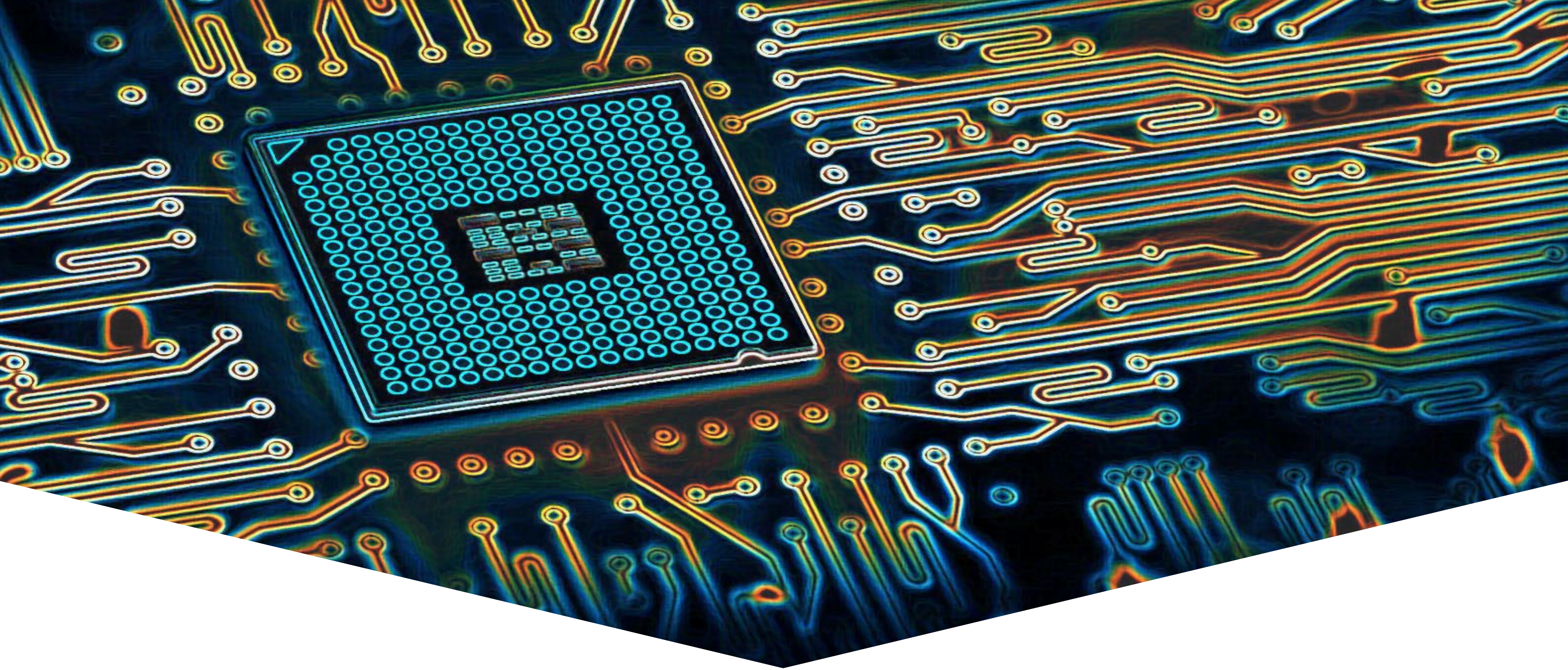

RTS10 Week 6

Planning

- Week 1: Introduction microcontroller architecture and STM32F411E-DISCO
- Week 2: Microcontroller architecture and programming in C
- Week 3: Cyclic executive and cooperative scheduler
- Week 4: Pre-emptive scheduler
- Week 5: FreeRTOS and pthreads
- **Week 6: Schedulability and response time analyses**
- Week 7: Introduction Rust
- Week 8: Embedded Rust

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Free study material

- Chapters 3 and 4 of: Ken Tindell and Hans Hansson, Real Time Systems by Fixed Priority Scheduling, Uppsala University, 1997.
- Chapter 12 of: Edward A. Lee and Sanjit A. Seshia, Introduction to Embedded Systems, A Cyber-Physical Systems Approach, Second Edition, MIT Press, ISBN 978-0-262-53381-2, 2017.

- Original papers:
  - C. L. Liu and J. W. Layland, Scheduling Algorithms for Multiprogramming in a Hard Real-Time Environment, JACM, Volume 20, Number1, pages 46 to 61, 1973
  - M. Joseph and P. Pandya, Finding Response Times in a Real-Time System, The Computer Journal, Volume 29, Number 5, pages 390-395, 1986

Task scheduling

In how many ways can you schedule 10 tasks (without preemption)?

