

## Embedded System Design and Modeling

## IX. Scheduling basics

- ▶ Scheduling = the process of arranging the execution of a set of **tasks** (runnables, threads, processes) which need to be run on the same processing device
  - ▶ i.e. decide which task is run when, for how long, etc.
- ▶ Encountered in multi-tasking systems
- ▶ Problems:
  - ▶ How to decide which task to run when?
  - ▶ Tasks can become deadlocked
- ▶ *Note:* Slides are heavily based on Prabal Dutta & Edward A. Lee, Berkeley 2017

- ▶ A task is a set of operations which have:
  - ▶ release (arrival) time: earliest time when it can be run
  - ▶ **start time**: actual starting time
  - ▶ **finish time**: actual ending time
  - ▶ execution time: actual running time, excluding any interruptions
  - ▶ **deadline**: latest time by which a task must be completed
- ▶ Tasks may be interrupted (preempted) by higher priority tasks, when priorities are defined
- ▶ Tasks may be periodic (e.g. run every 10ms) or aperiodic

# Task

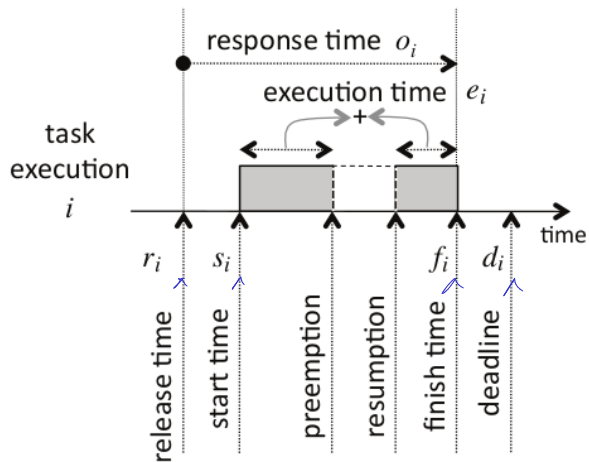


Figure 12.1: Summary of times associated with a task execution.

# Scheduling

- ▶ The scheduling problem: Given a set of tasks with their own times, which all need to run on the same processor, how to decide which task to run when?
- ▶ Typically a job for the operating system (kernel)

## Considerations:

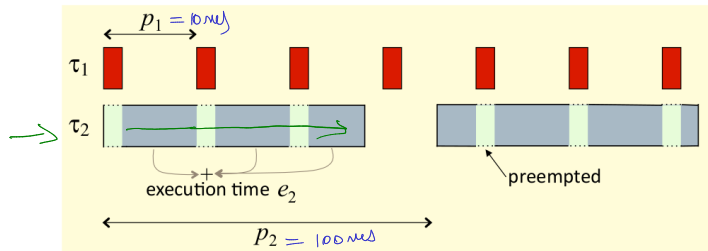
- ▶ Preemptive vs. non-preemptive scheduling
- ▶ Periodic vs. aperiodic tasks
- ▶ Fixed priority vs. dynamic priority
- ▶ Priority inversion anomalies
- ▶ Other scheduling anomalies

# Preemptive vs. non-preemptive

- ▶ Non-preemptive: once started, no task can be interrupted until it finishes
- ▶ Preemptive: a task can be interrupted (the OS decides exactly when)
- ▶ Scheduling for preemptive systems is more complex:
  - ▶ Every task has a priority
  - ▶ At any instant, the task with the **highest priority** must be executed
  - ▶ Any high priority task must take precedence over a lower priority task

# Rate Monotonic Scheduling (RMS)

- ▶ Algorithm for scheduling periodic tasks
- ▶ Given  $N$  **periodic** tasks, how to assign priorities to them?
- ▶ **Rate Monotonic Scheduling (RMS)**: assign task priority by period:  
task with smaller period has higher priority



	Period	Priority
$T_1$	50ms	2
$T_2$	20ms	3
$T_3$	10ms	4
$T_4$	20ms	3
$T_5$	100ms	1

$\Rightarrow$

Figure 12.3: Two periodic tasks  $T = \{\tau_1, \tau_2\}$  with a preemptive schedule that gives higher priority to  $\tau_1$ .



