Real-Time Scheduling in Distributed Environments

Arnab Sarkar
Dept. of Computer Sc. & Engg.
IIT Guwahati

Setting the Stage

- Real-time Systems
  - A system whose specification includes both functional as well as temporal notions of correctness.
  - Logical Correctness: Produces correct outputs.
  - Temporal Correctness: Produces outputs at the right time.
    - *It is not enough to say that “brakes were applied”*
    - *You want to be able to say “brakes were applied at the right time”*

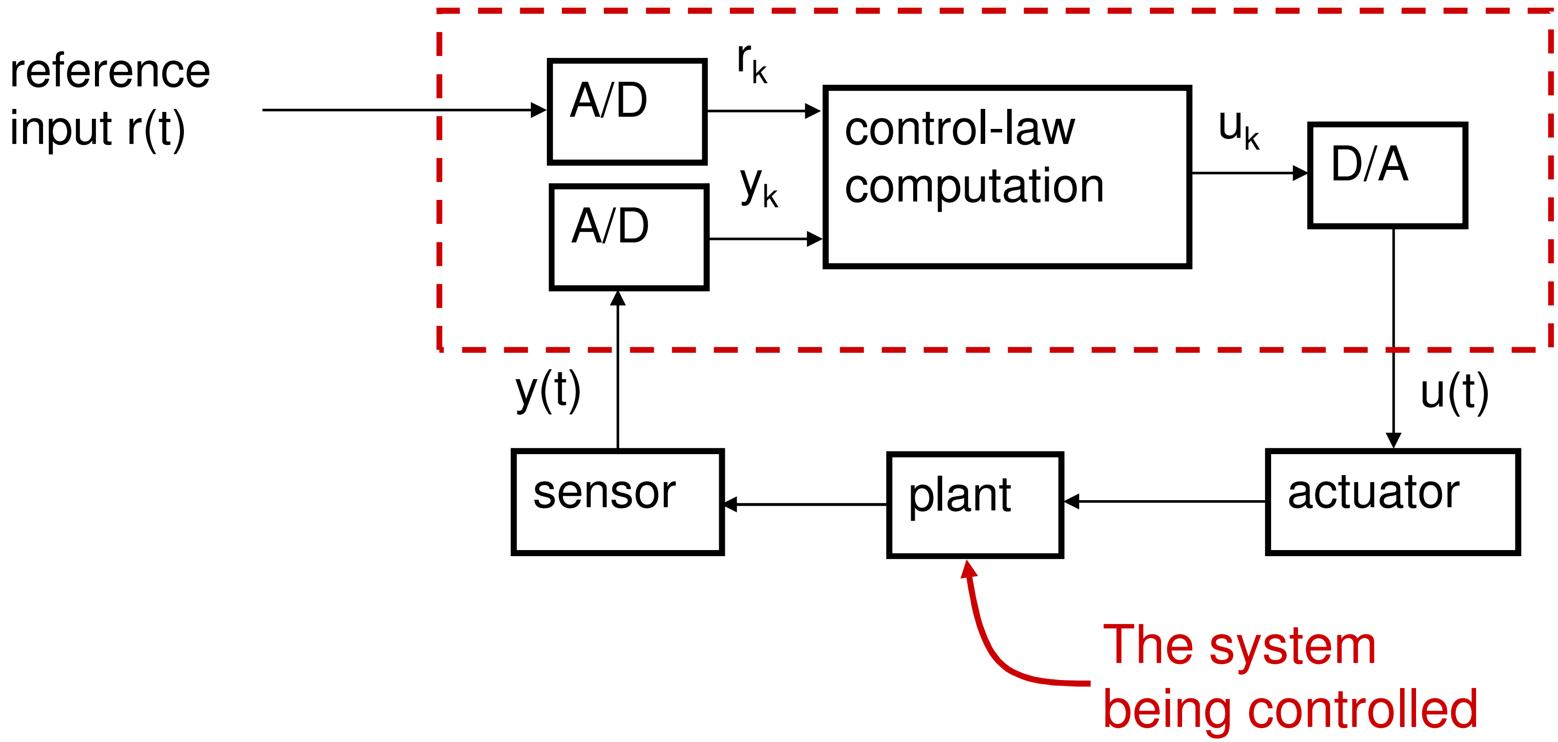
Setting the Stage

- *Real-time systems enable us to:*
  - Manage the vast power generation and distribution networks,
  - Control industrial processes for chemicals, fuel, medicine, and manufactured products,
  - Control automobiles, ships, trains and airplanes,
  - Conduct video conferencing over the Internet and interactive electronic commerce, and
  - Send vehicles high into space and deep into the sea to explore new frontiers and to seek new knowledge.

Example of a Real-Time System

Many real-time systems are ***control systems***.

