ECE 350 Real-time Operating Systems

Lecture 6: Real-time Systems

Prof. Seyed Majid Zahedi

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

Outline

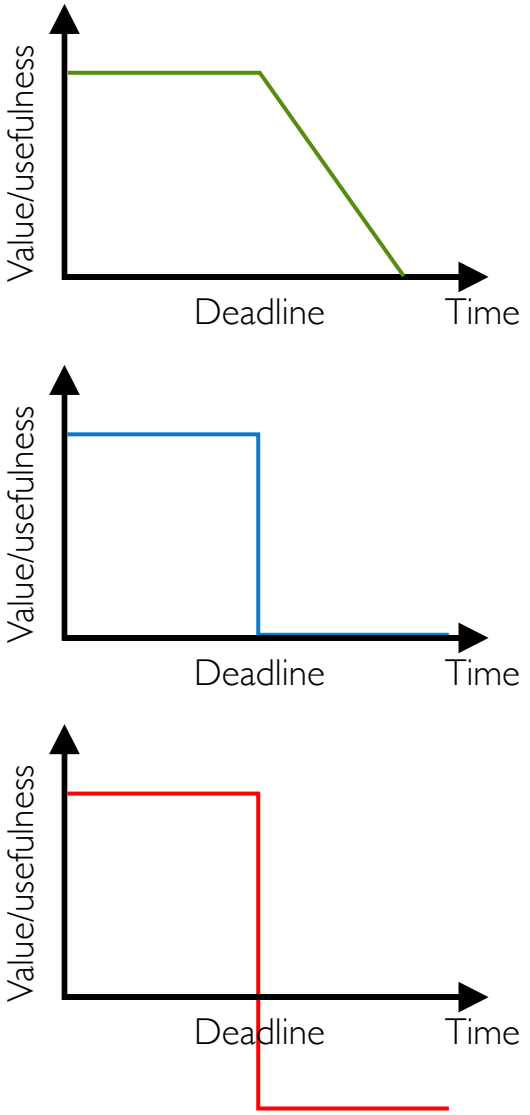
- Real-time systems
  - Definitions and features
- Real-time operating systems
  - Desirable properties, interrupt handling, memory management
- Uniprocessor real-time scheduling
  - RM, EDF, LLF, …
  - Priority inversion
- Multiprocessor scheduling
  - Different scheduling classes, remote blocking

Real-time Systems (RTSes)

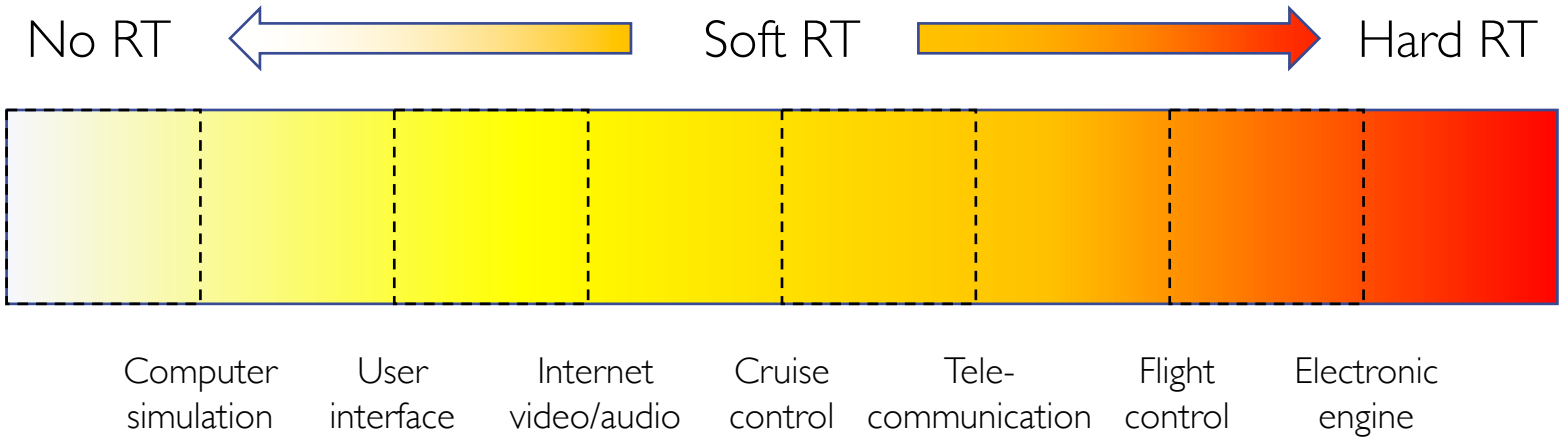
- Definition
  - Systems whose correctness depends on their temporal aspects as well as their functional aspects
- Performance measure
  - Timeliness on timing constraints (deadlines)
  - Speed/average case performance are less significant
- Key property
  - Predictability on timing constraints

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



General-purpose OS are Inadequate for RTSes

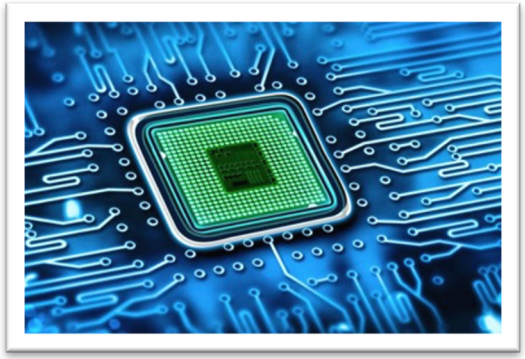
- Multitasking/scheduling
  - Provided through system calls
  - Does not take time into account and could introduce unbounded delays
- Interrupt management
  - Achieved by setting interrupt priority more than process priority
  - Increases system reactivity but may cause unbounded delays even due to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

Real-time Operating System (RTOS): Desirable Properties

- 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

- 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 ⇒ source of non-determinism!
  - Possible solution: processors without cache
    - Slow execution, but more predictable!

System Calls and Interrupts

- 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 1: 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.)

