

# ECE 350

## Real-time Operating Systems



# Lecture 6: Real-time Systems

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Prof. Seyed Majid Zahedi

<https://ece.uwaterloo.ca/~smzahedi>

# Outline

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- Real-time systems
  - Definitions and features
- Real-time operating systems
  - Desirable properties, interrupt handling, memory management
- Uniprocessor real-time scheduling
  - RM, EDF, LLF, ...
  - Priority inversion
- Multiprocessor scheduling
  - Different scheduling classes, remote blocking

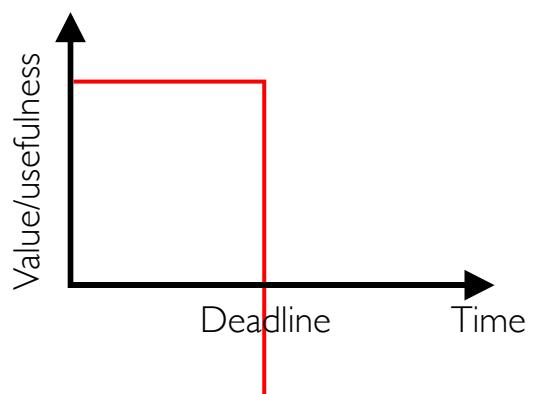
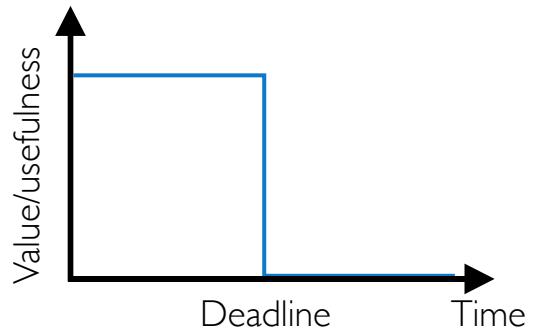
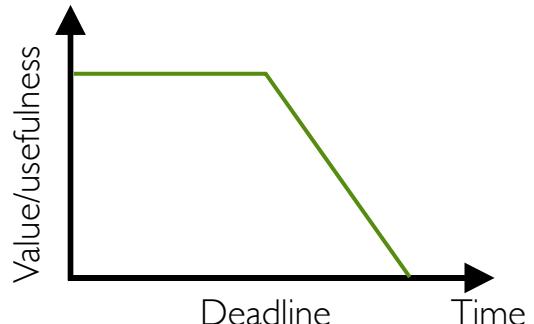
# Real-time Systems (RTSes)

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- Definition
  - Systems whose correctness depends on their **temporal** aspects as well as their **functional** aspects
- Performance measure
  - **Timeliness** on timing constraints (**deadlines**)
  - Speed/average case performance are less significant
- Key property
  - **Predictability** on timing constraints

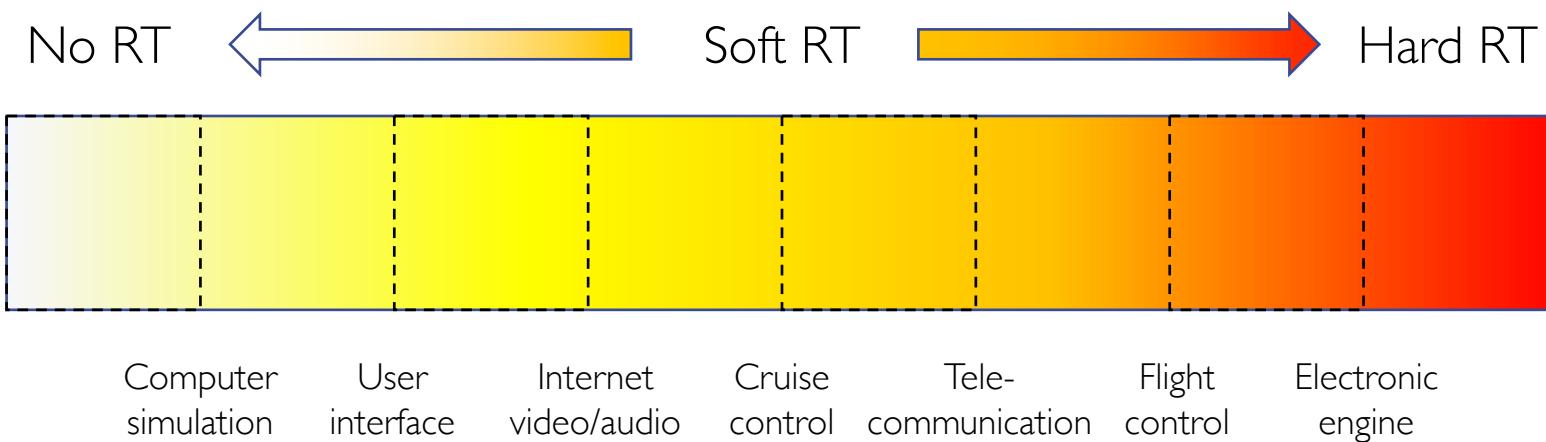
# Types of Real-time Systems

- **Soft**: must try to meet all deadlines
  - System does not fail if a few deadlines are missed
- **Firm**: result has no use outside deadline window
  - Tasks that fail are discarded
- **Hard**: must always meet all deadlines
  - System fails if deadline window is missed



# Real-time Spectrum

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# General-purpose OS are Inadequate for RTSes

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- Multitasking/scheduling
  - Provided through system calls
  - Does not take time into account and could introduce unbounded delays
- Interrupt management
  - Achieved by setting interrupt priority more than process priority
  - Increases system reactivity but may cause unbounded delays even due to unimportant interrupts
- Basic IPC and synchronization primitives
  - May cause priority inversion
  - Causes unbounded delays

# Real-time Operating System (RTOS): Desirable Properties

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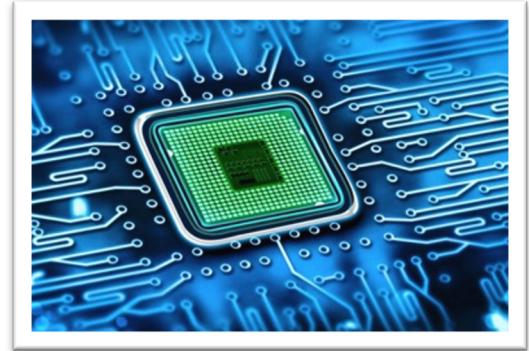
- Predictability
  - Guaranteeing in advance deadline satisfaction
  - Notifying when deadline cannot be guaranteed
- Timeliness
  - Handling tasks with explicit time constraints
- Fault tolerance
  - Avoiding crashes even with HW/SW failures
- Design for peak load
  - All scenarios must be considered
- Maintainability



# Microarchitecture

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- I/O devices and CPU typically share the same bus
  - DMA steals CPU memory cycle to transfer data (cycle stealing)
  - CPU waits until the transfer is completed
    - Source of **non-determinism!**
  - Possible solution: **time-slice method**
    - Each memory cycle is split in two adjacent time slots one for CPU one for DMA
    - More costly, but more predictable!
- Caches speedup execution by keeping data close to CPU
  - The same load/store instruction could experience different delays depending on **hitting or missing** in cache  $\Rightarrow$  source of non-determinism!
  - Possible solution: processors without cache
    - Slow execution, but more predictable!



