EE345M/EE380L:
Real Time Operating Systems

Guest Lecture - Real-Time Scheduling

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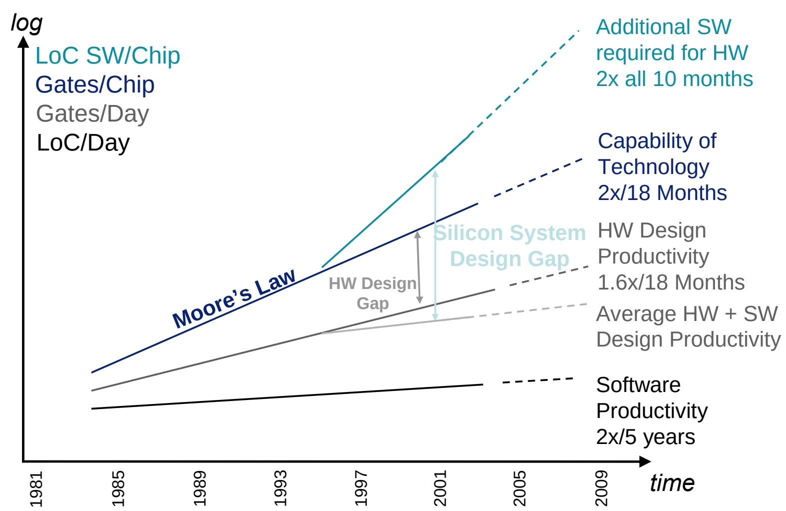
UT ECE

Outline

- **Real-time scheduling problem**
  - Scheduling models
  - Scheduling algorithms
- **Classic periodic task scheduling**
  - Rate-monotonic and earliest-deadline-first
  - Scheduling anomalies
- **Multi-processor scheduling**
  - Symmetric and asymmetric multi-processing

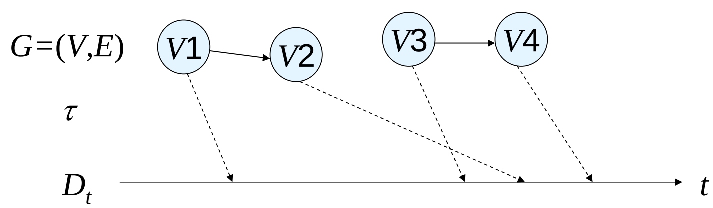
Embedded Software



Source: W. Ecker, W. Müller, R. Dömer, *Hardware-dependent Software - Principles and Practice*, Springer 2009.

Scheduling

- **Assume that we are given a specification graph $G=(V,E)$**
- **A *schedule* τ of G is a mapping**
  $$V \rightarrow D_t$$
  of a set of tasks V to start times from domain D_t



➢ **In traditional embedded system design (simple model)**
  - Uni-processor scheduling
  - Hardware accelerators as special case

Source: P. Marwedel

Scheduling Model

- **Task model of computation**
  - Set of tasks $\{ T_1, T_2, \ldots \}$
    - Task T_i := process/actor
  - Independent tasks vs. task graph
    - Task graph = precedence graph (= HSDF)
  - Aperiodic vs. periodic (vs. sporadic) tasks
    - Timed model of computation: arrival/release time a_i, period t_i
- **Task metrics**
  - Execution time e_i
    - Estimation? Worst case upper bounds
- **Real-time constraints and cost functions**
  - Throughput fixed in uni-processor case, focus on latency
    - Response time r_i = finish time f_i – arrival time a_i
    - Deadline d_i: $r_i < d_i$, in periodic case often $d_i = t_i$ (soft vs. hard deadlines)
    - Lateness $l_i = r_i - d_i$

Real-Time Scheduling

- **Static vs. quasi-static (static order) vs. dynamic**
  - Statically known arrival times and dependencies?
  - Statically known execution times (bounds)?
  - ➢ Many algorithms support static & dynamic
    - Design-time priority/order to provide guarantee/bounds
    - Run-time triggering (self-timed execution) to recover variations
- **Preemptive vs. non-preemptive**
  - Non-simultaneous task arrivals, long-running tasks?
    - Preemption to increase responsiveness, but context switch overhead