- 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

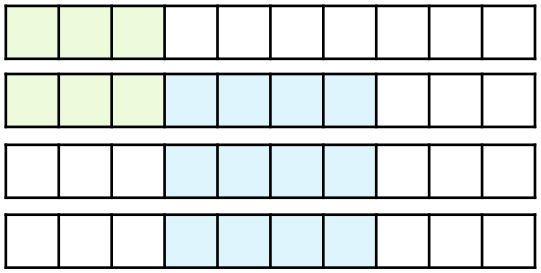
- General-purpose OSes allow each process to access only its own virtual address
  - Virtual and physical address spaces are divided into virtual and physical *pages*
  - Virtual to physical page translations are stored in memory as *page tables (PT)*
  - To speedup memory accesses, PT entries are cached 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

- 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

```
p1 = malloc(3)
p2 = malloc(4)
free(p1)
p1 = malloc(4)
```

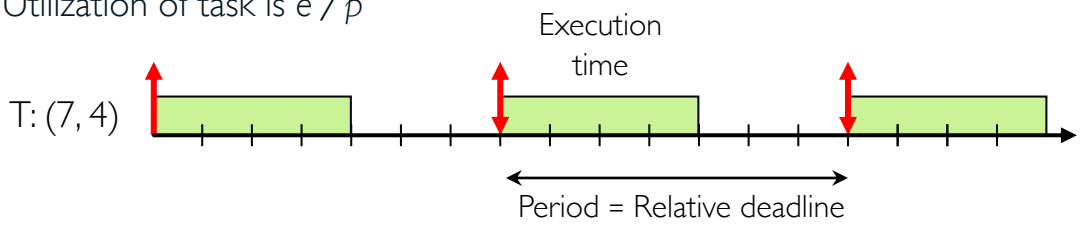


Defragmentation is not feasible, all copies of `p2` become broken if OS moves allocated

  - 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

- General-purpose schedulers are system-oriented
  - Maximize avg. system throughput
- RTSes need task-centric scheduling
  - Minimize worst-case response time for each task
  - Predictability ≠ 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



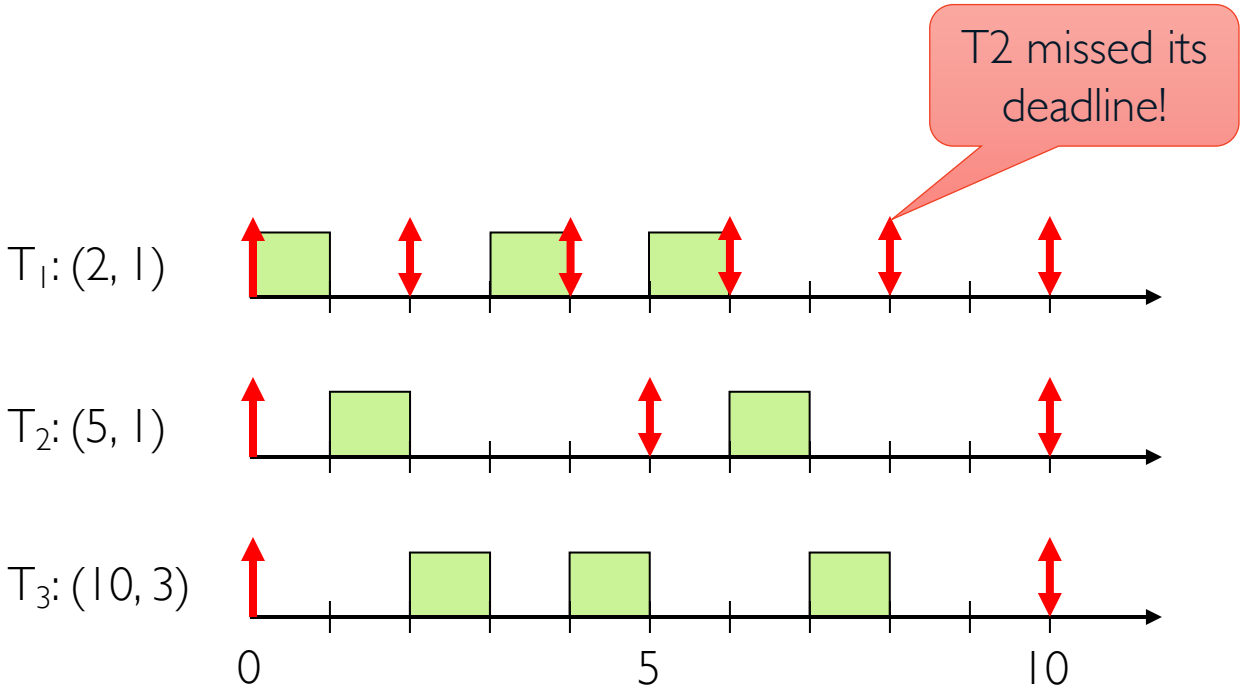
  - Aperiodic: arrive randomly without any hard deadline
  - Sporadic task arrives randomly with hard deadline
  - Independent vs. interdependent and preemptable vs. non-preemptable

Terminology of Real-time Scheduling

- 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*

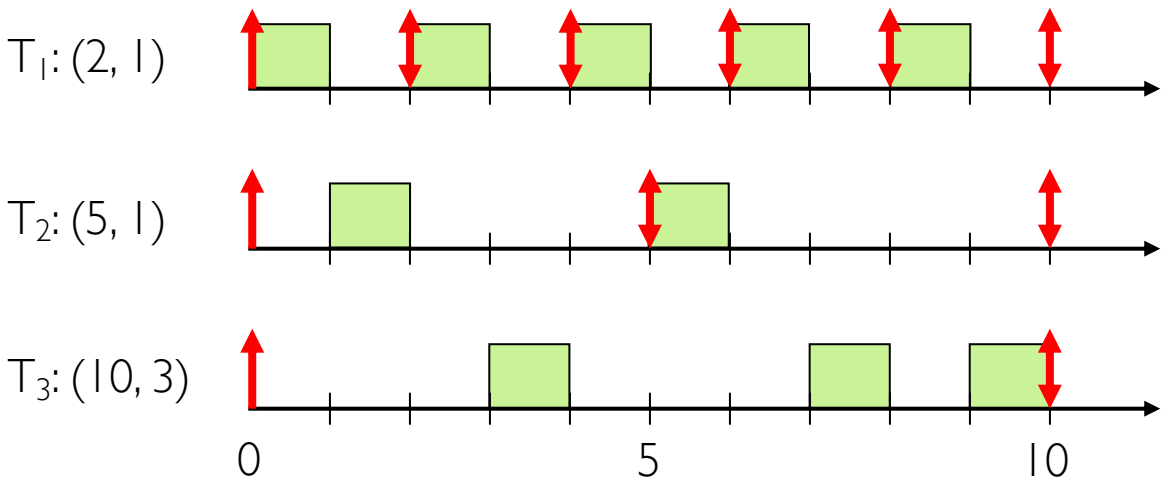
General-purpose Schedulers for RTSes

- RR example:

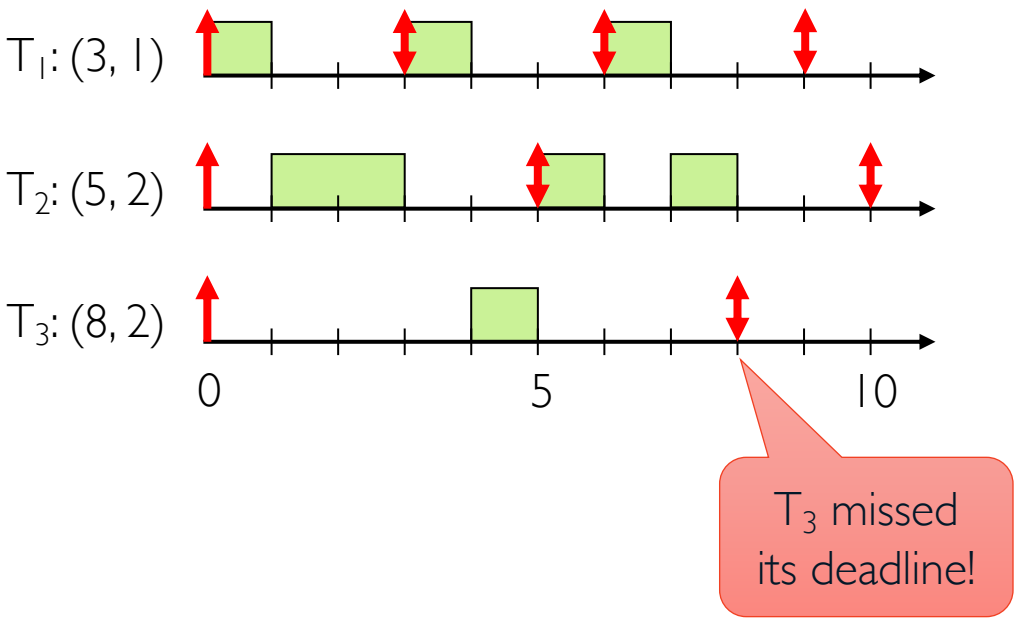


Rate Monotonic (RM)

- 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



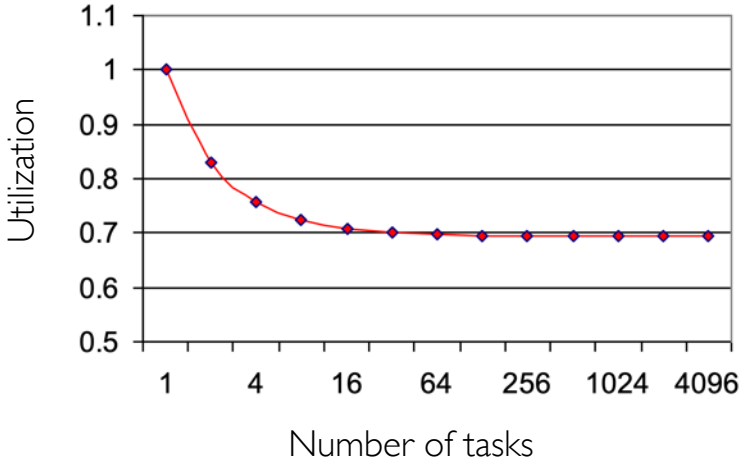
RM: Schedulability



RM: Schedulability Test [Liu & Layland 1973]

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

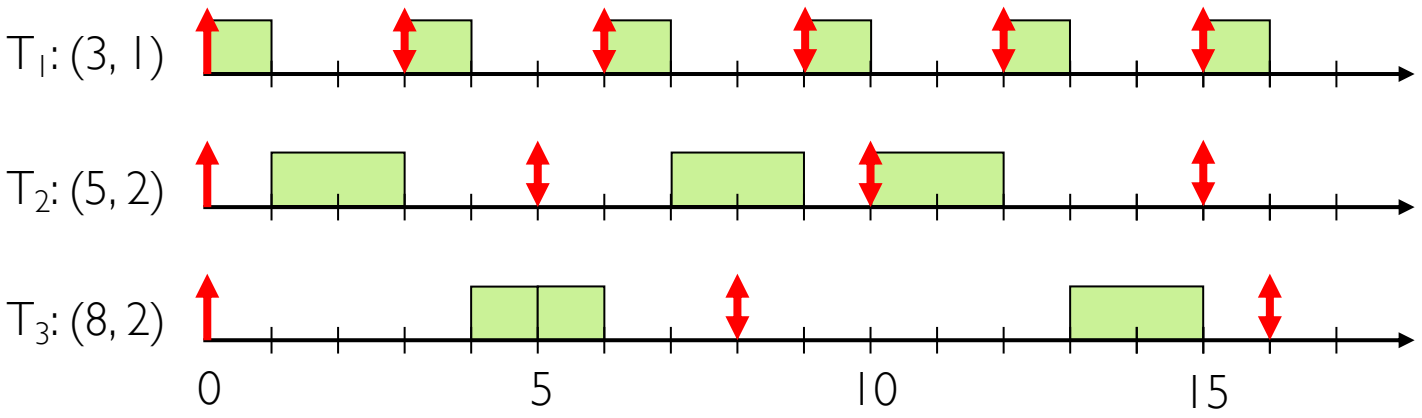
$$\sum_{i=1}^{n} \left(\frac{e_i}{p_i} \right) \leq n(2^{1/n} - 1)$$



- 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) $\geq 3(2^{1/3}-1)$ (≈ 0.78) $\Rightarrow$ No guarantee!