Example: A simple one-sensor, one-actuator control system.



Example of a Real-Time System

Pseudo-code for this system:

set timer to interrupt periodically with period *T*;
at each timer interrupt **do**
    do analog-to-digital conversion to get *y*;
    compute control output *u*;
    output *u* and do digital-to-analog conversion;
end do

T is called the ***sampling period***. *T* is a key design choice. *T*ypical range for *T*: seconds to milliseconds.

Another Example

- **Multimedia**
  - Want to process audio and video frames at steady rates.
    - TV video rate is 30 frames/sec. HDTV is 60 frames/sec.
    - Telephone audio is 16 Kbits/sec. CD audio is 128 Kbits/sec.
  - **Other requirements:** Lip synchronization, low jitter, low end-to-end response times (if interactive).

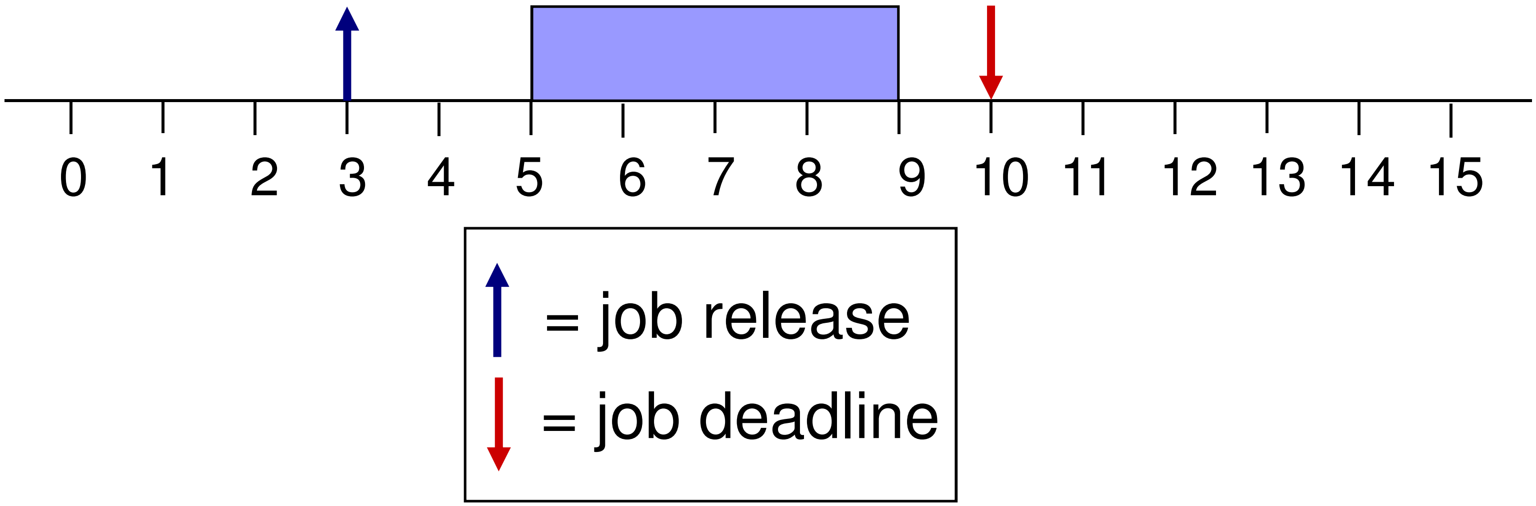
Characteristics of Real Time Tasks

- **Task:** A sequential piece of code.
- **Job:** Instance of a task.
  - Jobs require **resources** to execute.
  - **Example resources:** CPU, network, disk, critical section.