➢ **Optimization objectives**
  - Schedulability analysis
    - Ability to satisfy all deadlines (while maximizing CPU utilization)
  - Minimize cost function
    - E.g. response times, lateness
  - Implementation overhead
    - Decision making, timed-triggered execution, preemption

Real-Time Scheduling Algorithms (1)

- **Aperiodic, independent tasks (task set)**
  - Simultaneous (at system start) arrival times
    - Earliest Due Date (EDD) minimizes max. lateness (non-preemptive)
  - Arbitrary arrival times (statically know or dynamic)
    - Earliest Deadline First (EDF) minimizes max. lateness (preemptive)
    - Without preemption optimality only possible if arrival times known
- **Aperiodic, dependent tasks (task graph)**
  - Simultaneous (at system start) arrival times
    - Latest Deadline First (LDF) minimizes max. lateness (non-preempt.)
  - Arbitrary arrival times (statically know or dynamic)
    - Modified EDF* w/ successor-adjusted deadlines

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Real-Time Scheduling Algorithms (2)

- **Periodic, independent tasks**
  - Schedulability only (preemptive, static or dynamic)
    - Rate Monotonic Scheduling (RMS) is optimal fixed priority scheme
      - » Does not achieve 100% CPU utilization for guaranteed schedulability
    - Earliest Deadline First (EDF) is optimal dynamic priority scheme
      - » 100% utilization, but runtime support/overhead for dynamic priorities
- **Periodic/sporadic, dependent tasks**
  - NP-complete in general
    - Use of heuristics, see multi-processor scheduling
    - Split into periodic, independent and aperiodic, dependent subgraphs
  - ➢ Scheduling anomalies through dependencies (blocking)
    - Deadlocks
    - Priority inversions

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Outline

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  - Scheduling anomalies
- **Multi-processor scheduling**
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Periodic Task Scheduling

- **Scheduling Policies**
  - RMS – Rate Monotonic Scheduling
    - Task Priority = Rate = 1/Period
    - RMS is the optimal preemptive *fixed-priority* scheduling policy
  - EDF – Earliest Deadline First
    - Task Priority = Current Absolute Deadline
    - EDF is the optimal preemptive *dynamic-priority* scheduling policy
- **Scheduling assumptions**
  - Single processor
  - All tasks are periodic
  - Zero context-switch time
  - Worst-case task execution times are known
  - No data dependencies among tasks

➢ **RMS and EDF have both been extended to relax these**

Metrics

- **How do we evaluate a scheduling policy**
  - Ability to satisfy all deadlines
  - CPU utilization
    - Percentage of time devoted to useful work
  - Scheduling overhead
    - Time required to make scheduling decision
- **Constraints**
  - Set of tasks *T* with period τ_i each

Rate Monotonic Scheduling (RMS)

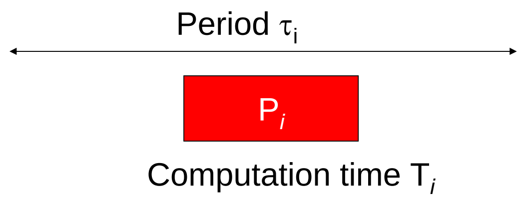
- **Model**
  - All process run on single CPU.
  - Zero context switch time.
  - No data dependencies between processes.
  - Process execution time is constant.
  - Deadline is at end of period.
  - Highest-priority ready process runs.

➢ **RMS [Liu and Layland, 73]**
  - Widely-used, analyzable scheduling policy.