- Choose one to start with (10 possibilities)
- Choose another to go second (9 possibilities)
- …

- Total of 10x9x8x7x6x5x4x3x2x1 = 10! = 3628800 possible schedules

Scheduling tasks

- *N* tasks can be scheduled in *N*! different ways
  - For example, 10 tasks: 3628800 possible schedules
  - With preemption there are many more possibilities
- The chosen schedule must meet all timing requirements
- A scheduling scheme (=plan) consists of:
  - An algorithm to find the "best" schedule
  - A method to predict the "worst-case" behavior of this schedule

Scheduling tasks... When do we do it?

- Static: the schedule is determined before the tasks are started
  - All task, their worst-case execution times and deadlines should be known beforehand
  - Using response time analysis, it is possible to prove that all deadlines are met.
  - All response times are predictable!
  - Not able to react on “unforeseen” situations
- Dynamic: the schedule is determined when the tasks are running.
  - Behavior is less predictable
  - Can respond dynamically to unforeseen circumstances (e.g., a calculation that takes longer than expected)

Scheduling Real-Time systems

- Almost always a static scheduling method is used

- Most commonly used : Preemptive Priority Based scheduling
  - On each moment in time the ready task with the highest priority is running
  - Scheduling scheme:
    - An algorithm to assign a priority to each task
    - A method to predict the “worst-case” behavior of this schedule given the assigned priorities and to prove that all timing requirements are met

Scheduling - Simple model

- The number of task is known: N
- All tasks are periodical, and all period times are known: T_i
- The tasks are independent from each other (no synchronization nor communication)
- System overhead is neglected
- The deadline of each task is equal to its period time: $D_i = T_i$
- The worst-case execution time of each task is known: C_i

This model is **too** simple (but difficult enough).
Later we will look at realistic models.

Cyclic executive (Super loop)

- The schedule is determined upfront and is explicitly programmed.
- Example:

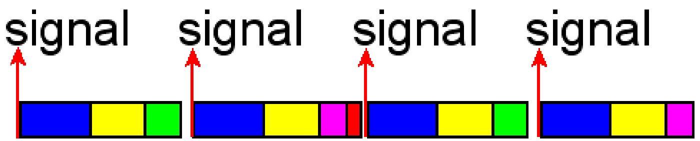
Taak	T	C
a	25	10
b	25	8
c	50	5
d	50	4
e	100	2

```
// Set timer to wake-up CPU every 25 ms
while (1) {
    sleep_until_wake_up(); a(); b(); c();
    sleep_until_wake_up(); a(); b(); d(); e();
    sleep_until_wake_up(); a(); b(); c();
    sleep_until_wake_up(); a(); b(); d();
}
```

- How to determine the schedulability?
- How to find a schedule?

Cyclic executive (Super loop)

signal = systick



- a $T = 25$ $C = 10$
- b $T = 25$ $C = 8$
- c $T = 50$ $C = 5$
- d $T = 50$ $C = 4$
- e $T = 100$ $C = 2$

minor cycle = 25 ns

major cycle = 100 ns

Utilization

U = 10/25+8/25+5/50+4/50+2/100

= **0,92**

What is the maximum utilization in the general case?

If C_e = 4 then U = **0,94** and the task set is **not** schedulable!

- Minor cycle = gcd(T_1, T_2, … T_n). Major cycle = lcm(T_1, T_2, … T_n).
- How to determine the schedulability?
- How to find a schedule?

Cyclic executive (Super loop)

- Characteristics:
  - There are no real tasks, only ordinary functions
  - Shared memory can be used for communication without protection (mutex is not needed)
  - All T's should be a multiple of the minor cycle time
  - System is deterministic (predictable)
- Issues:
  - Tasks with large differences in T's result in a large major cycle
  - Sporadic tasks (interrupts) can not be included!
  - Poorly maintainable, adaptable and expandable
  - Determining the schedule is NP-hard! (read: very, very hard)
- Alternatives:
  - **Fixed-Priority Scheduling** (FPS)
  - Earliest Deadline First (EDF)

FPS Fixed-priority Preemptive Scheduling

- Each task runs with a statically determined fixed priority
- This priority is determined by the timing requirements of all tasks
- The scheduling is preemptive:
  - When a task with a higher priority becomes ready, the running task will be preempted (interrupted)