Earliest Deadline First (EDF)

- 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]

- 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

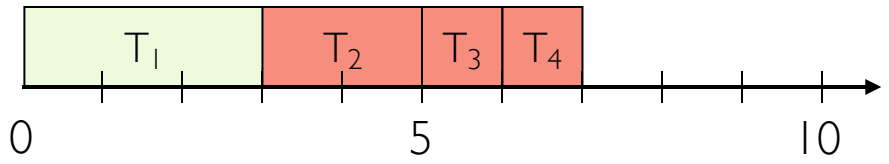
$$\sum_{i=1}^{n} \left(\frac{e_i}{p_i} \right) \leq 1$$

- System is overloaded if

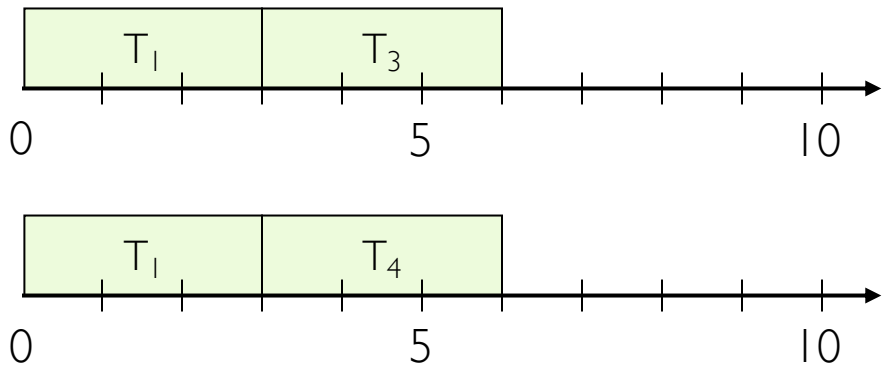
$$\sum_{i=1}^{n} \left(\frac{e_i}{p_i} \right) > 1$$

Overloaded System under EDF

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

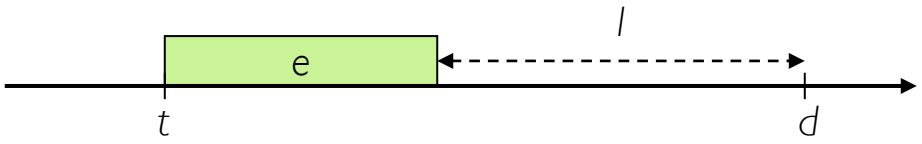


- Better schedules

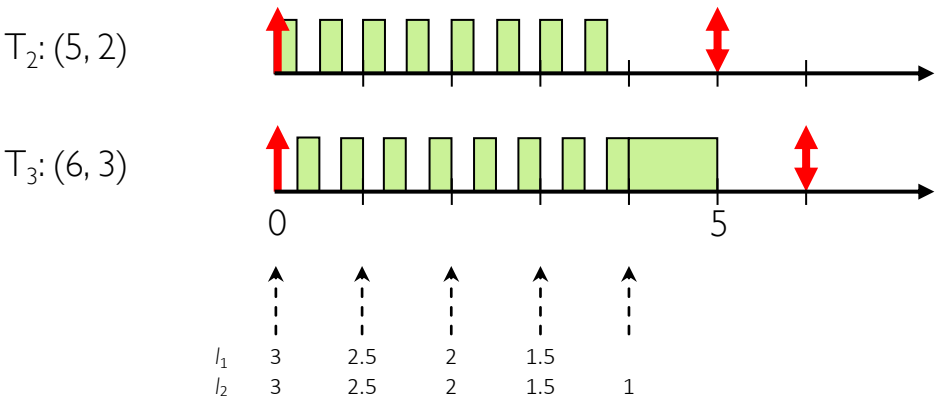


Least Laxity First (LLF)

- 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

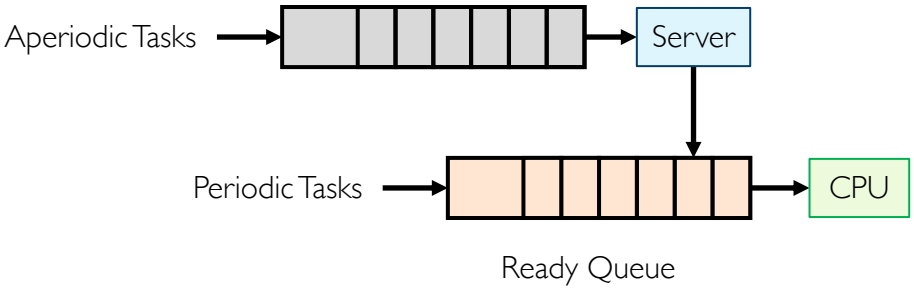


RM vs. EDF vs. LLF

- 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

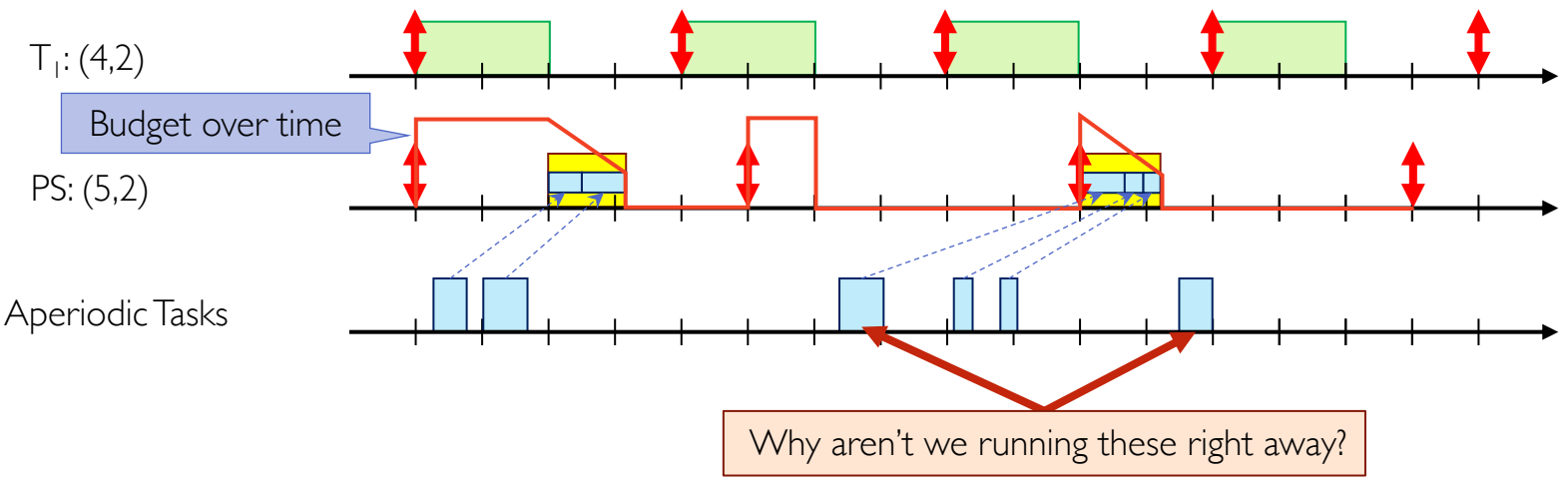
Scheduling Mixed Periodic and Aperiodic Tasks