# System Calls and Interrupts

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- System call handler is usually **non-preemptable**
  - Real-time task could be **delayed** while handler runs
  - Delays could lead to **missed deadlines**
  - Possible solution: make all kernel primitives, including system call handlers, preemptable!
- Interrupt handler should **remain** non-preemptable
  - Interrupt handler runs immediately when interrupts happen
  - While handler runs, execution of interrupted task is delayed
  - Solution I: disable all interrupts, only keep timer interrupt, tasks directly communicate with any I/O devices they need, data is transferred by polling
    - + Unbounded delays due to unexpected device handling is eliminated
    - + Time for data transfers can be estimated precisely
    - + No change of kernel is needed when adding devices
    - – Performance of processor is degraded (busy waiting)
    - – Tasks must know low level details of drives



# System Calls and Interrupts (cont.)

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- Solution II: disable interrupts, only keep timer interrupts, handle I/O by timer-activated device routines within kernel tasks, data is transferred by polling
  - + Unbounded delays due to unexpected device handling is eliminated
  - + Execution time of periodic device routines can be estimated in advance
  - + Hardware details are encapsulated in dedicated device routines
  - – Performance of processor is degraded (still busy waiting for I/O)
  - – Kernel has to be modified every time new device is added
  - – Communicating with devices involves more inter-task communications than first solution
- Solution III: enable interrupts, reduce device drivers to least possible size, driver activates proper task to handle device, kernel runs driver-activated tasks like any other task, user tasks may have higher priority than driver-activated tasks
  - + Busy waiting is eliminated
  - + Kernel doesn't need to be modified when adding new devices!
  - o Communicating with devices may still involve some inter-task communications
  - o Unbounded delay due to unexpected device handling is not eliminated but is dramatically reduced

# Memory Management

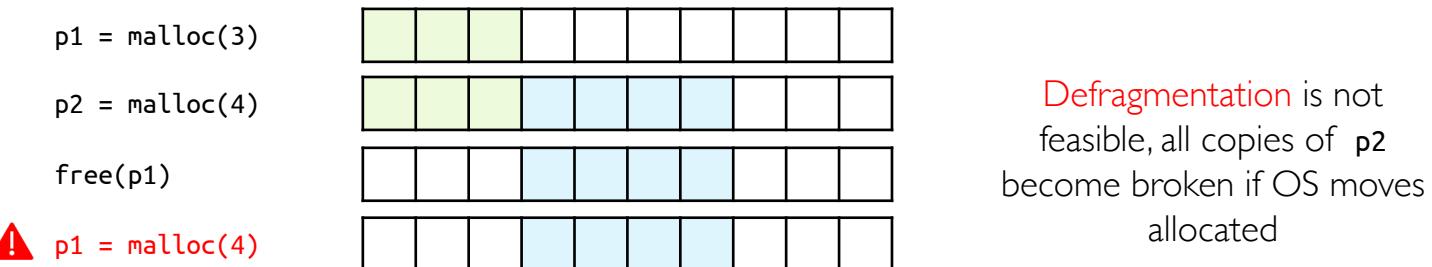
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- General-purpose OSes allow each process to access only its own virtual address
  - Virtual and physical address spaces are divided into virtual and physical *pages*
  - Virtual to physical page translations are stored in memory as *page tables (PT)*
  - To speedup memory accesses, PT entries are cached in *translation lookaside buffer (TLB)*
  - TLBs introduce non-deterministic delay (hit or miss)
  - Possible solution: avoid using virtual memory, allow user tasks to use physical memory
- When memory is full, most OSes swap out some pages to make room for others (this is called *paging*, more about it later!)
  - Accessing evicted pages causes *page fault*
  - Page fault handling & *page replacement policy* cause non-deterministic delays
  - Possible solution: use selective page locking to increase determinism

# Programming Languages

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- Dynamic memory operations (e.g., malloc and free) are **unpredictable**
  - Memory allocator runs **non-deterministic** space optimization algorithms
  - Requests could fail due to **fragmentation** even if there is free memory

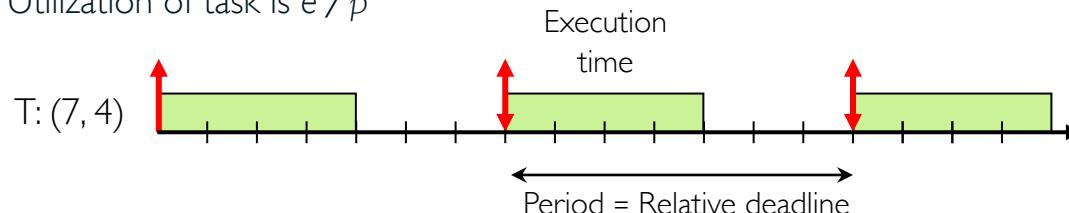


- Possible solution: partition memory into fixed-size blocks (**partition pools**)
- Another solution: prevent dynamic data structures all together
  - Flexibility is reduced in dynamic environment
- Recursion could lead to **unbounded execution time**
  - Possible solution: only allow time-bound loops
- Example of RT programming languages
  - Real-Time Java, Concurrent C, Euclid

# Scheduling

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- General-purpose schedulers are **system-oriented**
  - Maximize avg. system throughput
- RTSes need **task-centric** scheduling
  - Minimize **worst-case** response time for each task
  - Predictability  $\neq$  fast computing
- Real-time tasks
  - **Periodic:** set of jobs arriving at fixed period ( $p$ )
    - Each job has worst-case execution time ( $e$ ) and hard relative deadline ( $d \leq p$ , usually  $d = p$ )
    - Utilization of task is  $e / p$



- **Aperiodic:** arrive randomly without any hard deadline
- **Sporadic** task arrives randomly with hard deadline
- **Independent** vs. **interdependent** and **preemptable** vs. **non-preemptable**

# Terminology of Real-time Scheduling

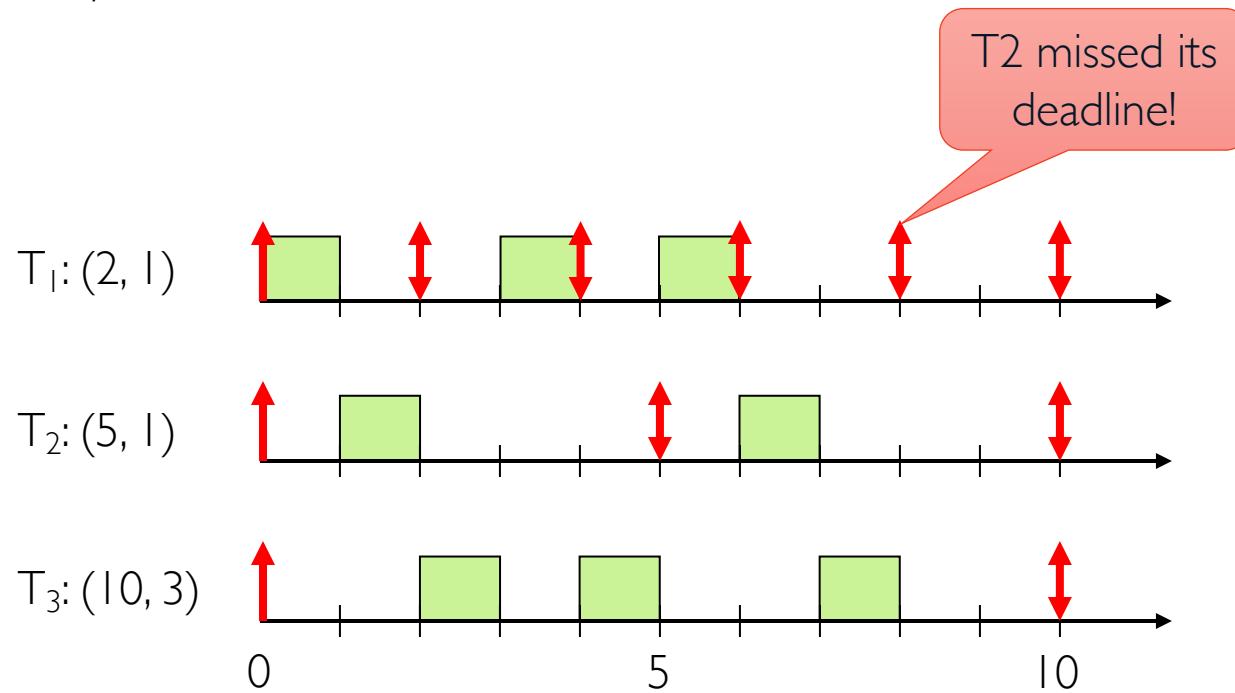
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- **Static scheduling:** priority of each task does not change over time
  - E.g., rate monotonic (RM)
- **Dynamic scheduling:** priority of each job does not change over time
  - E.g., earliest deadline first (EDF)
- **Fully-dynamic scheduling:** priority of each job could change over time
  - E.g., least laxity first (LLF)
- Schedule  $S$  is **feasible** if all deadline are met
- Task set  $T$  is **schedulable** under scheduling class  $C$  if there exists scheduling algorithm  $A$  in  $C$  that produces feasible schedule for  $T$
- Scheduling algorithm  $A$  is **optimal** w.r.t. scheduling class  $C$  if it produces feasible schedule for any schedulable task set  $T$  under  $C$