- **Release time of a job:** The time at which the job becomes ready to execute.

- **Absolute Deadline of a job:** The time instant by which the job must complete execution.
- **Relative deadline of a job:** "Deadline – Release time".

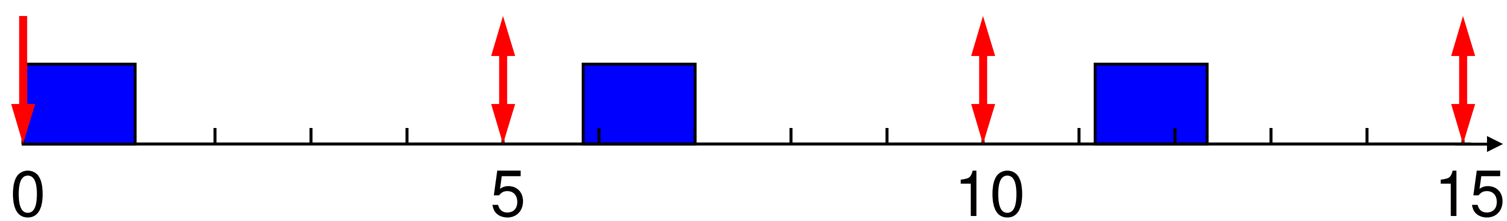
Example



- Job is released at time 3.
- Its (absolute) deadline is at time 10.
- Its relative deadline is 7.
- Its response time is 6.

Real-Time Periodic Task

- Task : a sequence of similar jobs
  - Periodic task (*p*,*e*)
    - Jobs repeat regularly
    - Period *p* = inter-release time (0 < *p*)
    - Execution time *e* (maximum execution time; 0 < *e* < *p*)
    - Utilization U = e/p