# Optimality of RMS

- ▶ A **feasible schedule** = all task finish times are before their deadlines
  - ▶ no deadline is exceeded
- ▶ **Theorem**: If the set of N tasks can be arranged to form a feasible schedule, then the RMS scheduling is feasible.

Feasible :

	<u>Period</u>	<u>Duration</u>	
$T_1$	100 ms	70 ms	→ 70 %
$T_2$	10 ms	2 ms	→ 20 %
			<u>90 %</u>

Impossible : (not feasible)

	<u>Period</u>	<u>Duration</u>	
$T_1$	100 ms	70 ms	→ 70 %
$T_2$	10 ms	5 ms	→ 50 %
			<u>&gt; 100 %</u>

## Earliest Deadline First (EDF)

- ▶ Algorithm for scheduling non-periodic tasks
- ▶ Given N non-periodic independent tasks with arbitrary arrival times and deadlines
- ▶ **Earliest Deadline First** (EDF) scheduling: execute the task with the earliest deadline among all available tasks
- ▶ Note: If a new task that just arrived can interrupt the current task, in case it has an earlier deadline

# Earliest Deadline First (EDF)

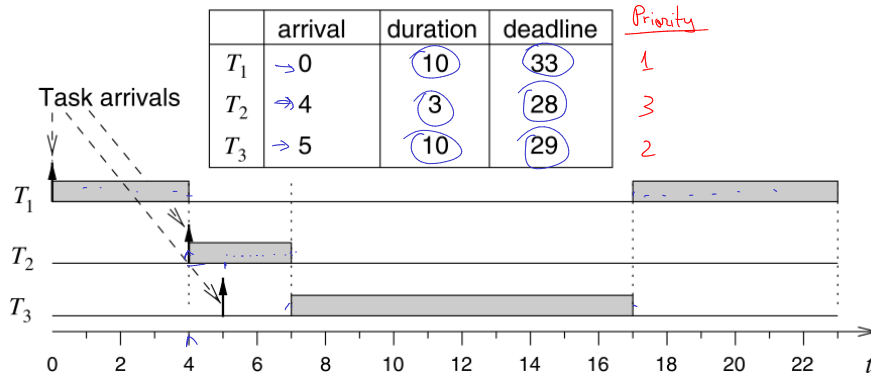


Figure 6.6. EDF schedule

## Earliest Deadline First (EDF)

Explanations for EDF example:

- ▶ At time 0 we have only task T1, start executing it
- ▶ At time 4 task T2 arrives, with deadline 28 which is smaller than T1's deadline 33. Interrupt T1 and start executing T2
- ▶ At time 5 task T3 arrives, with deadline 29 which is later than T2. Keep executing T2
- ▶ At time 7 task T2 finishes. Out of T1 and T3, T3 has the earliest deadline, so start executing T3
- ▶ At time 17 task T3 finishes. Only T1 is left, so resume executing T1 until it finishes

# Optimality of EDF

- ▶ **Theorem:** EDF scheduling minimizes the maximum lateness of the tasks

- ▶ The maximum lateness of a set of N tasks is:

$$L_{max} = \max(\underline{f_i} - \underline{d_i})$$

$L_{max} > 0$  : deadline is surpassed  
 $L_{max} < 0$  : all deadlines are met

i.e. the maximum exceeding of a deadline

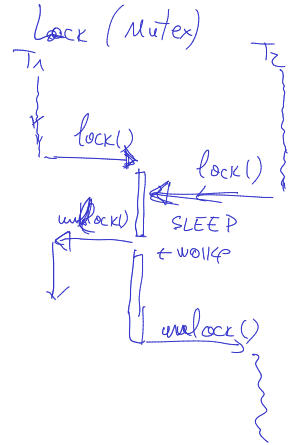
- ▶  $f_i$  is the actual finish time of the task
  - ▶  $d_i$  is the deadline of the task, i.e. when it was supposed to be finished
  - ▶ lateness of a task is  $L = f_i - d_i$
  - ▶ if  $L > 0$ , the task is late, i.e. its deadline was exceeded
  - ▶ if  $L < 0$ , the task is early, i.e. it finished ahead its deadline
- ▶ EDF minimizes the maximum lateness among all tasks. If no deadline is exceeded,  $L_{max} < 0$  and EDF maximizes the safety margin between the finish time and the deadline