# General-purpose Schedulers for RTSes

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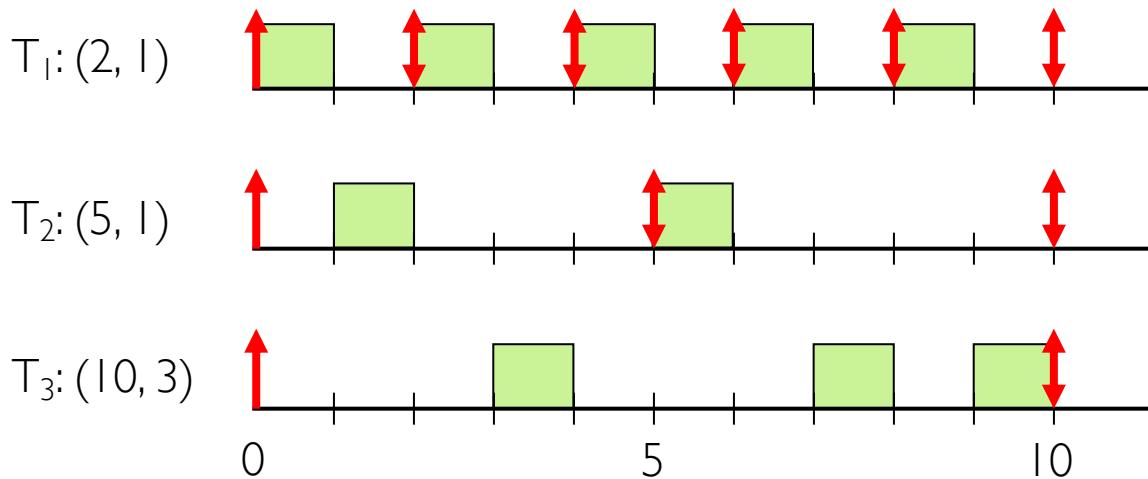
- RR example:



# Rate Monotonic (RM)

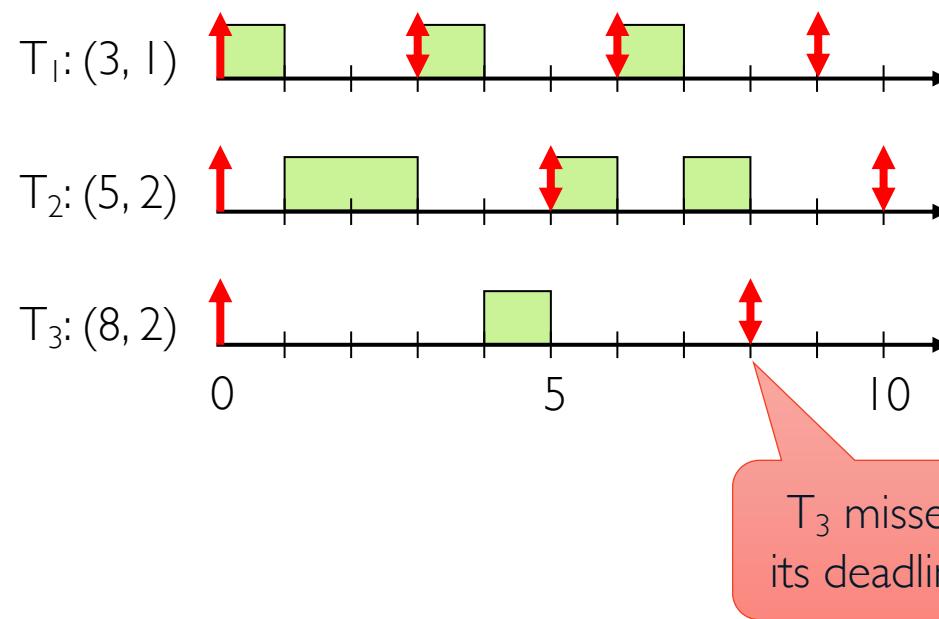
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- RM makes following assumptions
  - Tasks are periodic and independent with known and fixed execution times
- RM is static online scheduling policy
  - Higher priorities are assigned to tasks with shorter periods
  - Priority of each task is fixed and doesn't change at run-time
  - RM is optimal w.r.t. static schedulers



# RM: Schedulability

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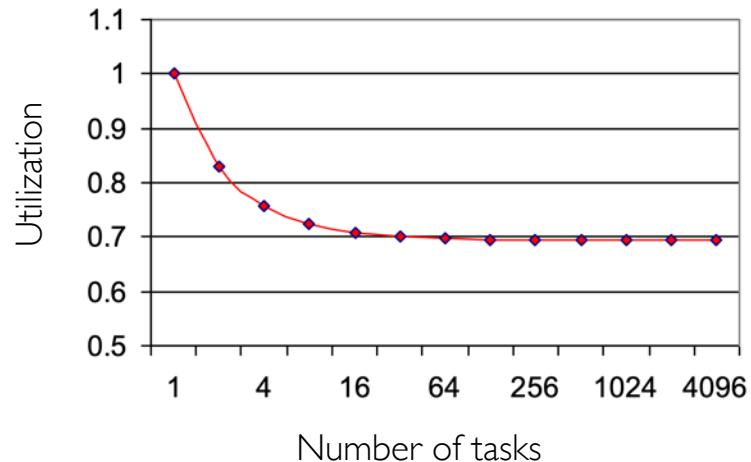


# RM: Schedulability Test [Liu & Layland 1973]

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- For  $n$  periodic tasks with execution time  $e_i$ , and deadline and period  $p_i$ , RM is guaranteed to produce feasible schedule if

$$\sum_{i=1}^n \left( \frac{e_i}{p_i} \right) \leq n(2^{1/n} - 1)$$

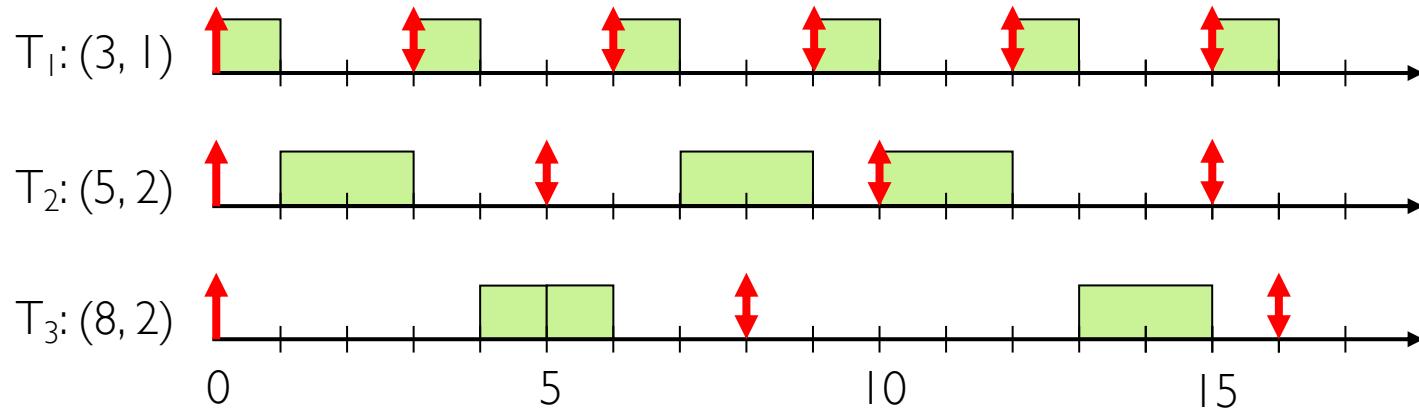


- If condition does not hold, then deadlines may or may not be met!
- Example:  $T_1(3,1)$ ,  $T_2(5,2)$ ,  $T_3(8,2)$ 
  - $1/3 + 2/5 + 2/8 (= 0.9833) \geq 3(2^{1/3}-1) (\approx 0.78) \Rightarrow$  No guarantee!