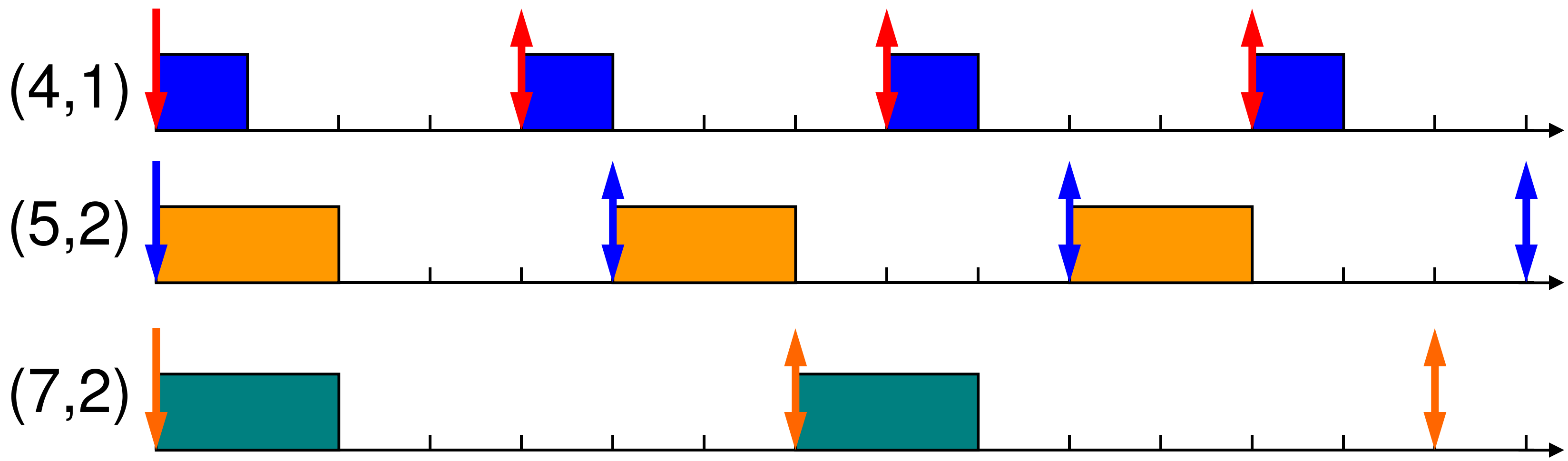


Deadlines: Hard vs. Soft

- Hard deadline
  - Disastrous or very serious consequences may occur if the deadline is missed
  - Validation is essential : can *all* the deadlines be met, even under worst-case scenario?
  - Deterministic guarantees
- Soft deadline
  - Ideally, the deadline should be met for maximum performance. The performance degrades in case of deadline misses.
  - Best effort approaches / statistical guarantees

Schedulability

- Property indicating whether a real-time system (a set of real-time tasks) can meet their deadlines



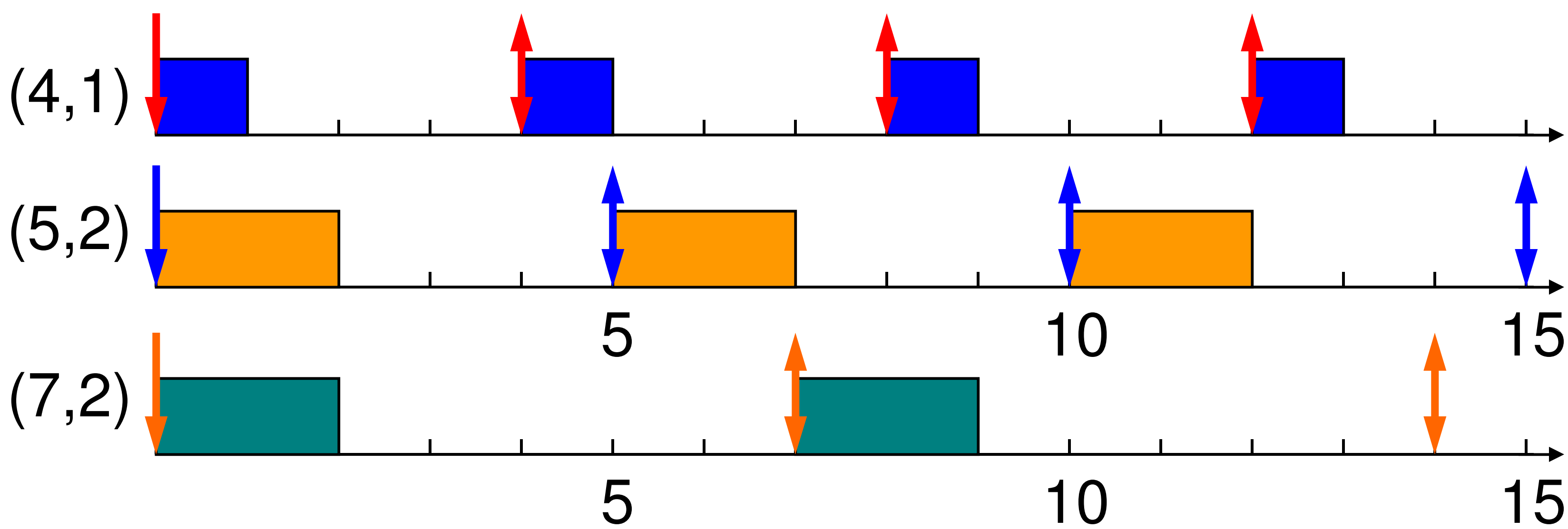
What’s Important in Real-Time

- Metrics for real-time systems differ from that for time-sharing systems.