RMPA = Rate Monotonic Priority Assignment

- The period time of a task determines the priority of that task
- The shorter the period time the higher the priority

$$T_i < T_j \Rightarrow P_i > P_j$$

- This (simple) method is **optimal**!
  - if some fixed-priority preemptive schedule exists, then, the rate monotonic fixed-priority preemptive schedule is also feasible

FPS-RMPA

Utilization based schedulability test:

$$U \equiv \sum_{i=1}^{N} \frac{C_i}{T_i} \leq N(2^{1/N} - 1)$$

N	Test
1	$U \leq 1.000$
2	$U \leq 0.828$
3	$U \leq 0.780$
4	$U \leq 0.757$
5	$U \leq 0.743$
10	$U \leq 0.718$
infinite	$U \leq 0.693$

- If this test is true, then **no** deadlines are missed!
- If this test is false, then **maybe** some deadlines are missed!

FPS-RMPA

- Utilization based schedulability test for *N* → ∞:

$$U \equiv \sum_{i=1}^{\infty} \frac{C_i}{T_i} \leq \lim_{N\to\infty} N(2^{1/N} - 1) = \lim_{N\to\infty} \frac{2^{1/N} - 1}{1/N}$$

$$U \leq \lim_{M\to 0} \frac{2^M - 1}{M} = \frac{0}{0} \quad \text{use L'Hôpital's rule}$$

$$U \leq \lim_{M\to 0} \frac{\ln 2}{1} = 0.693$$

L'Hôpital's rule

FPS-RMPA Schedulability examples

- Possibilities:
  - Does not meet the test and some deadlines are not met
  - Does not meet the test but all deadlines are met
  - Does meet the test and all deadlines are met

- Meeting the test is sufficient evidence that all deadlines are met. But it is not necessary to satisfy the test in order to meet all deadlines.

FPS-RMPA Response time analysis

- In contrast to the utilization test, this analysis determines the exact response times. So, we can say exactly whether all deadlines are met (and by what margin).

$$R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

R_i appears on the **left** and the **right** side of the equation. This equation can not be simply solved (because the ceiling function is not invertible).

R_i is the response time of task i
$hp(i)$ is the set of tasks with a higher priority than task i

FPS-RMPA Response time analysis

$$R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

- The response time of the highest priority task is: $R = C$
- All other tasks can be preempted. Their response time is: $R_i = C_i + I_i$
- Where I_i is the maximum "interference" time. This will occur when all tasks with a higher priority than ***i*** start at the same time as task ***i***
- The number of times task ***j*** with a higher priority than ***i*** can preempt task ***i*** is given by:

$$\text{Number of Releases} = \left\lceil \frac{R_i}{T_j} \right\rceil$$

- So, $I_{i,j}$ equals: $\left\lceil \frac{R_i}{T_j} \right\rceil C_j$

FPS-RMPA Response time analysis

- The total maximum interference time is the sum of the maximum interference time of every task with a higher priority:

$$R_i = C_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

- Which can be solved by using a recurrence relation:

$$w_i^{n+1} = C_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil C_j$$

Start with $w_i^0 = 0$ and continue until: $w_i^n = w_i^{n+1}$ or $w_i^{n+1} > T_i$

FPS-RMPA Response time analysis

Further extension of the analysis method is necessary to include:

- Sporadic tasks
- Tasks with $D < T$
- Interaction between tasks
- Release jitter
- Tasks with $D > T$
- Release offsets

FPS-RMPA $D < T$ and Sporadic tasks

- $D < T$:
  - Use DMPA instead of RMPA:

$$D_i < D_j \Rightarrow P_i > P_j$$

  - Use the following stop condition in the response time analysis:

$$W_i^{n+1} > D_i$$

- Sporadic tasks (interrupts):
  - Use the minimum time between two “starts” of this task as the period time T = minimum inter-arrival interval
  - For most sporadic tasks $D < T$

Assignment

Een programma bestaat uit 4 taken T_1 t/m T_4. Deze taken gebruiken geen gedeelde resources. In de tabel 1 staat i voor het nummer van de taak, T_i voor de periodetijd van taak i en C_i voor de maximale executietijd van taak i. Gegeven is dat de deadline van elke taak gelijk is aan zijn periodetijd.