# Earliest Deadline First (EDF)

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- EDF is dynamic online scheduling policy
  - Scheduler always schedules active task with **earliest deadline**
  - Current priority of tasks depends on how close their deadline is
  - Tasks' priorities change during execution
  - EDF is optimal w.r.t. all online schedulers



# EDF: Schedulability Test [Liu & Layland 1973]

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- Even EDF won't work if you have too many tasks
- For  $n$  periodic tasks with execution time  $e_i$  and deadline and period  $p_i$ , EDF is guaranteed to produce feasible schedule if

$$\sum_{i=1}^n \left( \frac{e_i}{p_i} \right) \leq 1$$

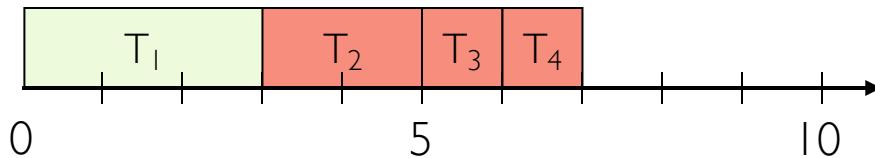
- System is overloaded if

$$\sum_{i=1}^n \left( \frac{e_i}{p_i} \right) > 1$$

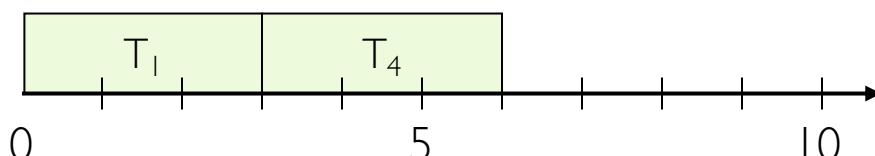
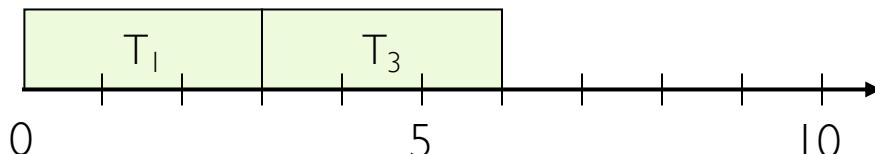
# Overloaded System under EDF

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- EDF schedule could be suboptimal for overloaded system
- Domino effect example:  $T_1(4,3), T_2(5,3), T_3(6,3), T_4(7,3)$

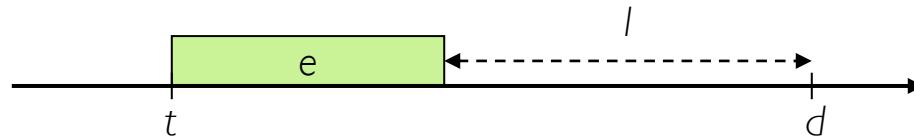


- Better schedules

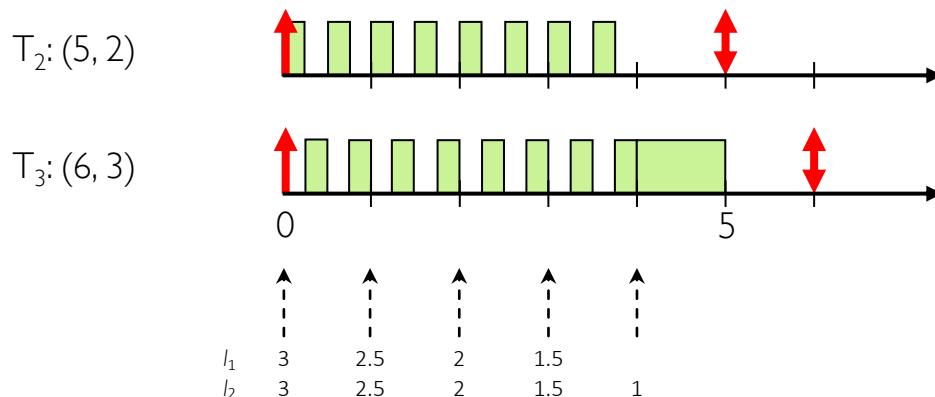


# Least Laxity First (LLF)

- LLF dynamically assigns priority to jobs based on their laxity (slack)
  - With absolute deadline  $d$  and remaining execution time  $e$ , laxity at time  $t$  is  $l = d - t - e$



- Job with the smallest laxity has the highest priority
- LLF is also optimal w.r.t. all online schedulers
- LLF is impractical to implement because laxity tie results in frequent context switches



# RM vs. EDF vs. LLF

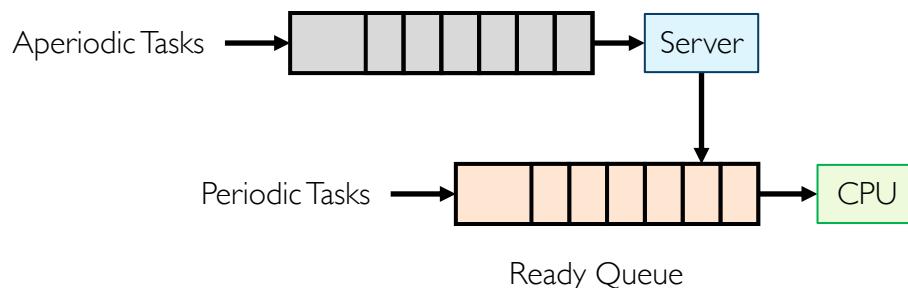
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- Rate monotonic (RM)
  - Simpler implementation, even in systems without explicit support for timing constraints (periods, deadlines)
  - Predictability for highest priority tasks
- Earliest deadline first (EDF)
  - Full processor utilization
  - Misbehavior during overload conditions
- Least laxity first (LLF)
  - Full processor utilization
  - Misbehavior when there are jobs with equal laxity

# Scheduling Mixed Periodic and Aperiodic Tasks

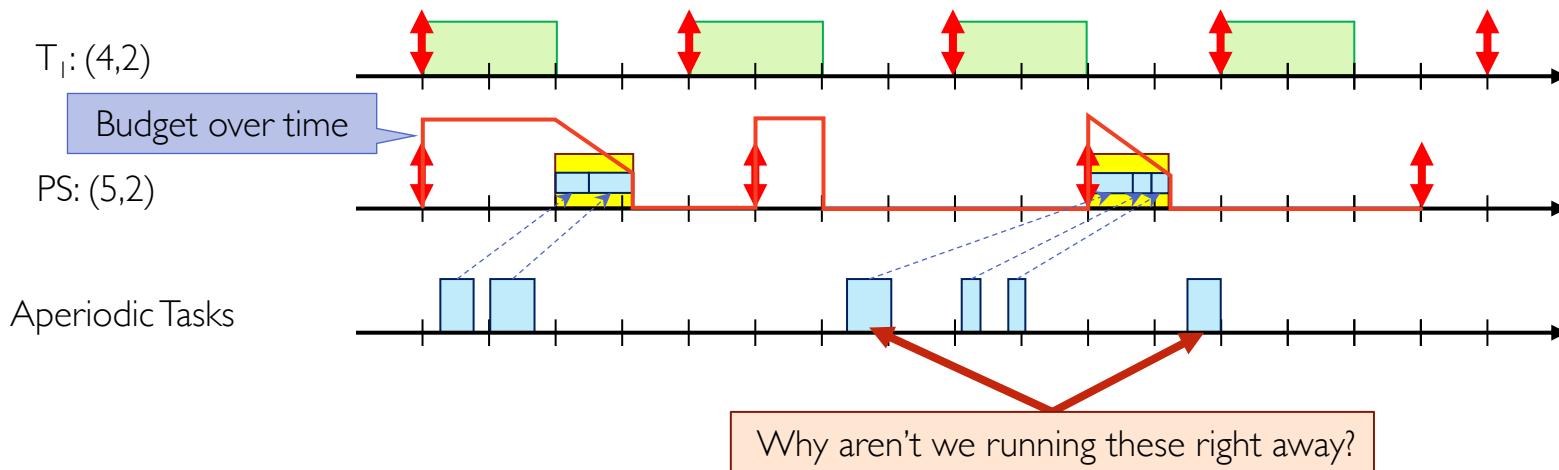
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- One idea: run aperiodic tasks as soon as they arrive
  - Response time for aperiodic tasks is minimized, but it's unbounded for periodic tasks
- Another idea: assign aperiodic tasks lowest priority (run if no periodic task runs)
  - Simple, bad response time for aperiodic tasks (applicable if they have no strict timing requirement)
- Better idea: aperiodic tasks can be served by periodically invoked **server**
  - Server can be accounted for in periodic task schedulability analysis
  - Server has period  $p_s$  and budget  $B_s$
  - Server can serve aperiodic tasks until budget expires
  - Servers have different flavors depending on details of when they are invoked, what priority they have, and how budgets are replenished



