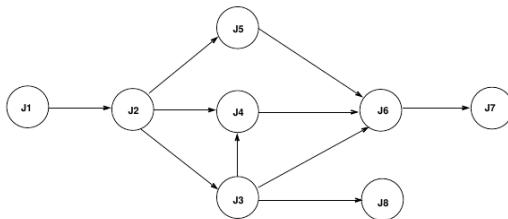


Figure 2: Precedence graph.

# Task 2

## Latest Deadline First

### Requirements 2.1:



- ▶ is *non-preemptive*
- ▶ *synchronous task activations*
- ▶ tasks are *dependent*, use *precedence graph*, going from *tail* to *head*
- ▶  $\max(D_i)$  ( $d_i$  if  $\forall J_j \in J : a_j = c \wedge c \neq 0$ ) for all tasks  $J_i$  *without successors* or whose *successors* have been all selected in the *precedence graph* inserted into the queue to be *executed last*
- ▶ at runtime, tasks are extracted from the *head of the queue*: the *first task* inserted in the queue will be *executed last*
- ▶ *minimizes the maximum lateness*

# Task 2

## Latest Deadline First

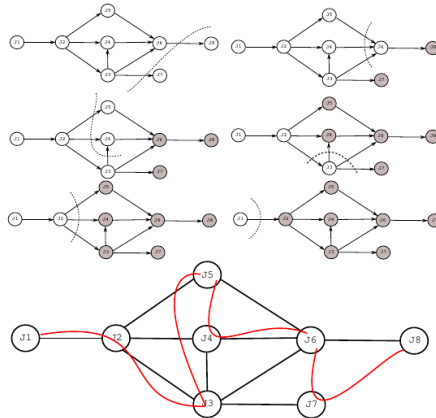


Figure 4: The LDF algorithm proceeds as depicted (figures left to right)



# Task 2

## Latest Deadline First

► queue of tasks: ( , , , , , , , )

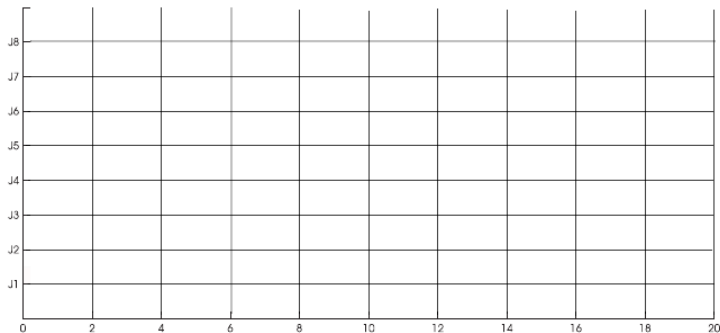


Figure 3: LDF schedule.

# Task 2

## Latest Deadline First

► queue of tasks:  $(J_1, J_2, J_3, J_5, J_4, J_6, J_7, J_8)$

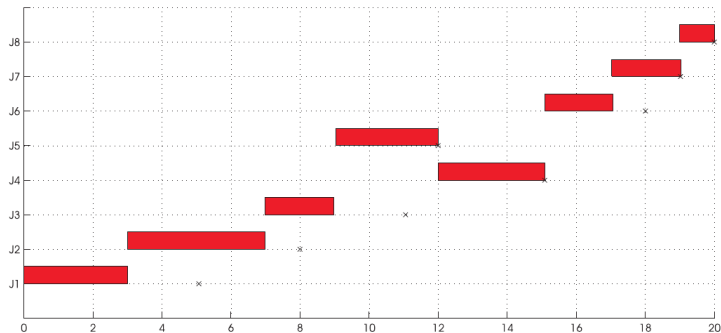


Figure 3: LDF schedule.