Tabel 1: De gegevens van de taken

i	T_i	C_i
1	100	50
2	280	45
3	200	20
4	300	40

Assignment_Week_6.pdf

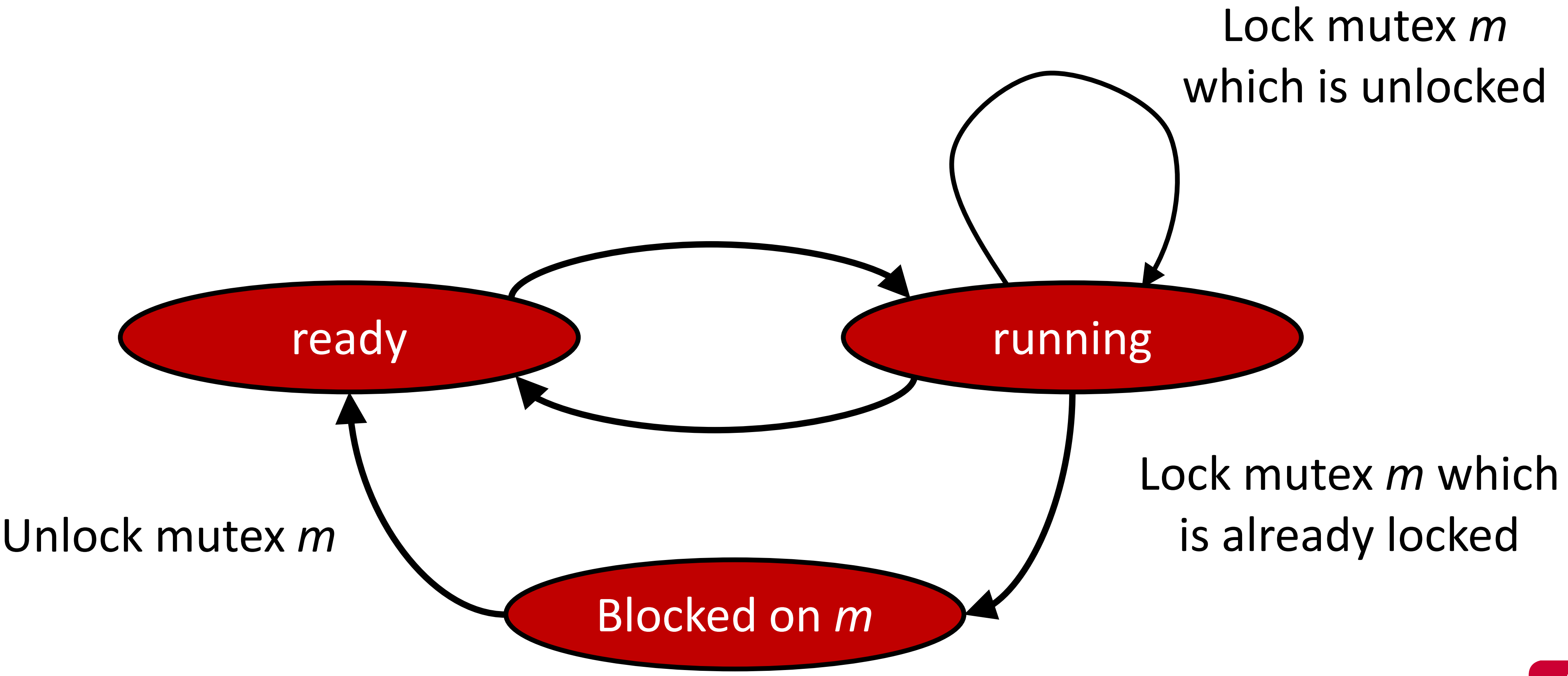
Alle gegeven tijden zijn in ms.

A Bepaal de schedulability van deze taken met behulp van de "Utilization based schedulability test". Geef de benodigde berekening en trek daaruit je conclusie!

B Bepaal de prioriteiten P_i van de verschillende taken als gebruik gemaakt wordt van FPS-RMPA (Fixed-priority Pre-emptive Scheduling – Rate Monotonic Priority Assignment). Het systeem kent 4 verschillende prioriteiten (1 t/m 4) waarbij 4 de hoogste prioriteit is.

C Bereken voor alle taken of de deadline wordt gehaald en geef, indien de deadline wordt gehaald, de response tijd R_i.

Task States


Lock mutex *m*
which is unlocked
ready
running
Lock mutex *m* which
is already locked
Unlock mutex *m*
Blocked on *m*

FPS-DMPO Blocking

- When a task with a lower priority has to wait on a task with a higher priority, the task is preempted.
- A preempted task is added to the ready queue before tasks with the same priority.
- When a task with a high priority has to wait on a task with a lower priority, the task is blocked (priority inversion).
- When a task is unblocked, it is added to the ready queue after tasks with the same priority.
- To predict the real-time behavior of a task, the maximum time a task can be blocked must be predictable (**bound blocking**).