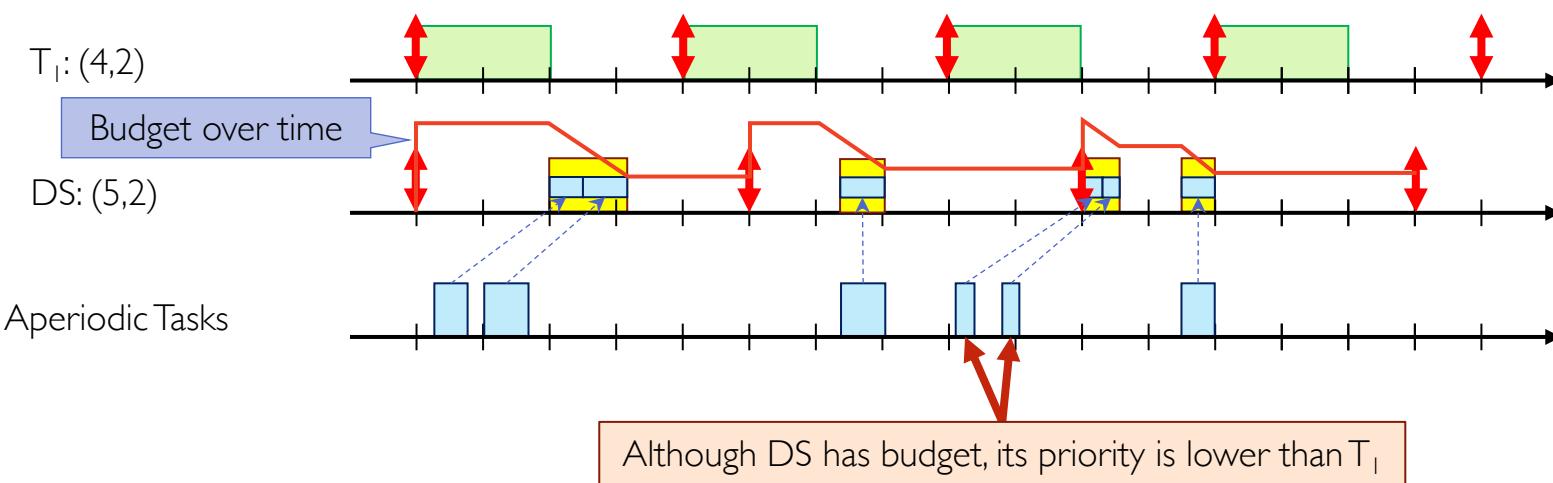
# Polling Server (PS)

- Periodic tasks and PS are scheduled based on RM
- Aperiodic arrivals are queued until PS is invoked
- At the beginning of its period, PS serves queued aperiodic tasks
- PS suspends itself when queue becomes empty or budget expires
- PS is treated as regular periodic task in schedulability analysis



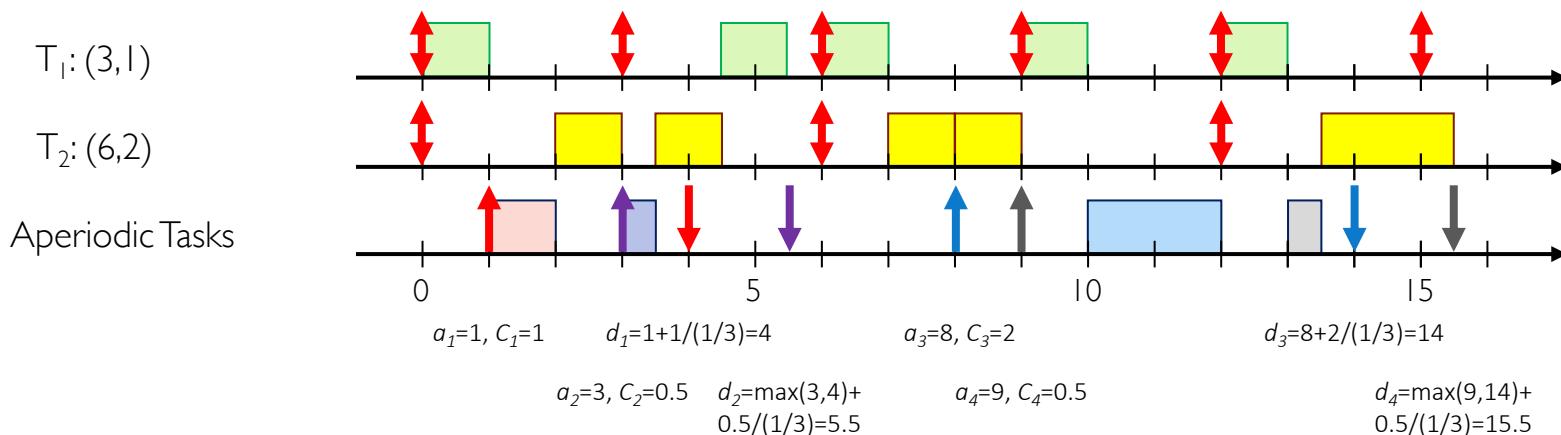
# Deferrable Server (DC)

- Basic approach is like polling server
- DS **preserves its budget** when queue becomes empty
  - But no cumulation: at the beginning of period, budget is reset to its full value
- DS is demand driven
  - Periodic tasks are ready to run at the beginning of their periods
  - DS can run during its period only in response to aperiodic-task arrivals



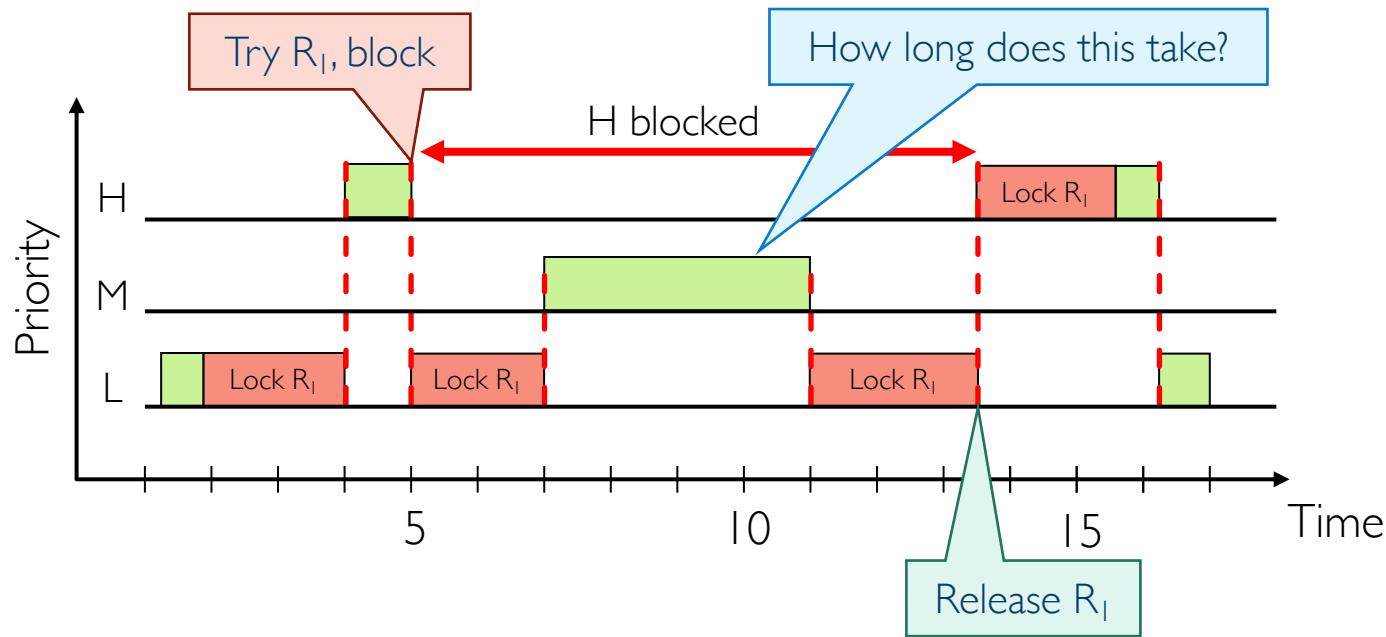
# Total-bandwidth Server (TBS)