# Task 3



# Task 3

## Earliest Deadline First

### Task 3.1:

	$J_1$	$J_2$	$J_3$	$J_4$	$J_5$
$a_i$	0	2	0	8	13
$C_i$	3	1	6	2	3
$d_i$	16	7	8	11	18

### Requirements 3.1:

- ▶ *is preemptive*
- ▶ *arbitrary arrival times*
- ▶ *the tasks are independent*
- ▶ *minimizes the maximum lateness*
- ▶  *$\min(d_i)$  for all remaining tasks  $J_i$  that have already arrived (are ready) and not finished every time the arrival time of a task is reached*

# Task 3

## Earliest Deadline First

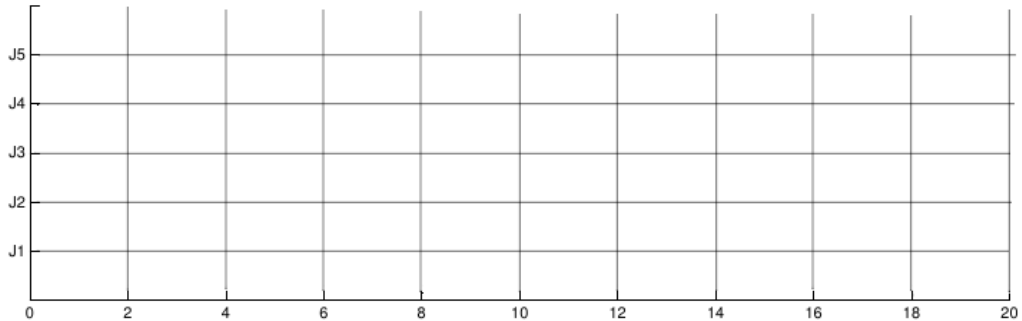


Figure 5: EDF schedule

# Task 3

## Earliest Deadline First

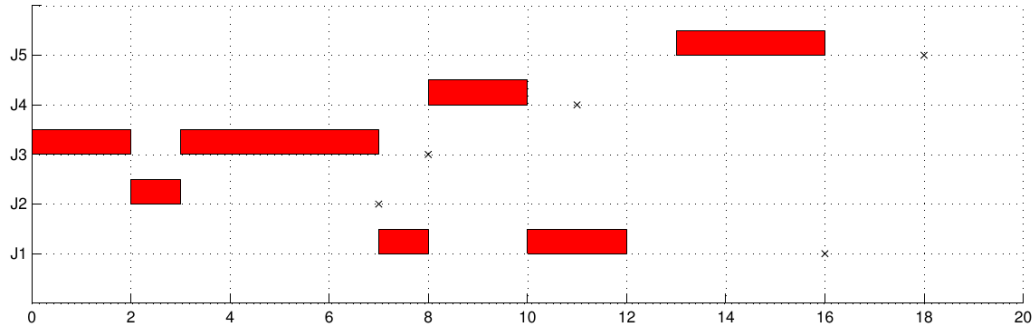


Figure 5: EDF schedule

# Task 3

## Earliest Deadline First

### Task 3.2:

- ▶ at time  $t = 3$ , a new task  $J_x$  arrives with execution time  $C_x = 2$  and deadline  $d_x = 10$ .
- ▶ still **guarantee the schedulability** of task set?

### Requirements 3.2:

- ▶ **acceptance test:**  $\forall i = 1, \dots, n \quad t + \sum_{k=1}^i c_k(t) \leq d_i$ 
  - ▶  $n$  is the number of **active tasks**

# Task 3

## Earliest Deadline First

### Requirements 3.3:

```
Algorithm: EDF_guarantee ( $J, J_{\text{new}}$ )
{
     $J' = J \cup \{J_{\text{new}}\};$  /* ordered by deadline */
     $t = \text{current\_time}();$ 
     $f_0 = t;$ 
    for (each  $J_i \in J'$ ) {
         $f_i = f_{i-1} + c_i(t);$ 
        if ( $f_i > d_i$ ) return(INFEASIBLE);
    }
    return(FEASIBLE);
}
```



# Task 3 I

## Earliest Deadline First

- ▶ check: with  $J_x$  schedule still feasible
- ▶ compute ahead the finishing times in consideration of  $J_x$
- ▶ consider the tasks in order of increasing deadlines:

	$J_2$	$J_3$	$J_x$	$J_4$	$J_1$	$J_5$
$a_i$	2	0	3	8	0	13
$C_i$	1	6	2	2	3	3
$d_i$	7	8	10	11	16	18