Priority inversion example

- Four tasks (a, b, c, and d) share two resources (Q and V).
- Each resource can only be used mutually exclusive (so each resource is protected with a mutex).

task	prio	execution	release time
d	4	EEQVE	4
c	3	EVVE	2
b	2	EE	2
a	1	EQQQE	0

E = task only needs the processor to run

Q = task needs processor and resource Q to run

V = task needs processor and resource V to run

Priority inversion example

Finish this **Gantt chart** yourself!

- Executing
- Executing with Q locked
- Executing with V locked
- Preempted
- Blocked

task	prio	execution	release time
d	4	EEQVE	4
c	3	EVVE	2
b	2	EE	2
a	1	EQQQE	0

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FPS-DMPO Priority inversion

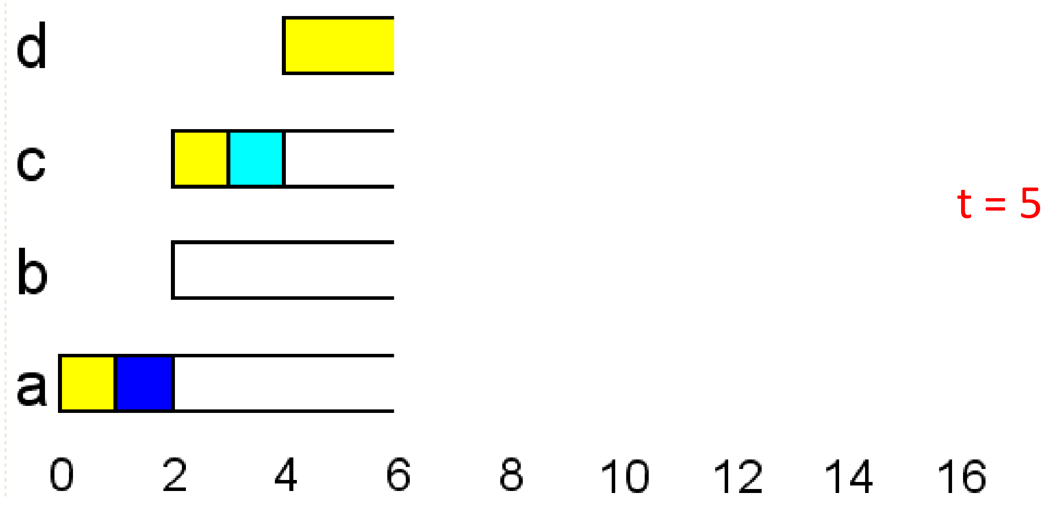
- Task d is being blocked by task a, b, and c (all tasks with a lower priority)!

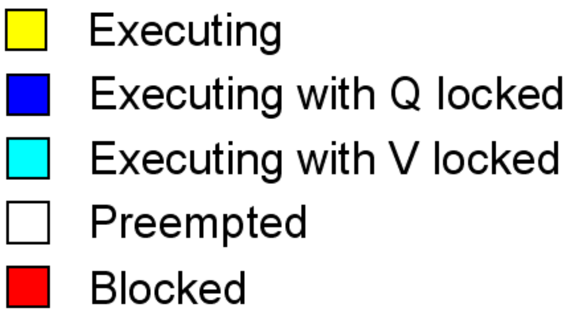
- Blocking (priority inversion) **can not** be **avoided** if we use mutual exclusive recourses.

- Blocking **can** be **bounded** by using priority inheritance:
  - When a task is blocked on a resource, then the task that owns the recourse gets (inherits) the priority of the blocked task.

Priority inheritance example

Finish this **Gantt chart** yourself!





task	prio	execution	release time
d	4	EEQVE	4
c	3	EVVE	2
b	2	EE	2
a	1	EQQQE	0

Blocking Priority inheritance

- The blocked time of each task is now bounded.

$$B_i = \sum_{k=1}^{K} usage(k,i)C_k$$

- B_i = maximum blocking time for task i
- K = total number of resources
- $usage(k, i)$ = Boolean function
  - 1 if there is a task with a priority lower than P_i and a task with a priority higher than or equal to P_i (this can be task i itself) which share resource $\boldsymbol{k}$.
  - 0 otherwise.
- C_k = maximum time for which resource k is locked.