	Time-Sharing Systems	**Real-Time Systems**
Capacity	High throughput	Schedulability
Responsiveness	Fast average response	Ensured worst-case response
Overload	Fairness	Stability

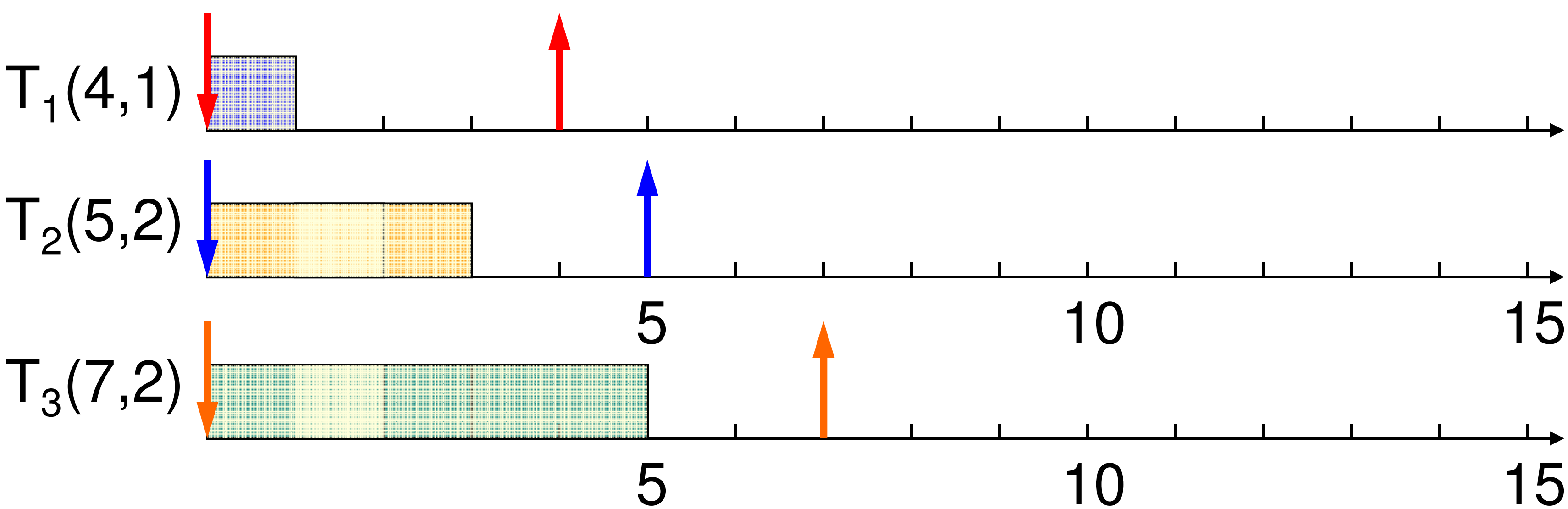
Real-Time Scheduling

- Determines the order of real-time task executions
- Static-priority scheduling
- Dynamic-priority scheduling