- 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



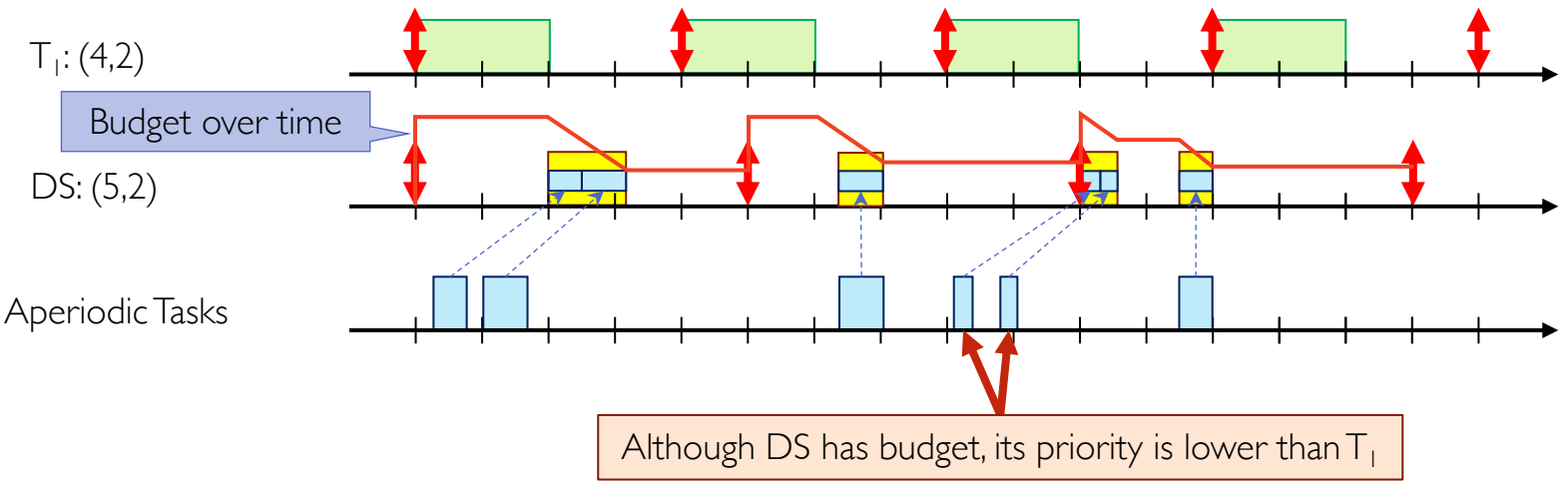
Polling Server (PS)

- 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



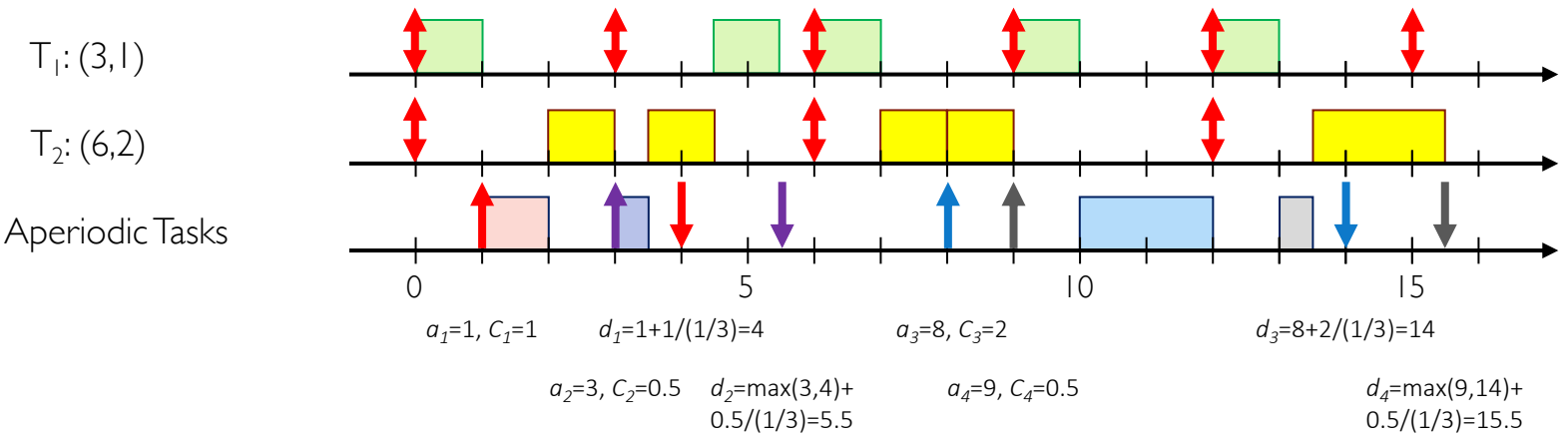
Deferrable Server (DC)