- ▶ test performed every time a new task arrives among all active task

# Task 3 II

## Earliest Deadline First

- ▶ until  $t = 3$  everything is feasible
  - ▶ at  $t = 0$  we have active tasks (arrived but not finished):  $\{J_1, J_3\}$ 
    - ▶ Put  $t = 0$
    - ▶ Task  $J_3$  :  $f_1 = t + c_3(0) = 0 + 6 = 6 \leq 8 \checkmark$
    - ▶ Task  $J_1$  :  $f_2 = f_1 + c_1(0) = 6 + 3 = 9 \leq 16 \checkmark$
  - ▶ at  $t = 2$  we have active tasks:  $\{J_1, J_2, J_3\}$ 
    - ▶ Put  $t = 2$
    - ▶ Task  $J_2$  :  $f_1 = t + c_3(2) = 2 + 1 = 3 \leq 7 \checkmark$

# Task 3 III

## Earliest Deadline First

- ▶ Task  $J_3$  :  $f_2 = f_1 + c_2(2) = 3 + 4 = 7 \leq 8 \checkmark$
- ▶ Task  $J_1$  :  $f_3 = f_2 + c_1(2) = 7 + 3 = 9 \leq 16 \checkmark$
- ▶ task  $J_2$  finishes **before** its deadline at  $t = 3$
- ▶ at  $t = 3$  we have active tasks:  $\{J_1, J_3, J_x\}$ 
  - ▶ Put  $t = 3$
  - ▶ Task  $J_3$  :  $f_1 = t + c_3(3) = 3 + 4 = 7 \leq 8 \checkmark$
  - ▶ Task  $J_x$  :  $f_2 = f_1 + c_x(3) = 7 + 2 = 9 \leq 10 \checkmark$
  - ▶ Task  $J_1$  :  $f_3 = f_2 + c_1(3) = 9 + 3 = 12 \leq 16 \checkmark$

# Task 3 IV

## Earliest Deadline First

- ▶ Thus, at  $t = 3$  all tasks in the system are feasible
- ▶ The next task to arrive is  $J_4$ . It arrives at  $t = 8$ . At  $t = 8$ , we have three active tasks:  $\{J_x, J_4, J_1\}$ 
  - ▶ Put  $t = 8$
  - ▶ Task  $J_x : f_1 = t + c_x(8) = 8 + 1 = 9 \leq 10 \checkmark$
  - ▶ Task  $J_4 : f_2 = f_1 + c_4(8) = 9 + 2 = 11 \leq 11 \checkmark$
  - ▶ Task  $J_1 : f_3 = f_2 + c_1(8) = 11 + 3 = 14 \leq 16 \checkmark$
  - ▶ Thus, at  $t = 8$  all tasks in the system are feasible.

# Task 3 V

## Earliest Deadline First

- ▶ next task  $J_5$  arrives at  $t = 13$ . At  $t = 13$ , we have two active tasks:  $\{J_1, J_5\}$ 
  - ▶ Put  $t = 13$
  - ▶ Task  $J_1$  :  $f_1 = t + c_1(13) = 13 + 1 = 14 \leq 16 \checkmark$
  - ▶ Task  $J_5$  :  $f_2 = f_1 + c_5(13) = 14 + 3 = 17 \leq 18 \checkmark$
  - ▶ hence, the whole **schedule is feasible**

# Task 3

## Earliest Deadline First

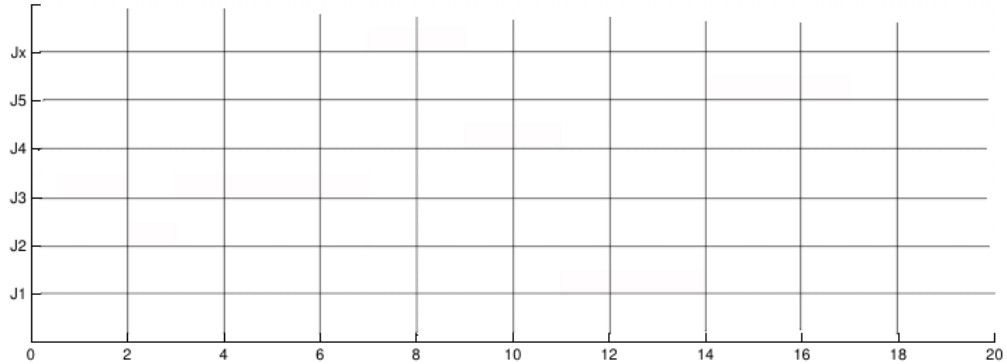


Figure 6: EDF schedule (with  $J_x$ )