➢ **Rate Monotonic Analysis (RMA)**
  - Theoretical analysis

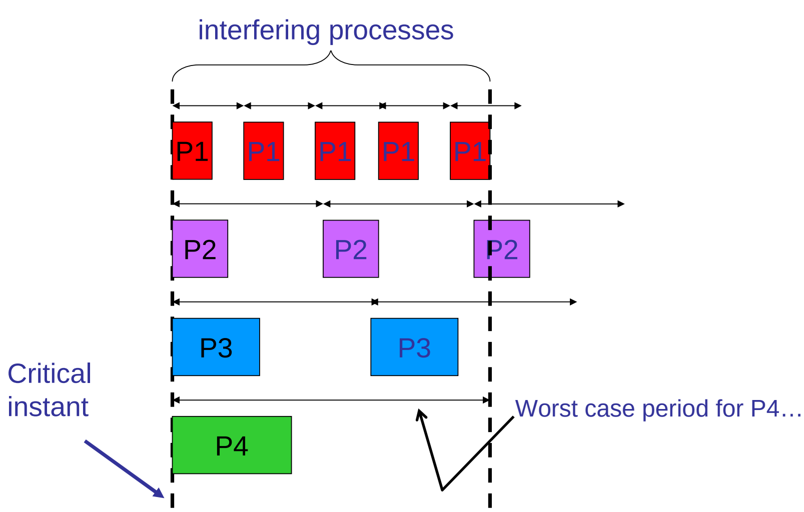
Process Parameters

- T_i is execution time of process *i*
- Deadline τ_i is period of process *I*



- **Response time**
  - Time required to finish a process/task.
- **Critical instant**
  - Scheduling state that gives worst response time.
    - Occurs when all higher-priority processes are ready to execute.

Critical Instant



RMS Priorities

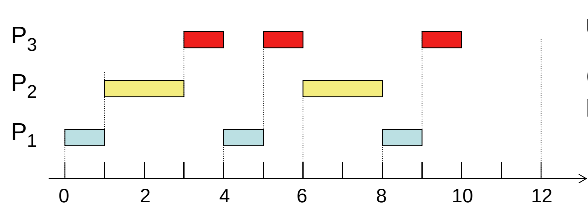
- **Optimal (fixed) priority assignment**
  - Shortest-period process gets highest priority
    - priority based preemption can be used…
  - Priority inversely proportional to period
  - Break ties arbitrarily

- **No fixed-priority scheme does better.**
  - *RMS provides the highest worst case CPU utilization while ensuring that all processes meet their deadlines*

RMS Example 1

Process P_i	Execution Time T_i	Period t_i
P_1	1	**4**
P_2	2	**6**
P_3	3	**12**

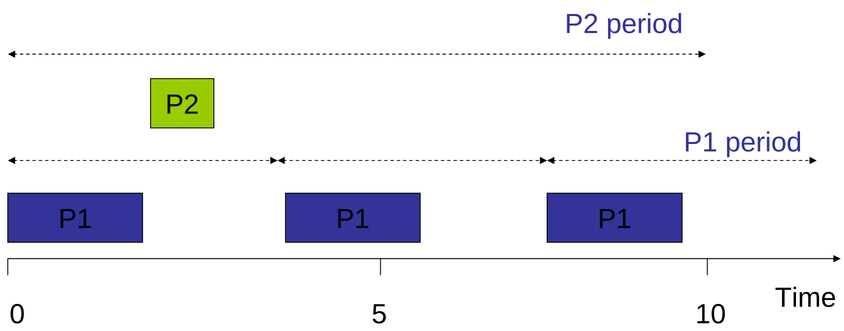
Static priority: P1 >> P2 >> P3



Unrolled schedule

(least common multiple of process periods)

RMS Example 2



RMS CPU Utilization

- **Utilization for *n* processes is**

  $\sum_i T_i / \tau_i$

- **Schedulability analysis**

  $\sum_i T_i / \tau_i \leq n(2^{1/n} - 1)$

- **As number of tasks approaches infinity, the *worst case* maximum utilization approaches 69%**
  - Yet, is not uncommon to find total utilizations around .90 or more (.69 is worst case behavior of algorithm)
  - Achievable utilization is strongly dependent upon the relative values of the periods of the tasks comprising the task set…

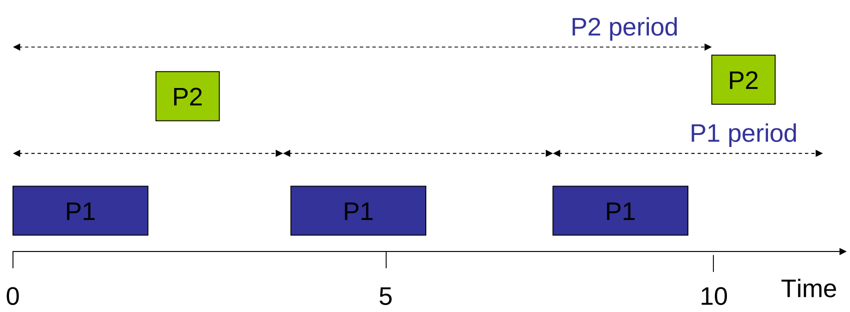
RMS Example 3

Process P_i	Execution Time T_i	Period t_i
P_1	1	**4**
P_2	6	**8**

Is this task set schedulable?? If yes, give the CPU utilization.