	<u>Finish time</u>	<u>Deadline</u>
$T_1$	70	75
$T_2$	65	75
$T_3$	72	80

$$L_{max} = -5 \text{ ms}$$

# Priority Inversion

- ▶ Although scheduling looks simple, some complicated and undesired effects might happen (scheduling anomalies) especially when tasks share resources and use critical sections
- ▶ **Priority Inversion**: scheduling anomaly where high-priority task is blocked while unrelated lower-priority tasks execute
- ▶ Can cause serious problems, such as system resets and data loss
  - ▶ Example: Mars Pathfinder mission in 1997.



# Priority Inversion

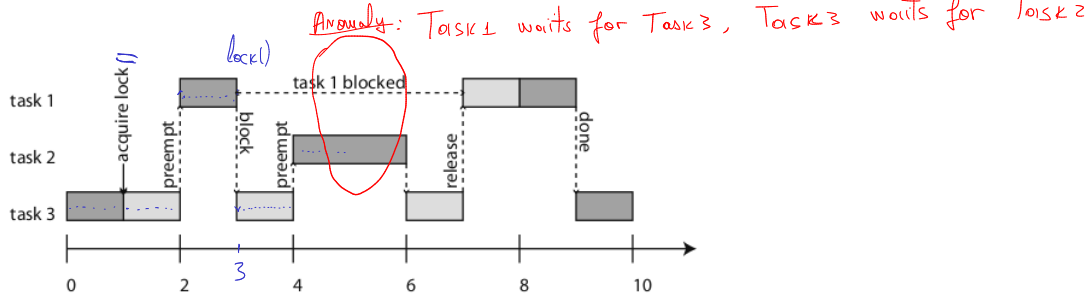
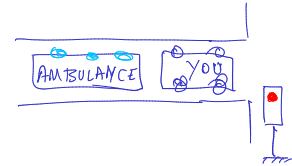


Figure 12.9: Illustration of priority inversion. Task 1 has highest priority, task 3 lowest. Task 3 acquires a lock on a shared object, entering a critical section. It gets preempted by task 1, which then tries to acquire the lock and blocks. Task 2 preempts task 3 at time 4, keeping the higher priority task 1 blocked for an unbounded amount of time. In effect, the priorities of tasks 1 and 2 get inverted, since task 2 can keep task 1 waiting arbitrarily long.



← explicit

# Avoiding Priority Inversion

- ▶ Options for avoiding priority inversion:
  - ▶ Priority inheritance
  - ▶ Priority ceiling
  - ▶ Priority boosting

## Priority inheritance protocol: (PIP)

- ▶ When a task blocks while trying to acquire a lock, the task holding the lock **inherits** the priority of the blocked task.
- ▶ This ensures that the task holding the lock cannot be preempted by a task with lower priority than the blocked task.



# Priority inheritance

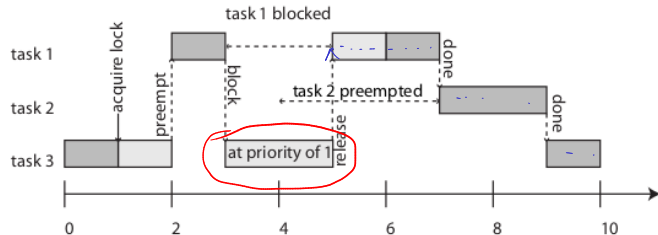


Figure 12.10: Illustration of the priority inheritance protocol. Task 1 has highest priority, task 3 lowest. Task 3 acquires a lock on a shared object, entering a critical section. It gets preempted by task 1, which then tries to acquire the lock and blocks. Task 3 inherits the priority of task 1, preventing preemption by task 2.