- Periodic tasks and TBS are scheduled based on EDF
  - Aperiodic and periodic tasks are both inserted in the same ready queue
  - Aperiodic tasks are artificially assigned deadline such that TBS's utilization does not exceed its given bandwidth  $U_{TBS}$
  - Aperiodic task  $T_i$  with computation time  $C_i$  arriving at time  $a_i$  is assigned deadline  $d_i = \max(d_{i-1}, a_i) + C_i / U_{TBS}$
  - Example:  $T_1(3,1)$  and  $T_2(6,2)$ ,
    - $T_1$  and  $T_2$  are schedulable if  $U_{TBS} \leq 1 - 2/3 = 1/3$



# Scheduling Interdependent Tasks: Synchronization

- Problem of deciding whether it is possible to schedule set of periodic tasks, that use semaphores to enforce mutual exclusion is **NP-hard** [I]
- General-purpose synchronization primitives allow *priority inversion*



[I] A.K. Mok, "Fundamental Design Problems of Distributed Systems for Hard Real Time Environments", PhD Thesis, Laboratory for Computer Science (MIT), MIT/LCS/TR-297. (1983).

# Priority Inversion and MARS Pathfinder

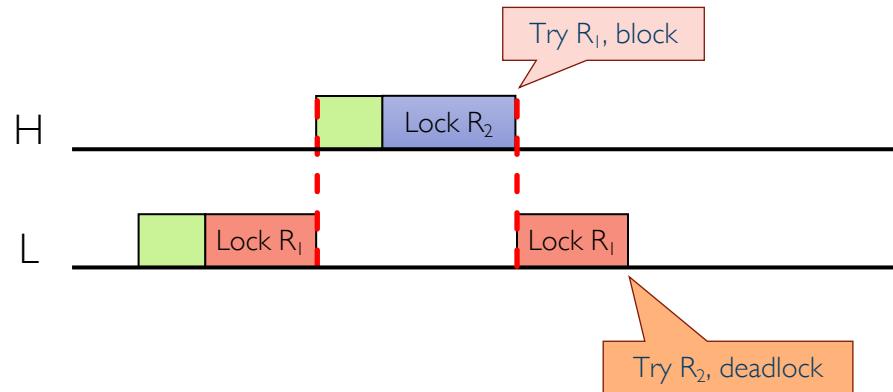
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- Landed on Martian surface on July 4th, 1997
- After it started gathering data, it began experiencing total system resets, each resulting in losses of data
  - Pathfinder had single shared information bus used by low and high-priority tasks
  - Low-priority task ran infrequently and used bus to publish its data, while holding mutex on bus
  - Every system reset started by low-priority task getting interrupted while holding mutex
  - Interrupt handler scheduled medium-priority task
  - High-priority task was blocked waiting for low-priority task which was waiting for medium-priority task to finish
  - After some time, watchdog timer went off, noticing that bus has not been executed for some time, it concluded that something had gone bad, and initiated total system reset



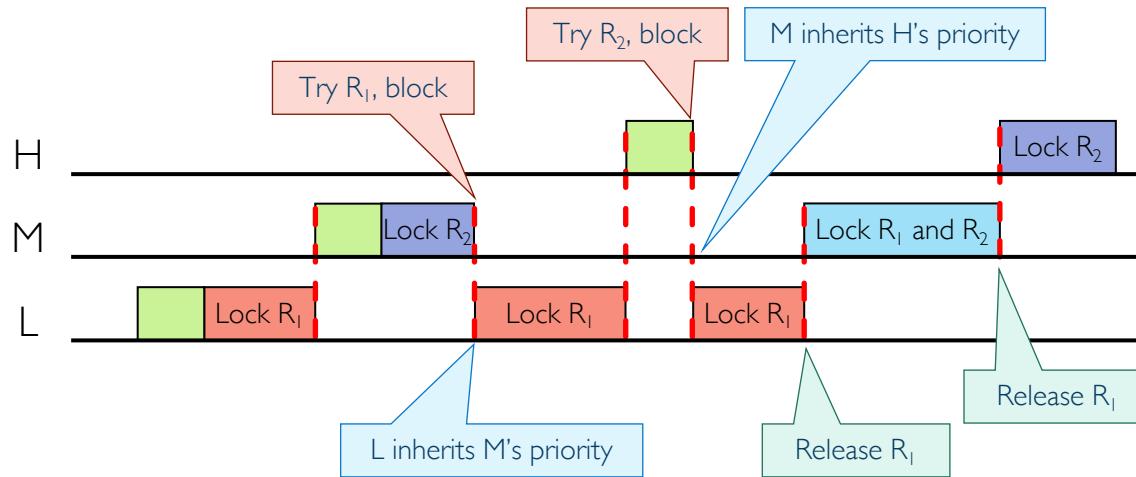
# Priority-inheritance Protocol (PIP)

- PIP increases priority of task to **maximum priority** of any task waiting for any resource locked by the task
  - If lower-priority task L has locked any resources required by higher-priority task H, then priority of L is increased to priority of H
  - Once task unlocks resources, it runs with its original priority
- RIP does not prevent **deadlock**



# PIP and Chained Blocking

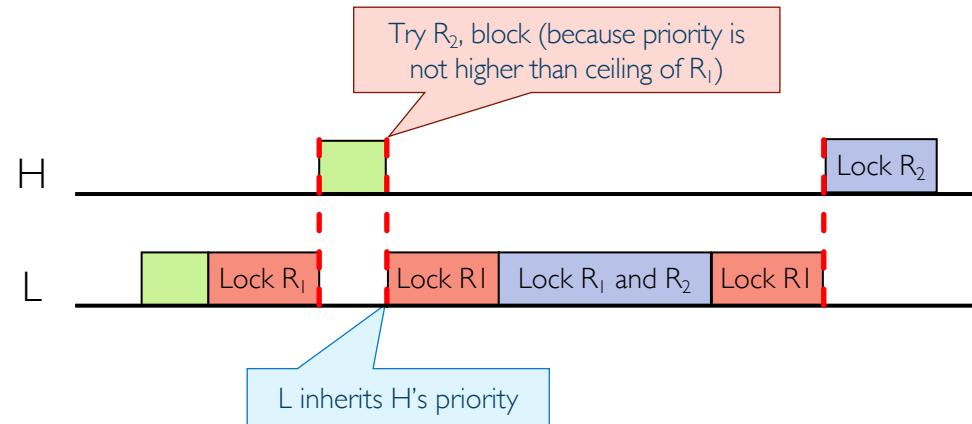
- PIP does not prevent *chained blocking*