RMS CPU Utilization (cont'd)

- **RMS cannot asymptotically *guarantee* use of 100% of CPU, even with zero context switch overhead.**
  - Must keep idle cycles available to handle worst-case scenario.
- **However, RMS guarantees all processes will always meet their deadlines.**



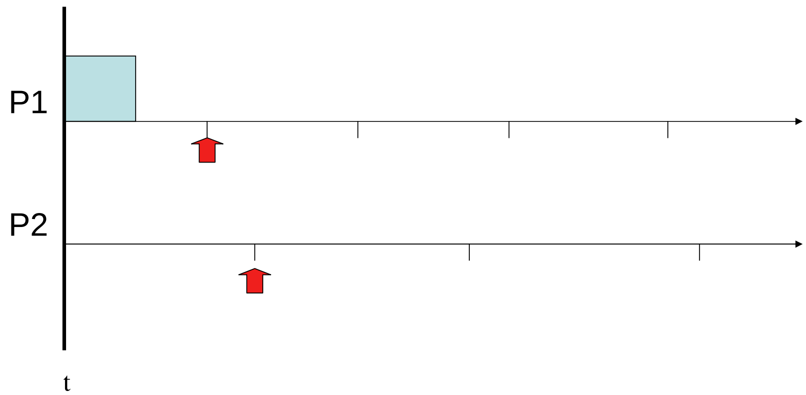
RMS Implementation

- **Statically fixed priority assignment**
  - Inversely proportional to period
- **Efficient implementation**
  - Scan processes
  - Choose highest-priority active process

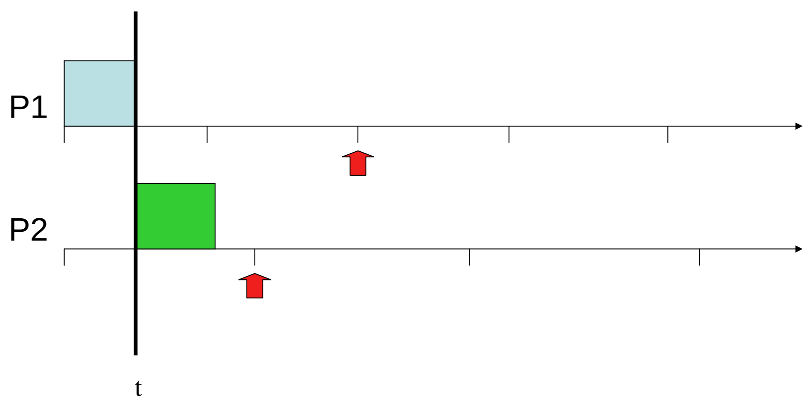
Earliest-Deadline-First (EDF) Scheduling

- ***Dynamic* priority scheduling scheme.**
  - Process closest to its deadline has highest priority
  - Requires recalculating processes at every timer interrupt
- **EDF analysis**
  - EDF can use 100% of CPU for worst case
  - Optimal for periodic scheduling
- **EDF implementation**
  - On each timer interrupt:
    - Compute time to deadline
    - Choose process closest to deadline
  - Generally considered too expensive to use in practice, unless the task count is small
    - Does not work in an OS with only fixed priorities!