# Task 3

## Earliest Deadline First

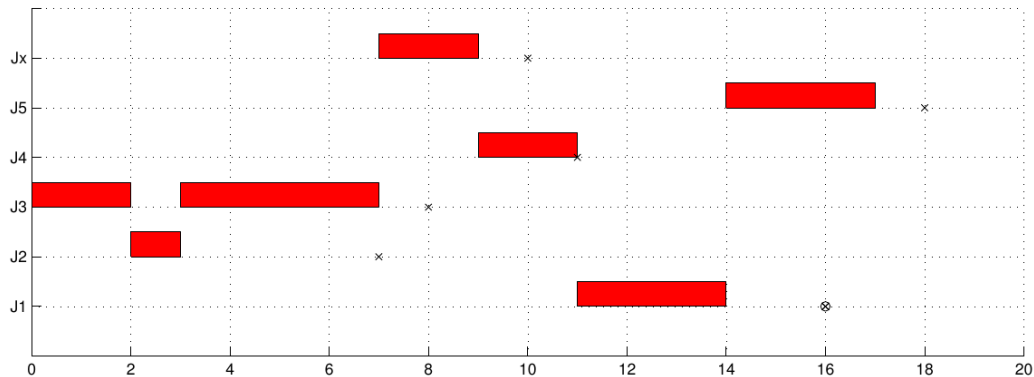


Figure 6: EDF schedule (with  $J_x$ )

# Task 4



# Task 4 I

## EDF\* - Example

### Task 4.1:

Given tasks  $A, B, C, D, E, F, G$  with precedences  $A \rightarrow C, B \rightarrow C, C \rightarrow E, D \rightarrow F, B \rightarrow D, C \rightarrow F, D \rightarrow G$ .

All tasks arrive at time  $t_0 = 0$ , have a common deadline  $d = 20$  and the following execution times:

	A	B	C	D	E	F	G
$C_i$	3	2	4	3	2	5	1

We will now prepare the tasks for EDF\*

# Task 4

## EDF\*

### Requirements 4.1:



- ▶ *preemptive*
- ▶ *arbitrary arrival times*
- ▶ *tasks are dependent*
- ▶ *release time and deadline* of individual tasks are modified such that all the *precedence constraints* are satisfied
- ▶ scheduling problem is *transformed* into a problem *without precedence constraints*, which can then be handled by a "normal" EDF scheduler

# Task 4 I

## EDF\* - Transformation

- ▶ EDF\* transforms the arrival time and deadline of every task in the following way:

### Deadline:

1. Task must finish the execution time within its deadline:  $f_i \leq d_i$
2. Task must not finish the execution time later than the maximum start time of its successor(s):  $f_i \leq d_j - C_j$

$$\rightarrow d_i^* = \min(d_i, \min(d_j^* - C_j : J_i \rightarrow J_j))$$

# Task 4 II

## EDF\* - Transformation

### Arrival time

1. Task must start the execution not earlier than its release time:  $s_j \geq r_j$
2. Task must not start execution earlier than the minimum finishing time of its predecessor(s):  $s_j \geq r_i + C_i$

$$\rightarrow r_j^* = \max(r_j, \max(r_i^* + C_i : J_i \rightarrow J_j))$$

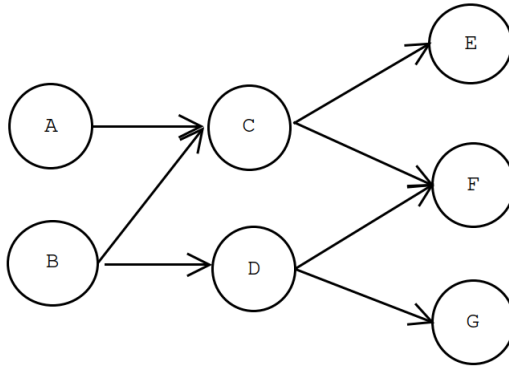
# Task 4

## EDF\* - Precedence graph example

Given the precedences  $A \rightarrow C$ ,  $B \rightarrow C$ ,  $C \rightarrow E$ ,  $D \rightarrow F$ ,  $B \rightarrow D$ ,  $C \rightarrow F$ ,  $D \rightarrow G$  we first draw the precedence graph:

# Task 4

## EDF\* - Precedence graph example



*Figure 1: Task 4: precedence graph*

# Task 4 I

## EDF\* - Transformation example

- ▶  $r_A^* = r_A, r_B^* = r_B$
- ▶  $r_C^* = \max\{r_C, \max\{r_A^* + C_A, r_B^* + C_B\}\} = \max\{0, \max\{3, 2\}\} = 3$
- ▶  $r_D^* = \max\{r_D, r_B^* + C_B\} = \max\{0, 2\} = 2$
- ▶  $r_F^* = \max\{r_F, \max\{r_C^* + C_C, r_D^* + C_D\}\} = \max\{0, \max\{7, 5\}\} = 7$
- ▶  $r_E^* = \max\{r_E, r_C^* + C_C\} = \max\{0, 7\} = 7$
- ▶  $r_G^* = \max\{r_G, r_D^* + C_D\} = \max\{0, 5\} = 5$

## Task 4 II

### EDF\* - Transformation example

- ▶  $d_E^* = d_F^* = d_G^* = 20$
- ▶  $d_C^* = \min\{d_C, \min\{d_E^* - C_E, d_F^* - C_F\}\} = \min\{20, \min\{18, 15\}\} = 15$
- ▶  $d_D^* = 15$
- ▶  $d_A^* = 11$
- ▶  $d_B^* = 11$

We now successfully have transformed the problem into one without precedence and can simply use EDF!



# Task 4

## EDF\* - Transformation example

- The modified **release times** and **deadlines** are:

	<i>A</i>	<i>B</i>	<i>C</i>	<i>D</i>	<i>E</i>	<i>F</i>	<i>G</i>
$r_i^*$	0	0	3	2	7	7	5
$d_i^*$	11	11	15	15	20	20	20

# Task 4 I

## EDF\* - Schedule

### Task 4.2:

- ▶ determine a resulting EDF\* schedule
- ▶ for this schedule, compute the **average of all response times** of the tasks

### Requirements 4.2:

- ▶ **average response time:**  $\bar{t}_r = \frac{1}{n} \sum_{i=1}^n (f_i - r_i)$ 
  - ▶ **metric to compare schedules**