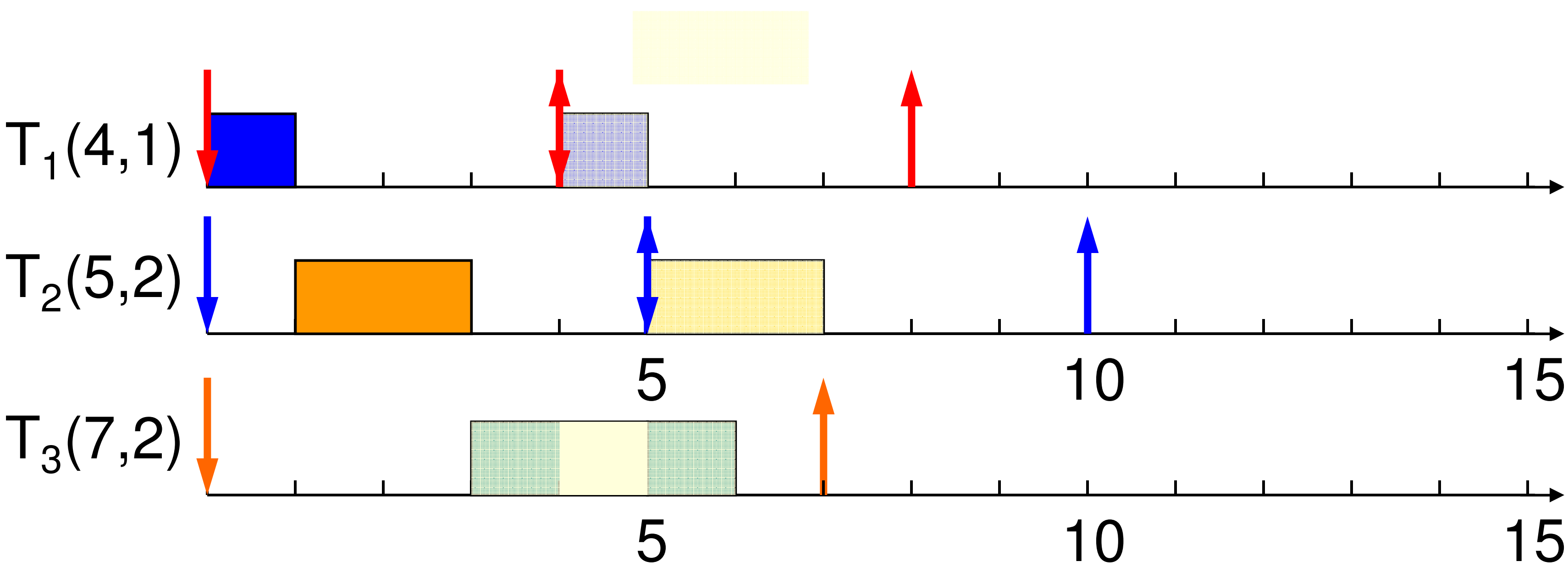
RM (Rate Monotonic)

- Optimal static-priority scheduling
- It assigns priority according to period
- A task with a shorter period has a higher priority
- Executes a job with the shortest period



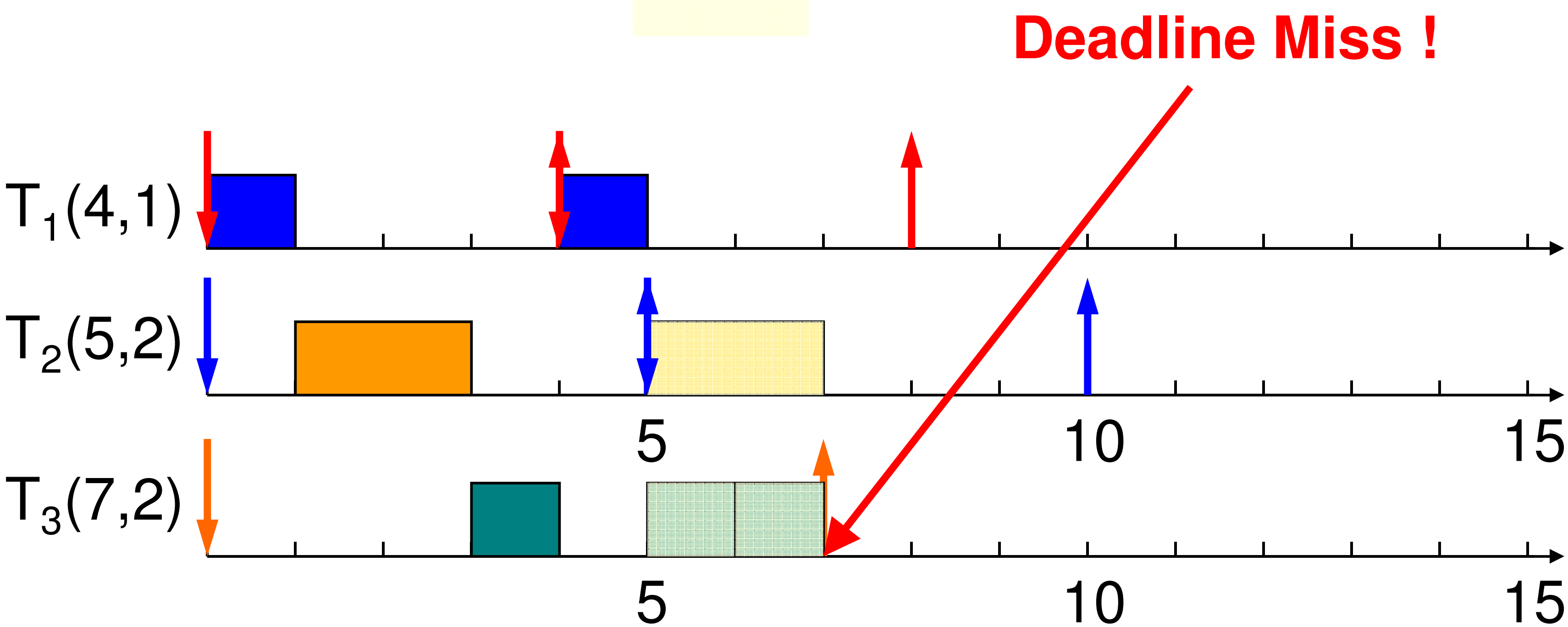
RM (Rate Monotonic)