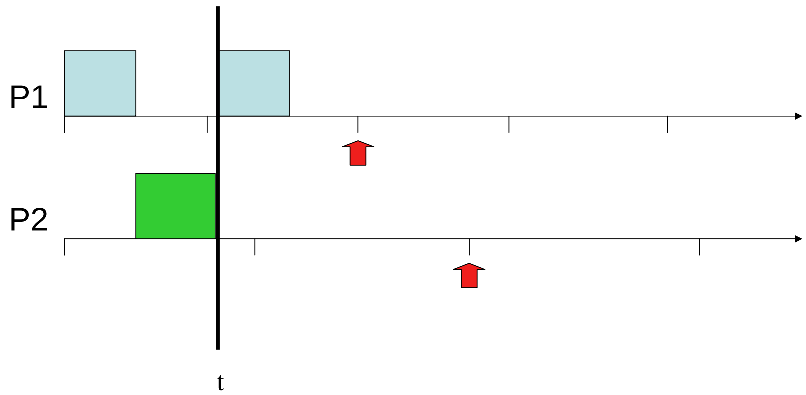
EDF Example



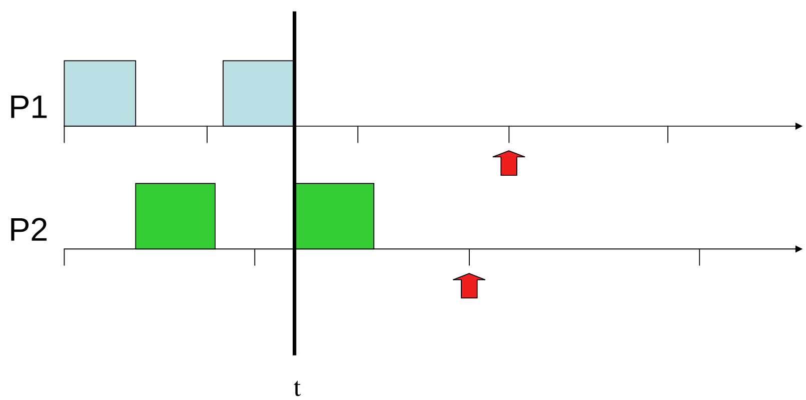
EDF Example



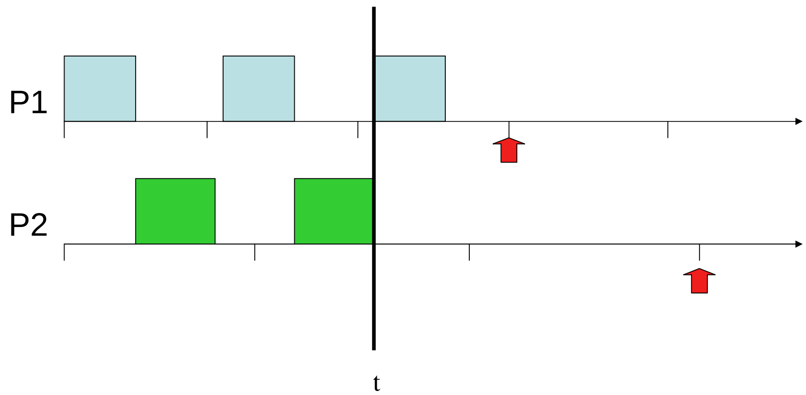
EDF Example



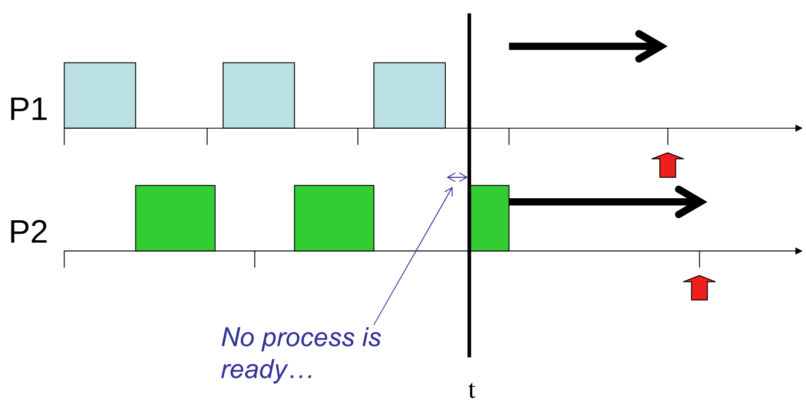
EDF Example



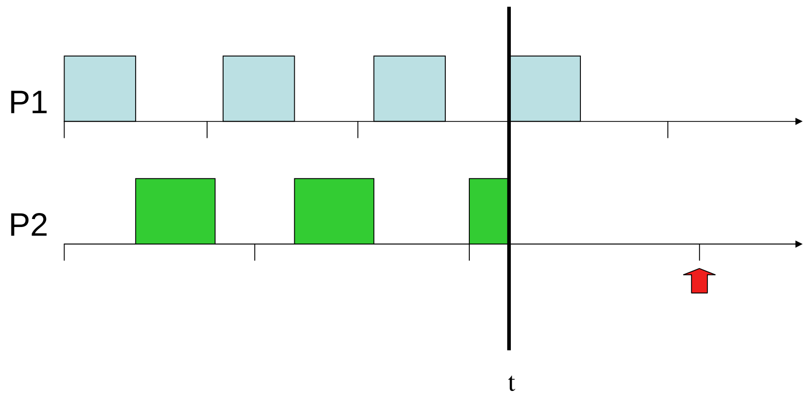
EDF Example



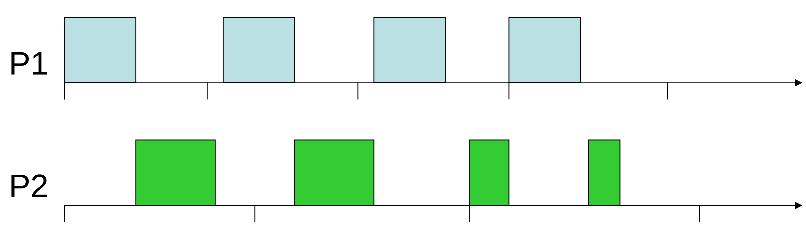
EDF Example



EDF Example

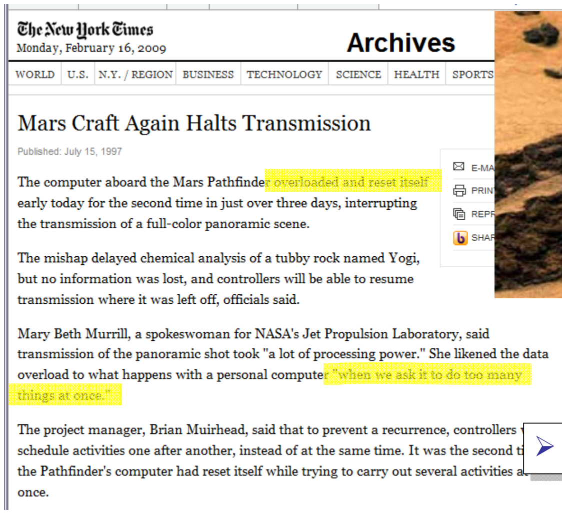


EDF Example



Scheduling Anomalies

- **"What really happened on Mars?" [WindRiver97]**



The New York Times
Monday, February 16, 2009
Archives

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Mars Craft Again Halts Transmission

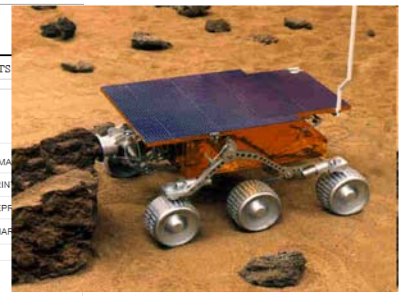
Published: July 15, 1997

The computer aboard the Mars Pathfinder overloaded and reset itself early today for the second time in just over three days, interrupting the transmission of a full-color panoramic scene.

The mishap delayed chemical analysis of a tubby rock named Yogi, but no information was lost, and controllers will be able to resume transmission where it was left off, officials said.

Mary Beth Murrill, a spokeswoman for NASA's Jet Propulsion Laboratory, said transmission of the panoramic shot took "a lot of processing power." She likened the data overload to what happens with a personal computer "when we ask it to do too many things at once."

The project manager, Brian Muirhead, said that to prevent a recurrence, controllers w... schedule activities one after another, instead of at the same time. It was the second ti... the Pathfinder's computer had reset itself while trying to carry out several activities a... once.