- 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



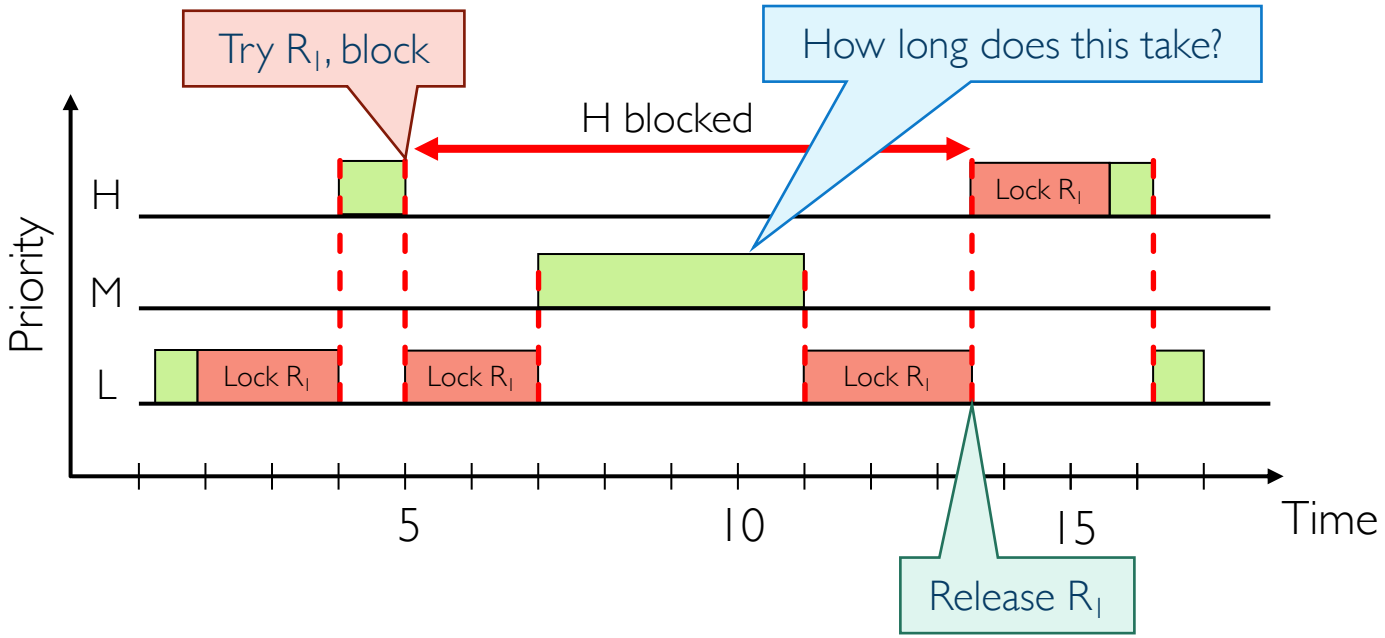
Total-bandwidth Server (TBS)

- 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 [1]
- General-purpose synchronization primitives allow *priority inversion*



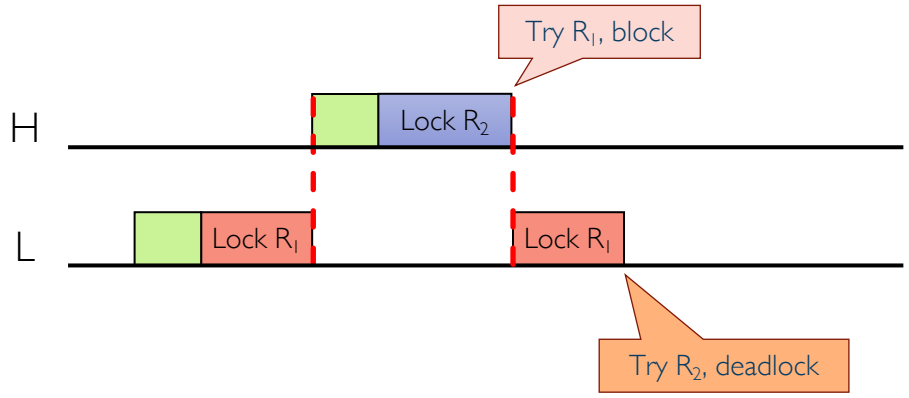
[1] A.K. Mok, "Fundamental Design Problems of Distributed Systems for Hard Real Time Environments", PhD Thesis, Laboratory for Computer Science (MIT), MIT/LCS/TR-297. (1983).

Priority Inversion and MARS Pathfinder

- 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

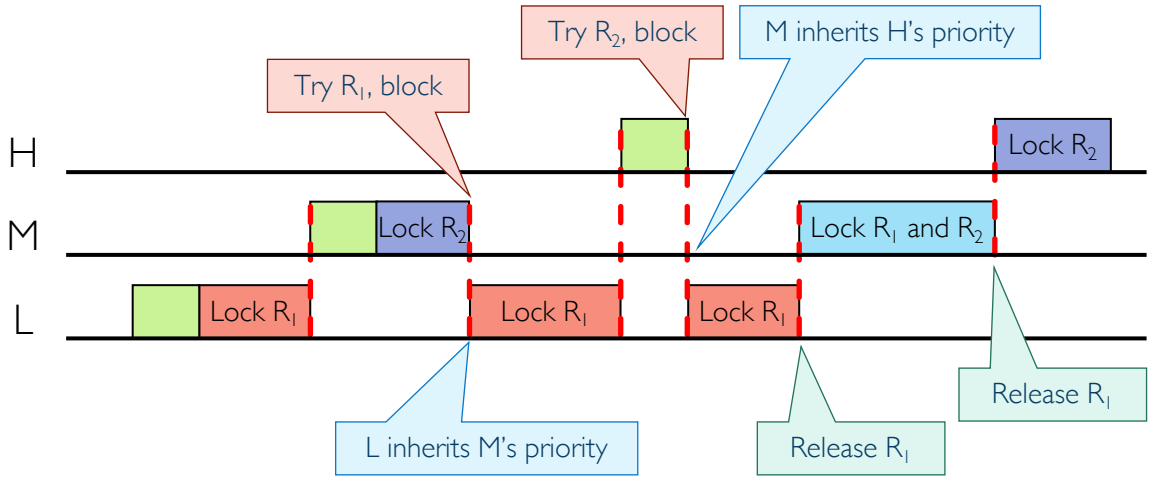
Priority-inheritance Protocol (PIP)