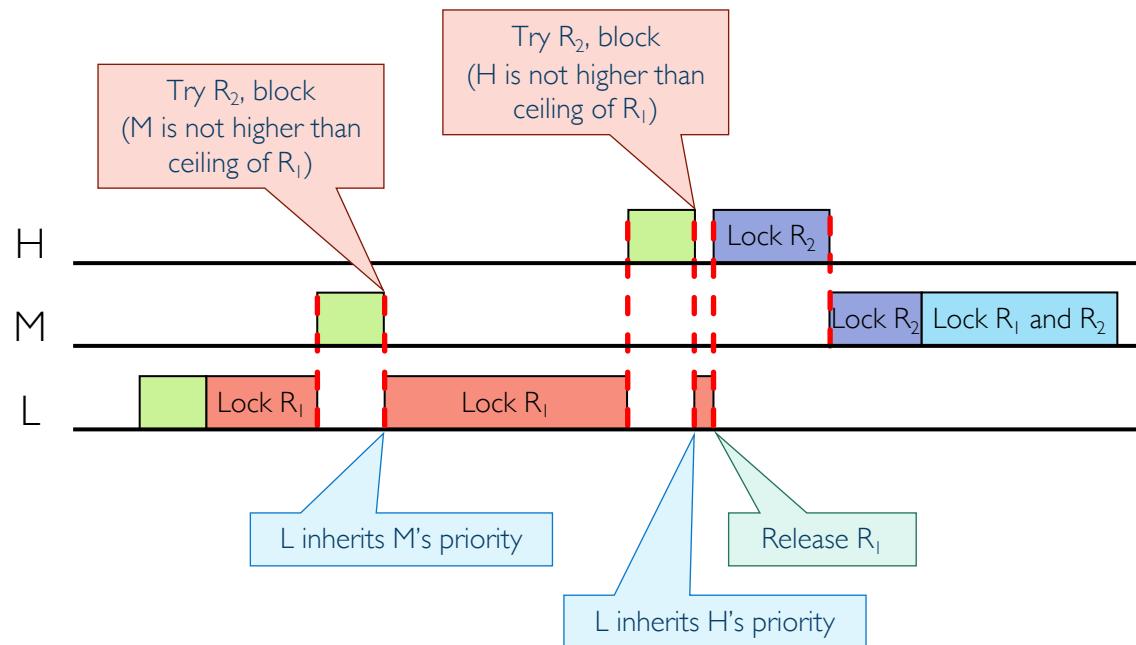
- H must wait for L and M

# Priority-ceiling Protocol (PCP)

- Each resource is assigned priority ceiling
  - Equal to the highest priority of any task that can lock it
- Each task can lock resources only if its priority is higher than priority ceilings of all resources currently locked by other tasks
- Each task runs at its assigned priority unless it has locked any resource needed by higher priority task
- After task unlocks resources, it runs with its original priority
- PCP prevents **deadlocks**



# PCP Prevents Chained Blocking



- H only waits for L

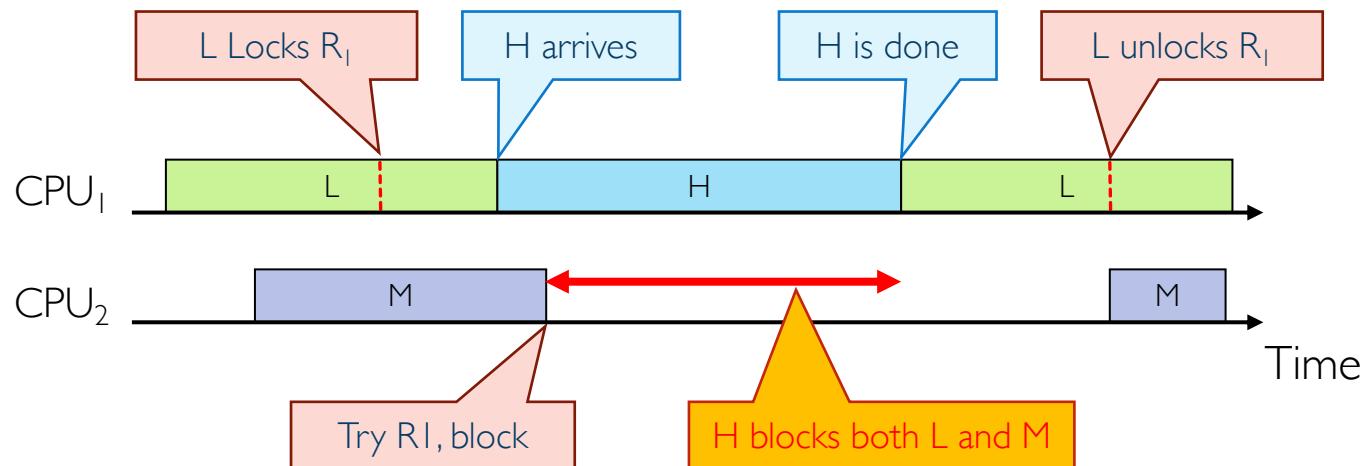
# EDF and Deadline Interchange

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- Deadline interchange is analogous to priority inversion
- Task which has locked resources could be preempted by another task with earlier deadline that needs those resources
- To avoid this, scheduler should assign to running task earliest deadline from among other tasks waiting for it

# Multiprocessors and Remote Blocking

- In uniprocessors, it is acceptable if high-priority task pre-empts lower-priority ones
- In multiprocessors, this is not necessarily desirable
  - Example: high-priority task H and low-priority task L are assigned to CPU<sub>1</sub>
  - Medium-priority task M runs on CPU<sub>2</sub>



- H is more important than either M or L, but is it more important than M and L?

# Multiprocessor Scheduling

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- No migration (partitioned): each task and its jobs must run on single CPU
- Restricted migration: each job must run on single CPU
  - Different jobs of the same task may run on different CPUs
- Full migration: each job can migrate between CPUs

	No Migration	Restricted Migration	Full Migration
Static	(S,N)	(S,R)	(S,F)
Dynamic	(D,N)	(D,R)	(D,F)
Fully Dynamic	(F,N)	(F,R)	(F,F)

# (.,N)-based Schedulers

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- Finding optimal assignment of N periodic tasks to M CPUs is equivalent to *bin-packing*
  - It's NP-hard problem
- Several polynomial-time heuristics have been proposed
  - First fit: assign each task to CPU that can accept it  
(based on feasibility test according to that CPU's uniprocessor scheduler)
  - Best fit: assign each task to CPU that can accept it and will have minimal remaining spare capacity
- Worst-case utilization is  $(M+1)/2$ 
  - E.g.,  $M+1$  tasks with  $e = 1 + \varepsilon$  and  $p = 2$  cannot be scheduled by any (.,N) scheduler
  - Almost half of resources could be left underutilized

# Some Other Scheduling Classes

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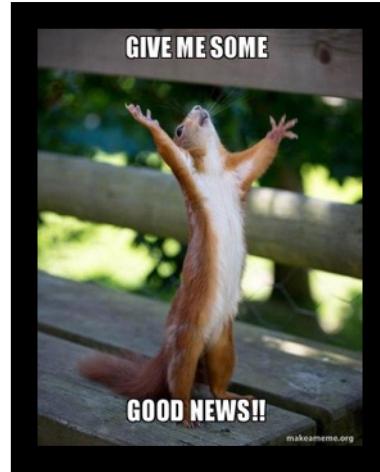
- **(D,R)-based:** jobs have fixed priority and must run on single CPU
  - Suitable for task sets in which each job has considerable amount of state (it is not desirable to migrate jobs between processors)
- **(D,F)-based:** jobs have fixed priority but can migrate
  - Preemption, and hence migration, can only happen because of new job arrival
  - E.g., *global EDF*: use single ready queue for all CPUs, set priorities according to EDF
    - No longer optimal:  $T_1(10,5), T_2(10,5), T_3(11,7)$  on 2 CPUs
    - EDF runs  $T_1$  and  $T_2$  first in parallel  $\Rightarrow T_3$  misses its deadline
- **(S,F)-based:** tasks have fixed priority, jobs can migrate
  - E.g., *global RM*: use single ready queue for all CPUs, set priorities according to RM
- Worst-case utilization of any  $(x,y)$ -based scheduler is  $(M+1)/2$ , unless  $x = y = F$  [!]

[!] Carpenter, J., Funk, S., Holman, P., Srinivasan, A., Anderson, J. H., & Baruah, S. K. (2004). A Categorization of Real-Time Multiprocessor Scheduling Problems and Algorithms.

# (F,F)-based Schedulers

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- Global LLF: use single ready queue for all CPUs, set priorities based on LLF
  - It schedules any instance that global EDF can schedule
  - Like global EDF, it is not optimal



- P-fair scheduling: allocate CPU time to enforce *proportionate progress*
  - Is **optimal** (both for uniprocessors and multiprocessors)
  - Produces feasible schedule for  $M$  CPUs and any task set  $T$  with  $U_T \leq M$

# P-fairness

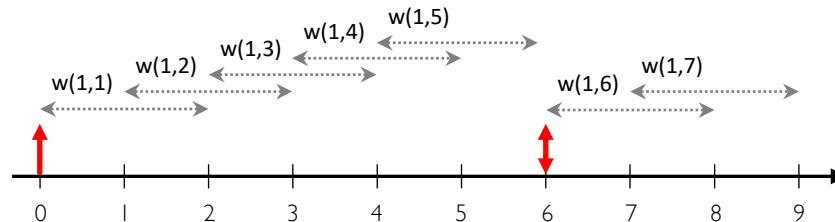
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- Main idea: allocate CPU time to each task  $i$  in proportion to its weight  $w_i = e_i / p_i$
- Divide time into small time quanta
  - All parameters are integer multiples of time quantum (e.g.,  $e_i, p_i \in \mathbb{Z}^+$ )
- Define lag for each task to captures discrepancy between what it should have received and what it actually received
  - $lag(i,t) = t \times w_i - allocated(i,t)$
- Schedule  $S$  is periodic if and only if for all task  $i$  and any integer  $k$ 
  - $allocated(i,k \times p_i) = k \times e_i$
- Schedule  $S$  is P-fair if and only if for all task  $i$  and time  $t$ 
  - $-1 < lag(i,t) < 1$
- Any P-fair schedule is periodic
  - At  $t = k \times p_i$ ,  $allocated(i,t)$  and  $t \times w_i$  are both integers  $\Rightarrow allocated(i,t) = k \times e_i$
  - Periodic schedules aren't necessarily P-fair (why?)