Courtesy NASA/JPL-Caltech

- ➢ **Priority inversion**

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Priority Inversion

- **Low-priority process keeps high-priority process from running.**
  - Improper use of system resources can cause scheduling problems
    - Low-priority process grabs I/O device.
    - High-priority device needs I/O device, but can't get it until low-priority process is done.
  - ➢ Can cause deadlock

- ➢ **Give priorities to system resources**
- ➢ **Have process inherit the priority of a resource that it requests**
  - ➢ Low-priority process inherits priority of device if higher

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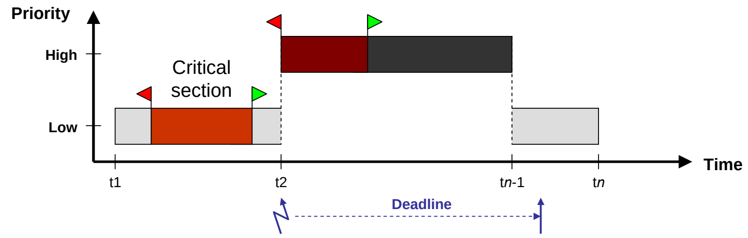
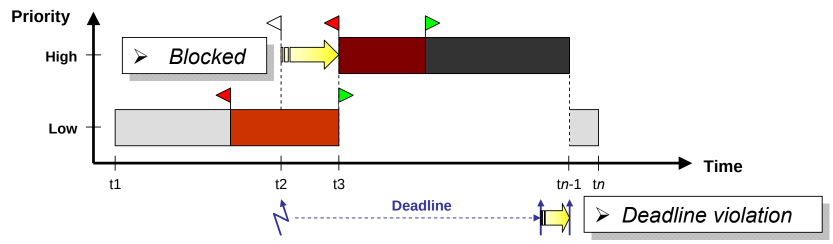
Priority-Based Scheduling

- **Normal operation**

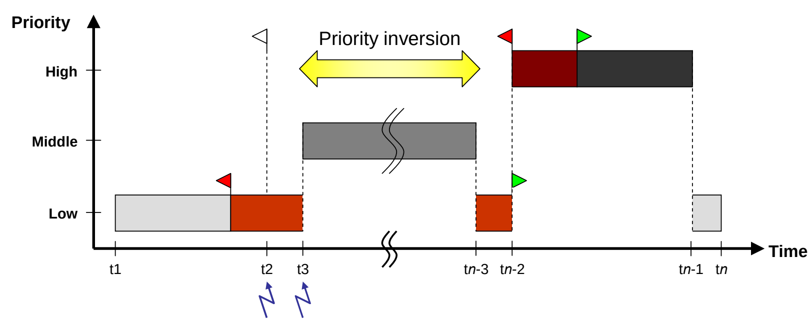


- **Priority inversion**



Priority Inversion

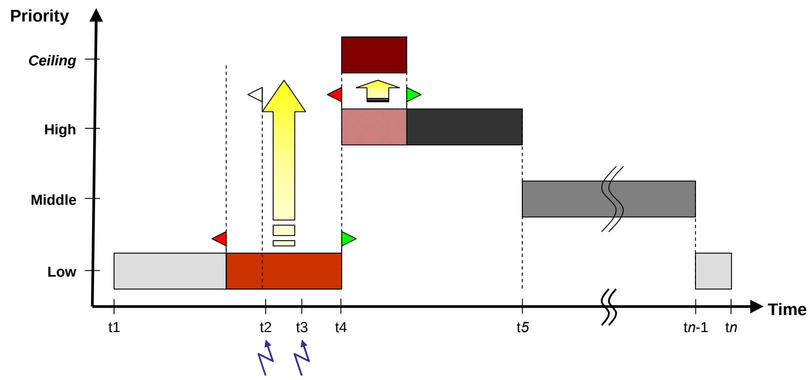
- **Low-priority process blocking a high-priority one**
  - Starvation of high priority processes



➢ **Avoid preemption in critical sections [Sha90]**
- ➢ Interrupt masking
- ➢ Priority Ceiling Protocol *(*PCP)
- ➢ Priority Inheritance Protocol (PIP)

Priority Ceiling Protocol (PCP)

- **Elevate priorities in critical sections**
  - Assign priority ceilings to semaphore/mutex