# Deadlock

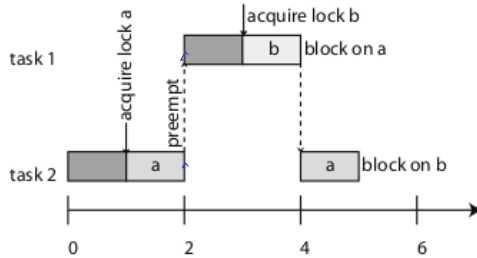


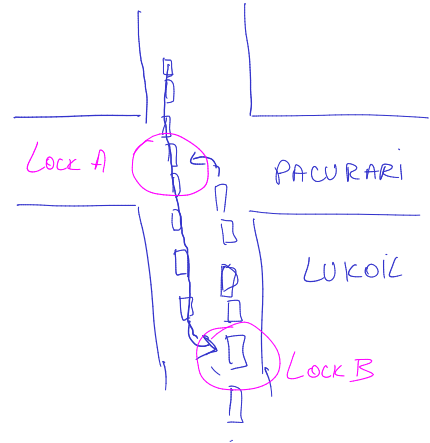
Figure 12.11: Illustration of **deadlock**. The lower priority task starts first and acquires lock a, then gets preempted by the higher priority task, which acquires lock b and then blocks trying to acquire lock a. The lower priority task then blocks trying to acquire lock b, and no further progress is possible.

# Deadlock

- ▶ A task holds a lock A and blocks waiting for a lock B
- ▶ Another task holds the lock B and blocks waiting for a lock A
- ▶ Result: both tasks are blocked for ever

Possible solutions:

- ▶ Priority ceiling
- ▶ Lock ordering



# Priority Ceiling Protocol

- ▶ Priorities can be used to prevent certain types of deadlocks
- ▶ **Priority ceiling protocol:**
  - ▶ Every lock is assigned a priority ceiling, equal to the priority of the highest-priority task that can lock it.
  - ▶ A task can acquire a lock only if its priority is **strictly higher** than the priority ceilings of all locks **currently held** by other tasks
- ▶ What happens:
  - ▶ Suppose all locks can be acquired by any task, so priority ceiling of all locks is equal to  $P_{max}$  = maximum priority among all tasks
  - ▶ Suppose one task holds a lock A, so priority ceiling of all locks **currently held** is  $P_{max}$
  - ▶ Another task cannot hold another lock B unless its prio is **strictly higher** than  $P_{max}$   $\Rightarrow$  impossible  $\Rightarrow$  can't lock B  $\Rightarrow$  no deadlock

# Priority Ceiling Protocol

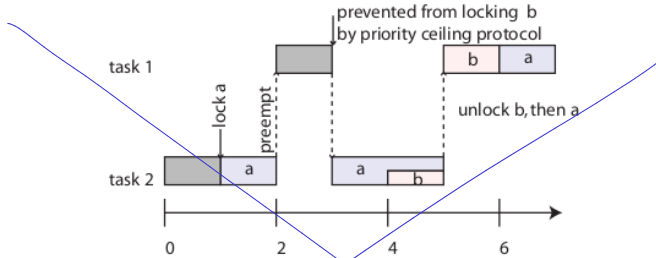


Figure 12.12: Illustration of the priority ceiling protocol. In this version, locks a and b have priority ceilings equal to the priority of task 1. At time 3, task 1 attempts to lock b, but it cannot because task 2 currently holds lock a, which has priority ceiling equal to the priority of task 1.

# Priority Ceiling Protocol

Drawbacks:

- ▶ Implementing the priority ceiling protocol requires being able to determine in advance which tasks acquire which locks

# Lock ordering

Assign each lock a unique numerical value, and require that locks be acquired in increasing order

Example:

- ▶ A system with three locks, A, B, and C, and two threads, T1 and T2.
- ▶ We have deadlock if T1 holds A and needs B, and T2 holds B and needs A

Solution with lock ordering:

- ▶ Assign each lock a unique numerical value: A=1, B=2, and C=3, and require that locks be acquired in increasing order
- ▶ T2 is not allowed to acquire B before A, so "*and T2 holds B and needs A*" is impossible
- ▶ T2 must first acquire A before it can get B, so it waits for T1 to release A
- ▶ Deadlock is avoided

lock() A

lock() B

lock() C

unlock() C

unlock() B

unlock() A