Blocking Response time analyze

$$R_i = C_i + B_i + I_i$$

$$R_i = C_i + B_i + \sum_{j \in hp(i)} \left\lceil \frac{R_i}{T_j} \right\rceil C_j$$

$$w_i^{n+1} = C_i + B_i + \sum_{j \in hp(i)} \left\lceil \frac{w_i^n}{T_j} \right\rceil C_j$$

Priority inheritance example

Calculate the maximum blocking time (B_i) for all tasks in the previous example

task	prio	execution	release time
d	4	EEQVE	4
c	3	EVVE	2
b	2	EE	2
a	1	EQQQE	0

$$B_i = \sum_{k=1}^{K} usage(k,i)C_k$$

E = task only needs the processor to run
Q = task needs processor and resource Q to run
V = task needs processor and resource V to run

$usage(k, i)$ = 1 if there is a task with a priority lower than P_i and a task with a priority higher than or equal to P_i (this can be task i itself) which share resource k.

Solution

task	prio	execution
d	4	EEQVE
c	3	EVVE
b	2	EE
a	1	EQQQQE

$$B_i = \sum_{k=1}^{K} usage(k,i)C_k$$

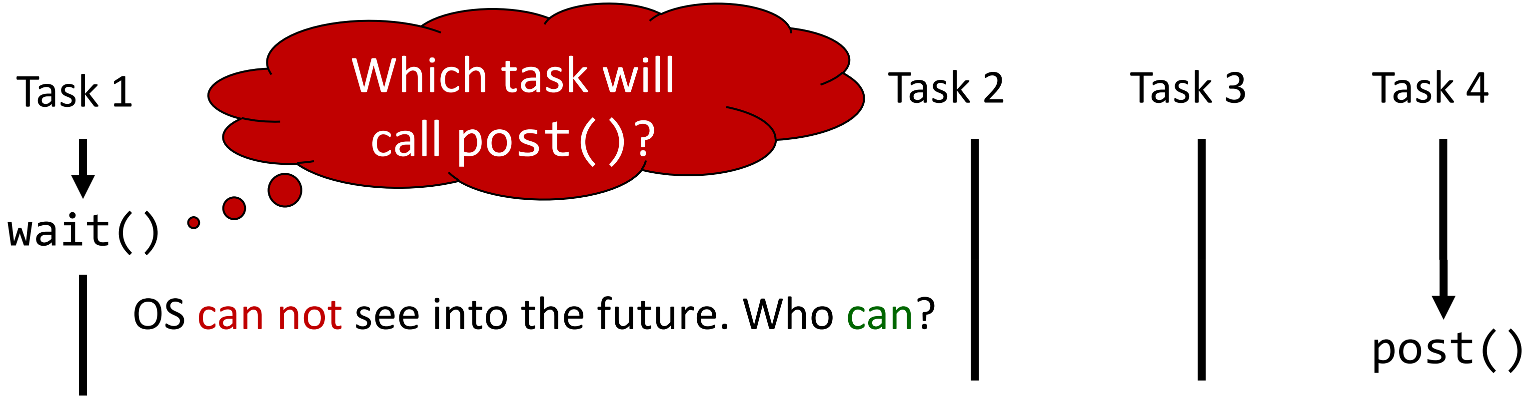
Table for $usage(k, i)$ and B_i

i	k = V	k = Q	B_i
d			
c			
b			
a			

$C_V =$, $C_Q =$

Blocking Priority inheritance

- Priority inheritance can not be implemented for semaphores and message queues!
  - When using a semaphore, it is often not possible to determine which task is causing the blocking (which task will call the `post()` for which a task blocked on `wait()` is waiting for)!
  - Example: using a semaphore with an initial count value of zero for synchronization purposes.



  - When using message passing it is often not possible to determine which task is causing the blocking (which task will perform the `send()` for which a task blocked on `receive()` is waiting for)!
- Solution: e.g., Priority Ceiling Protocol

Next weeks... Rust

Why Rust?

- Performance
  - Rust is blazingly fast and memory-efficient: it can power performance-critical services and run on embedded devices.
- Reliability
  - Rust’s rich type system and ownership model guarantee memory-safety and thread-safety — enabling you to eliminate many classes of bugs at compile-time.
- Productivity

Report Week 3 – 6

This report should include two parts:

- the relevant source codes of the weekly assignments for week 3 to 5 and a short explanation per assignment, this explanation should also include difficulties and decisions made to finish the assignment;
- the elaboration of the calculation task (Dutch: rekenopdracht) you will receive in week 6.

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