- ➢ **Change task priority on semaphore/mutex access**
  - ➢ Also avoid potential deadlocks
  - ➢ Potential overhead & blocking of unrelated processes

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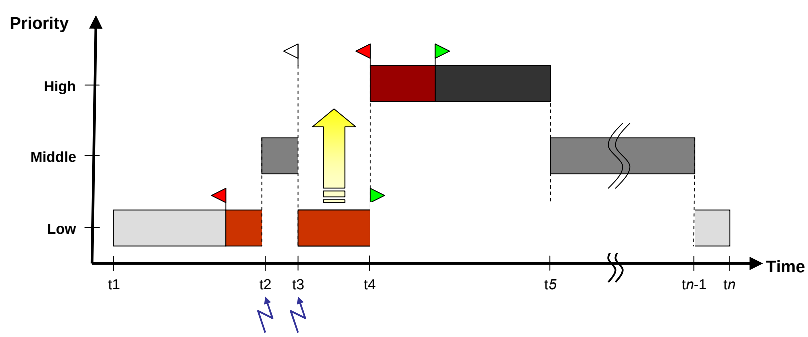
Priority Inheritance Protocol (PIP)

- **Dynamically elevate priorities only when needed**
  - Raise priorities to level of requesting task



- ➢ **Change priority on request by higher-priority task**
  - ➢ Potential for deadlocks remains
  - ➢ Potentially multiple priority changes per critical section

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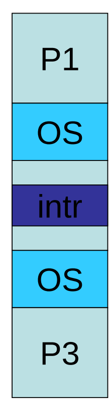
Performance Evaluation

- **Context switch time**
  - Non-zero context switch time can push limits of a tight schedule
  - Hard to calculate effects
    - Depends on order of context switches
  - In practice, OS context switch overhead is small
- **May want to test**
  - Context switch time assumptions on real platform
  - Scheduling policy

What about interrupts?

- **Interrupt overhead**
  - Interrupts take time away from processes
  - Other event processing may be masked during interrupt service routine (ISR)
  - Perform minimum work possible in the interrupt handler
- **Device processing structure**
  - Interrupt service routine (ISR) performs minimal I/O.
    - Get register values, put register values
  - Interrupt service process/thread performs most of device function.



Caches

- **Processes can cause additional caching problems.**
  - Even if individual processes are well-behaved, processes may interfere with each other
  - Worst-case execution time with *bad cache behavior* is usually much worse than execution time with good cache behavior

➢ **Perform schedulability analysis without caches**
  - Take any online performance gains as “free lunch”

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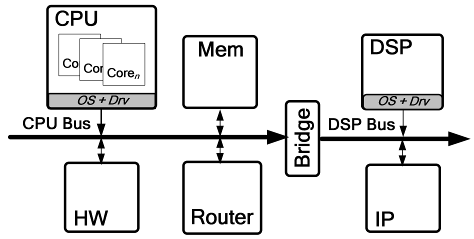
Multi-Processor System-on-Chip (MPSoC)

- **Multi-processor**
  - Heterogeneous
  - Asymmetric multi-processing (AMP)
  - Distributed memory & operating system



- **Multi-core**
  - Homogeneous
  - Symmetric multi-processing (SMP)
  - Shared memory & operating system
  - ➢ Multi-core processors in a multi-processor system
- **Many-core**
  - > 10 cores …

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MPSoC Scheduling

- **Scheduling**
  - Real-time scheduling on homogeneous multi-cores (SMP)
    - – Partitioned or global queue schedulers
    - – Task migration, load balancing, cache pollution
    - ➢ Uni-processor extensions: partitioned EDF, global EDF, PFair, …
  - Heterogeneous multi-processor scheduling (AMP)
    - – Minimize makespan (maximize throughput)
    - – Tight dependency on partition
    - – Distributed or centralized OS, coordination
    - ➢ Heuristics for static scheduling w/ dependencies: Hu's, list scheduling

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Summary

- **Embedded systems are real-time**
  - Doesn't equal fast
  - But means timing guarantees
- **Real-time scheduling**
  - Crucial to meeting timing guarantees
    - – Deadlines
    - – Latency/make-span
    - – Responsiveness