# Subtasks and Pseudo Parameters

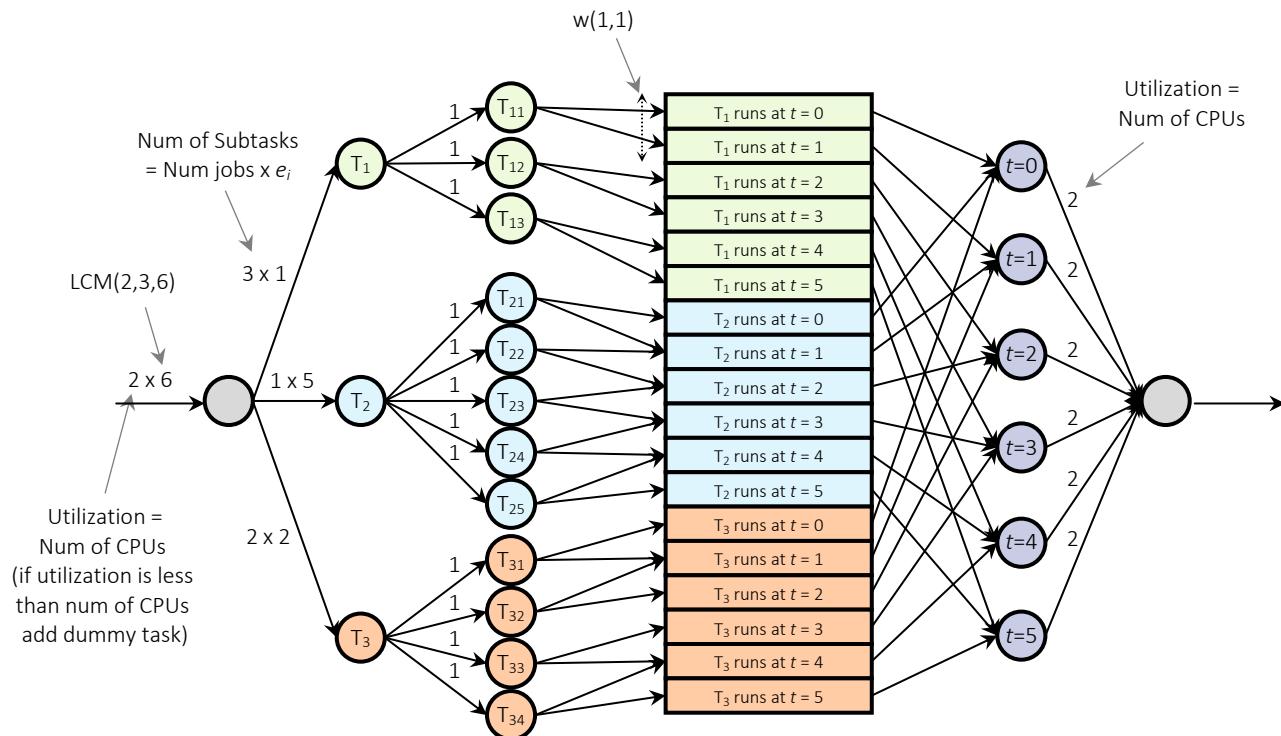
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- Divide task  $i$  into quantum-sized **subtasks**
  - $T_{ij}$  denotes the  $j^{\text{th}}$  subtask of task  $i$
- **Pseudo-release:** Let  $r(i,j)$  denote the earliest time  $T_{ij}$  could be scheduled
  - $r(i,j) = \min t (\geq 0): (t + 1) \times w_i - j > -1 = \left\lfloor \frac{j-1}{w_i} \right\rfloor$
- **Pseudo-deadline:** Let  $d(i,j)$  denote the latest time by which  $T_{ij}$  must have been scheduled
  - $d(i,j) = \max t (\geq 0): (t - 1) \times w_i - (j - 1) < 1 = \left\lceil \frac{j}{w_i} \right\rceil$
- **Window:** Let  $w(i,j) = [r(i,j), d(i,j)]$  denote the interval during which  $T_{ij}$  must be scheduled
  - **Window overlaps**, denoted by  $b(i,j) = d(i,j) - r(i,j+1)$ , are either 0 or 1
  - Example:  $T_1(6,5)$ 
    - $r(1,1) = 0, d(1,1) = 2$
    - $r(1,2) = 1, d(1,2) = 3$
    - $r(1,3) = 2, d(1,3) = 4$
    - ...



# Existence of P-fair Schedule

- Example: scheduling  $T_1(2,1)$ ,  $T_2(6,5)$ , and  $T_3(3,2)$  on two CPUs



- Integral flow theorem**: If all edges have integral capacity, then integral maximal flow exists
- Network flow problem has integer solution  $\Rightarrow$  P-fair schedule exists

# P-fair (PF) Scheduling Algorithm

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- PF prioritizes subtasks on earliest-pseudo-deadline-first (EPDF) basis
- At time  $t$ ,  $T_{ij}$  has higher priority than  $T_{mn}$  ( $T_{ij} > T_{mn}$ ), if any of following holds
  - I.  $d(i,j) < d(m,n)$
  - II.  $d(i,j) = d(m,n)$  and  $b(i,j) > b(m,n)$
  - III.  $d(i,j) = d(m,n)$ ,  $b(i,j) = b(m,n) = 1$ , and  $T_{i(j+1)} > T_{m(n+1)}$
- If neither subtask has priority over other, then tie can be broken arbitrarily
- Intuition behind (II): scheduling  $T_{ij}$  earlier prevents it from shortening  $w(i,j+1)$ 
  - Makes it easier to schedule  $T_{i(j+1)}$  by its pseudo-deadline
  - Similar intuition behind (III)

# PF Discussion

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- PF incurs very high **overheads** by making scheduling decisions at every time quantum
- Also, all processors need to **synchronize** on boundary between quanta when scheduling decisions are made
- Extensions to PF try to mitigate some of these problems
  - E.g., PD, PD<sup>2</sup>, ERfair

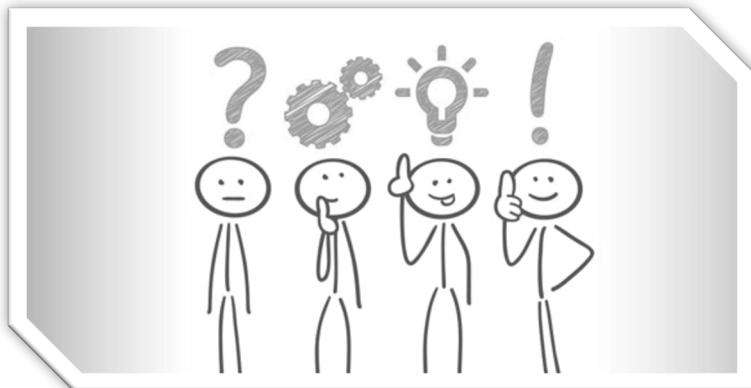
# Summary

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- Real-time systems have strict timing constraints
- General-purpose operating systems are inadequate for real-time systems
- Real-time operating systems should provide predictability
  - Memory management, interrupt handling, scheduling, etc.
- Scheduling in real-time systems is task-centric
  - All tasks should meet their deadlines
  - Worst-case execution time is important not average throughput
- Optimal scheduler exist for uniprocessor systems
  - RM, EDF, and LLF
- Scheduling real-time tasks on multiprocessors is challenging
  - Optimal uniprocessor scheduler are no longer optimal for multiprocessors
  - Partitioning tasks between processors is a “hard” problem
  - Optimal schedulers exist, but they typically incur high overhead

# Questions?

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