# Task 4

## EDF\* - Schedule

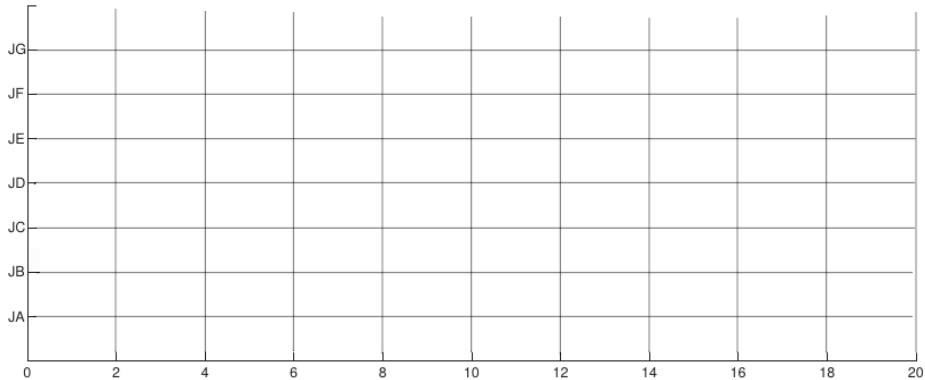


Figure 7: EDF\* schedule

# Task 4

## EDF\* - Schedule

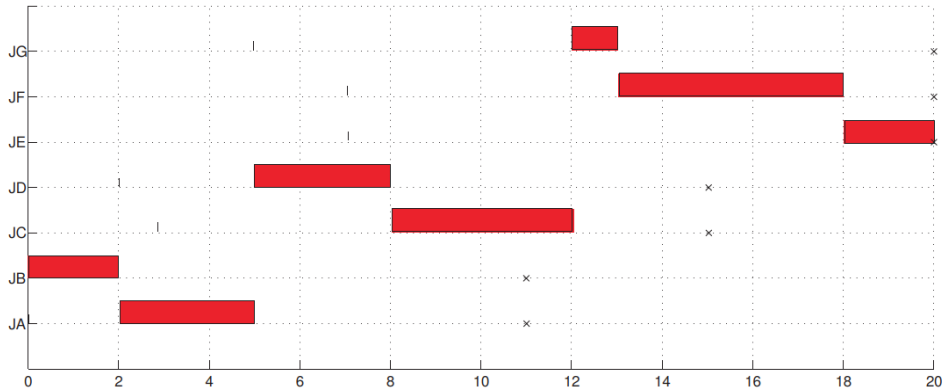


Figure 7: EDF\* schedule

# Task 4 I

## EDF\* - Schedule

Solution 4.2:

$$\triangleright \bar{t}_r = \frac{1}{7} \sum_{i=1}^7 (f_i - r_i) = \frac{5 + 2 + 12 + 8 + 20 + 18 + 13}{7} = \frac{54}{7} = 7.714$$

# Task 4 I

## EDF\* - Schedule

### Task 4.3:

- ▶ additional precedence constraint  $E \rightarrow A$
- ▶ still a **feasible schedule** for the task set

### Requirements 4.3:

- ▶ *Precedence relations between tasks can be described through an **acyclic directed graph**  $G$  where tasks are represented by nodes and precedence relations by arrows.  $G$  induces a partial order on the task set.*

# Task 4 II

## EDF\* - Schedule

### Solution 4.3:



- ▶ *No, the task set is no longer schedulable. Under the new conditions, the constraints among tasks A, C and E introduce a cycle in the precedence graph.*
- ▶ *As a result, none of the three tasks can be executed as first and therefore, no feasible schedule exists.*

# Task 5



# Task 5 I

## Earliest Deadline First – Star

### Task 5.1:

$J_1 \rightarrow J_2, J_2 \rightarrow J_3, J_3 \rightarrow J_4, J_5 \rightarrow J_6, J_6 \rightarrow J_7, J_6 \rightarrow J_8, J_2 \rightarrow J_7, J_7 \rightarrow J_4, J_8 \rightarrow J_7.$

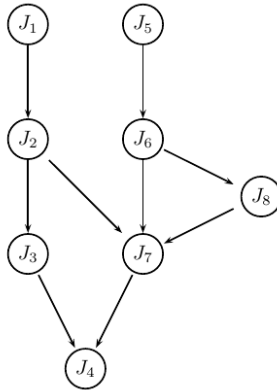
	$J_1$	$J_2$	$J_3$	$J_4$	$J_5$	$J_6$	$J_7$	$J_8$
$r_i$	0	3	4	0	0	2	0	2
$d_i$	3	8	15	15	10	10	10	11
$C_i$	1	3	3	3	1	1	2	1

► construct precedence graph

# Task 5 II

## Earliest Deadline First – Star

### Solution 5.1:



# Task 5 I

## Earliest Deadline First - Star

### Task 5.2:

- ▶ apply EDF\* algorithm for modified arrival times and deadlines

Table 1: Modified arrival times and deadlines

	$J_1$	$J_2$	$J_3$	$J_4$	$J_5$	$J_6$	$J_7$	$J_8$
$r_i^*$								
$d_i^*$								
$C_i$	1	3	3	3	1	1	2	1

# Task 5 II

## Earliest Deadline First - Star

- ▶  $r_1^* = r_1 = 0, r_5^* = r_5 = 0$
- ▶  $r_2^* = \max\{r_2, r_1^* + C_1\} = \max\{3, 0 + 1\} = 3$
- ▶  $r_6^* = \max\{r_6, r_5^* + C_5\} = \max\{2, 0 + 1\} = 2$
- ▶  $r_3^* = \max\{r_3, r_2^* + C_2\} = \max\{4, 3 + 3\} = 6$
- ▶  $r_8^* = \max\{r_8, r_6^* + C_6\} = \max\{2, 2 + 1\} = 3$
- ▶  $r_7^* = \max\{r_7, \max\{r_2^* + C_2, r_6^* + C_6, r_8^* + C_8\}\} = \max\{0, \max\{3+3, 2+1, 3+1\}\} = 6$
- ▶  $r_4^* = \max\{r_4, \max\{r_3^* + C_3, r_7^* + C_7\}\} = \max\{0, \max\{6+3, 6+2\}\} = 9$