- 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

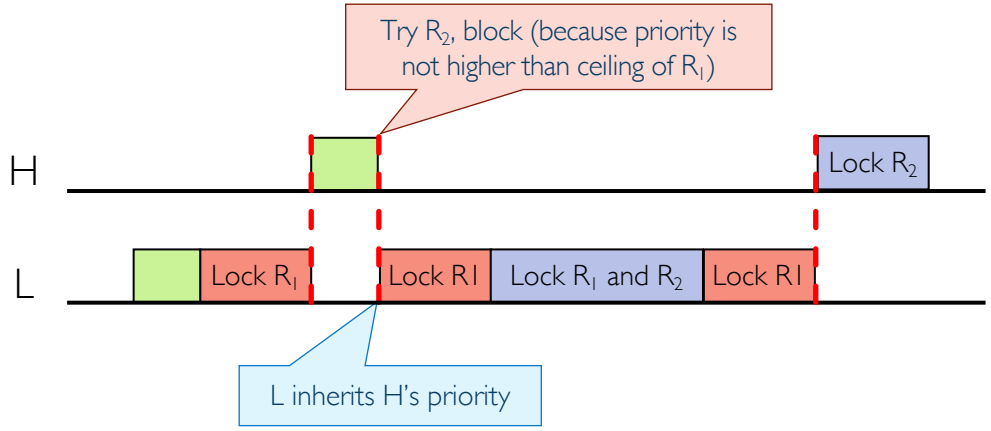
- PIP does not prevent *chained blocking*



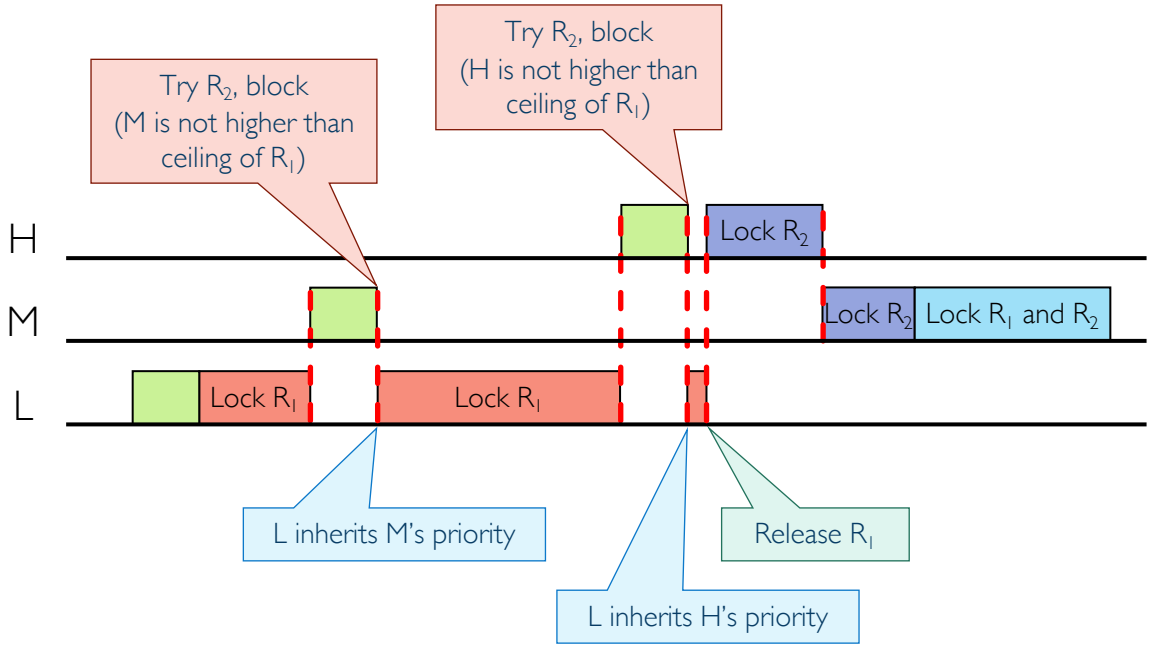
- H must wait for L and M

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



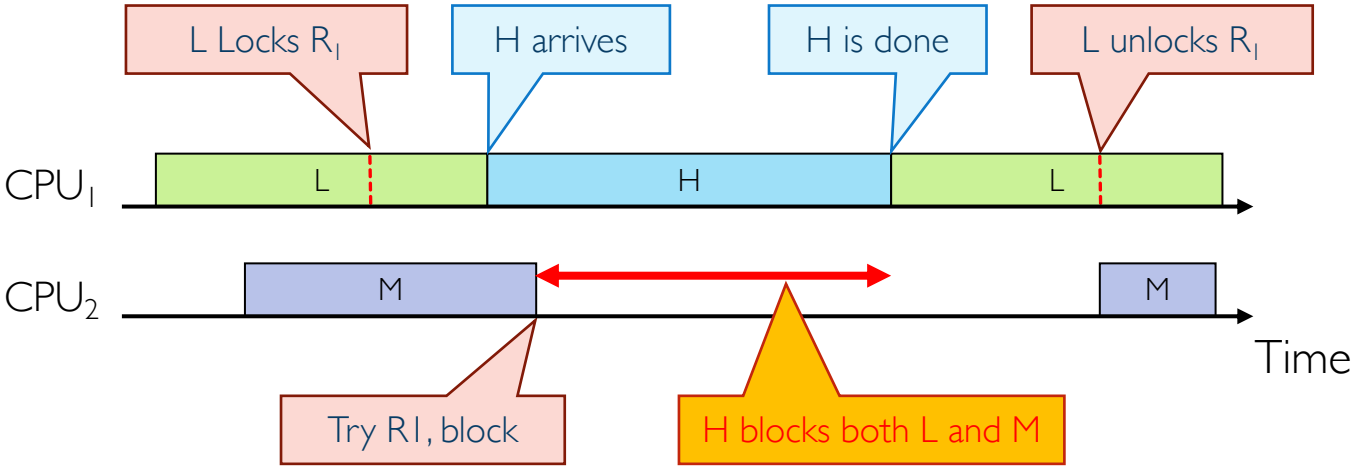
- H only waits for L

EDF and Deadline Interchange

- 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_1
  - Medium-priority task M runs on CPU_2