# Task 5 III

## Earliest Deadline First - Star

- ▶  $d_4^* = d_4 = 15$
- ▶  $d_3^* = \min\{d_3, d_4^* - C_4\} = \min\{15, 15 - 3\} = 12$
- ▶  $d_7^* = \min\{d_7, d_4^* - C_4\} = \min\{10, 15 - 3\} = 10$
- ▶  $d_2^* = \min\{d_2, \min\{d_3^* - C_3, d_7^* - C_7\}\} = \min\{8, \min\{12 - 3, 10 - 2\}\} = 8$
- ▶  $d_1^* = \min\{d_1, d_2^* - C_2\} = \min\{3, 8 - 3\} = 3$
- ▶  $d_8^* = \min\{d_8, d_7^* - C_7\} = \min\{11, 10 - 2\} = 8$
- ▶  $d_6^* = \min\{d_6, \min\{d_7^* - C_7, d_8^* - C_8\}\} = \min\{10, \min\{10 - 2, 8 - 1\}\} = 7$

# Task 5 IV

## Earliest Deadline First - Star

►  $d_5^* = \min\{d_5, d_6^* - C_6\} = \min\{10, 7 - 1\} = 6$

# Task 5 V

## Earliest Deadline First - Star

### Solution 5.2:

	$J_1$	$J_2$	$J_3$	$J_4$	$J_5$	$J_6$	$J_7$	$J_8$
$r_i^*$	0	3	6	9	0	2	6	3
$d_i^*$	3	8	12	15	6	7	10	8
$C_i$	1	3	3	3	1	1	2	1

# Task 5 I

## Earliest Deadline First - Start

### Task 5.3:



- ▶ dual-core platform
- ▶ at any time  $t$ , both cores execute the two ready tasks ( $r_i^* \leq t$ ) with **earliest deadlines**
- ▶ a single task **cannot** be executed on two cores simultaneously
- ▶ construct schedule:



# Task 5 II

## Earliest Deadline First - Start

### Task 5.3:

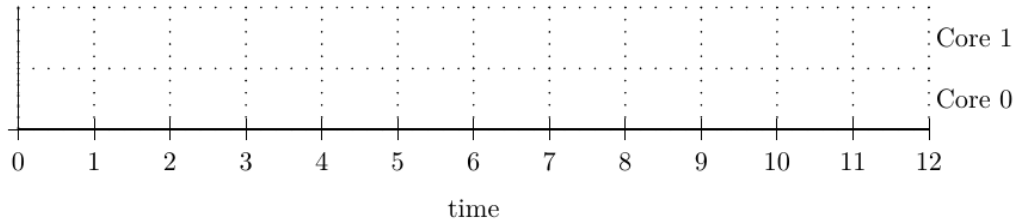


Figure 8: EDF schedule for part (3)

# Task 5 III

## Earliest Deadline First - Start

### Solution 5.3:

► *one of several solutions* since the tasks can run either on core 0 or core 1

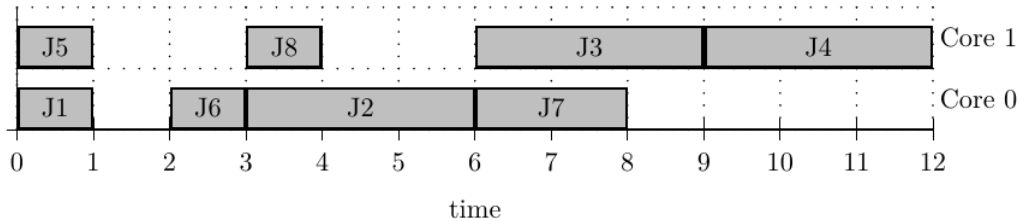


Figure 9: One solution for part (3)

# Task 5 I

## Earliest Deadline First - Start

### Task 5.4:

- ▶ Will executing on the **quad-core platform** with the same scheduling rule reduce the completion time of the application?
  - ▶ 4 cores execute the four ready tasks with earliest deadlines

### Solution 5.4:

- ▶ No,  $J_4$  **cannot** be started earlier than time 9. Therefore, the **minimum finish time** of the application is 12 (as the finish time for the dual core platform)