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

Multiprocessor Scheduling

- 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

- 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

- (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: us 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 [1]

[1] 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

- 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

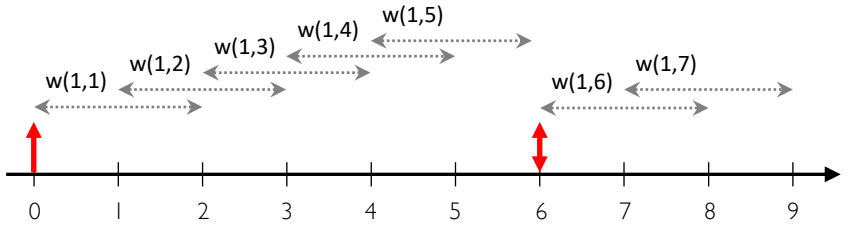
- P-fair scheduling: allocate CPU time to enforce *proportionate progress*
  - Is optimal (both for uniprocessors and multiprocessors)
  - Produces feasible schedule for M CPUs and any task set T with $U_T \leq M$

P-fairness

- 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?)

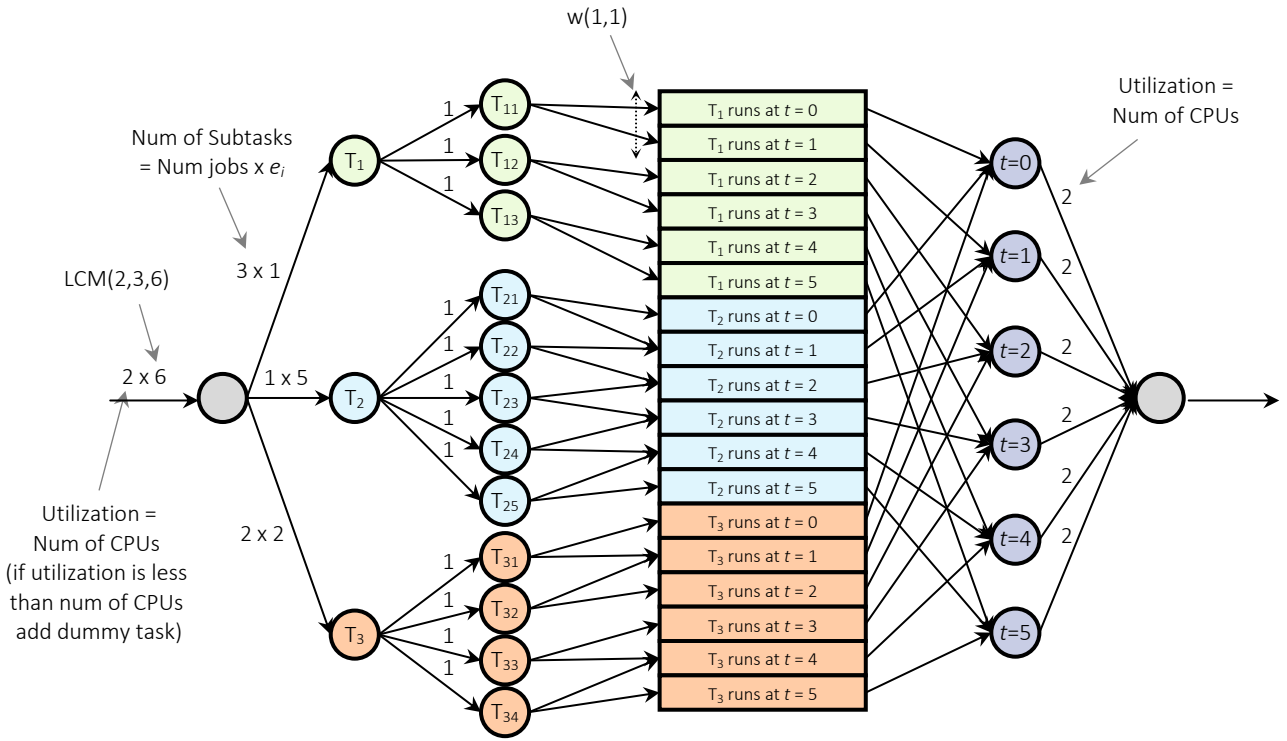
Subtasks and Pseudo Parameters

- Divide task i into quantum-sized subtasks
  - T_{ij} denotes the j^{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 ⇒ P-fair schedule exists

P-fair (PF) Scheduling Algorithm

- PF priorities subtasks on earliest-pseudo-deadline-first (EPDF) basis

- At time t, T_{ij} has higher priority than T_{mn} ($T_{ij} \succ T_{mn}$), 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 $T_{i(j+1)} \succ T_{m(n+1)}$

- 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)

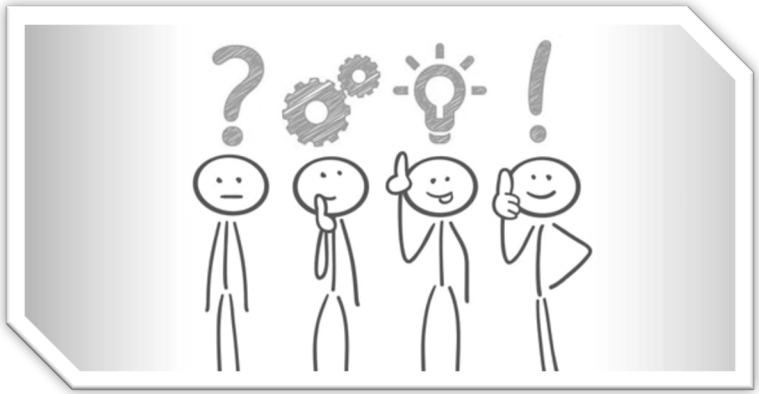
PF Discussion

- 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^2, ERfair

Summary

- 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?



Acknowledgment

- Slides by courtesy of Anderson, Culler, Stoica, Silberschatz, Joseph, Canny, Lee (Insup), Drews, and Andersson (Björn)