- Executes a job with the shortest period



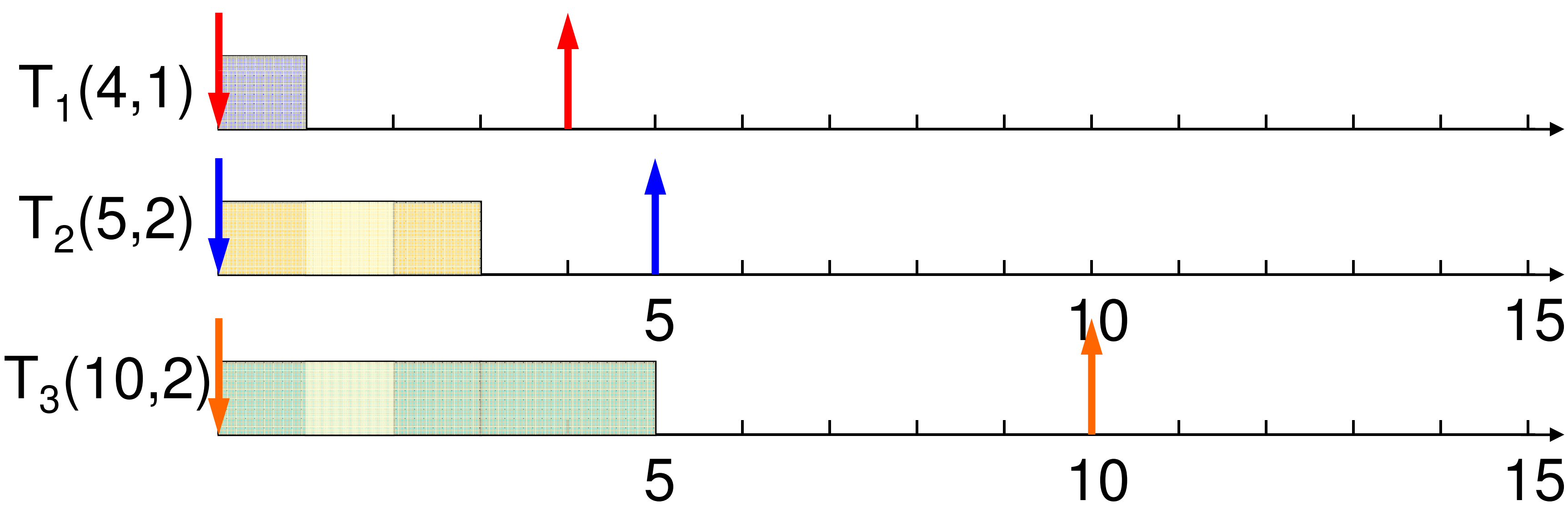
RM (Rate Monotonic)

- Executes a job with the shortest period



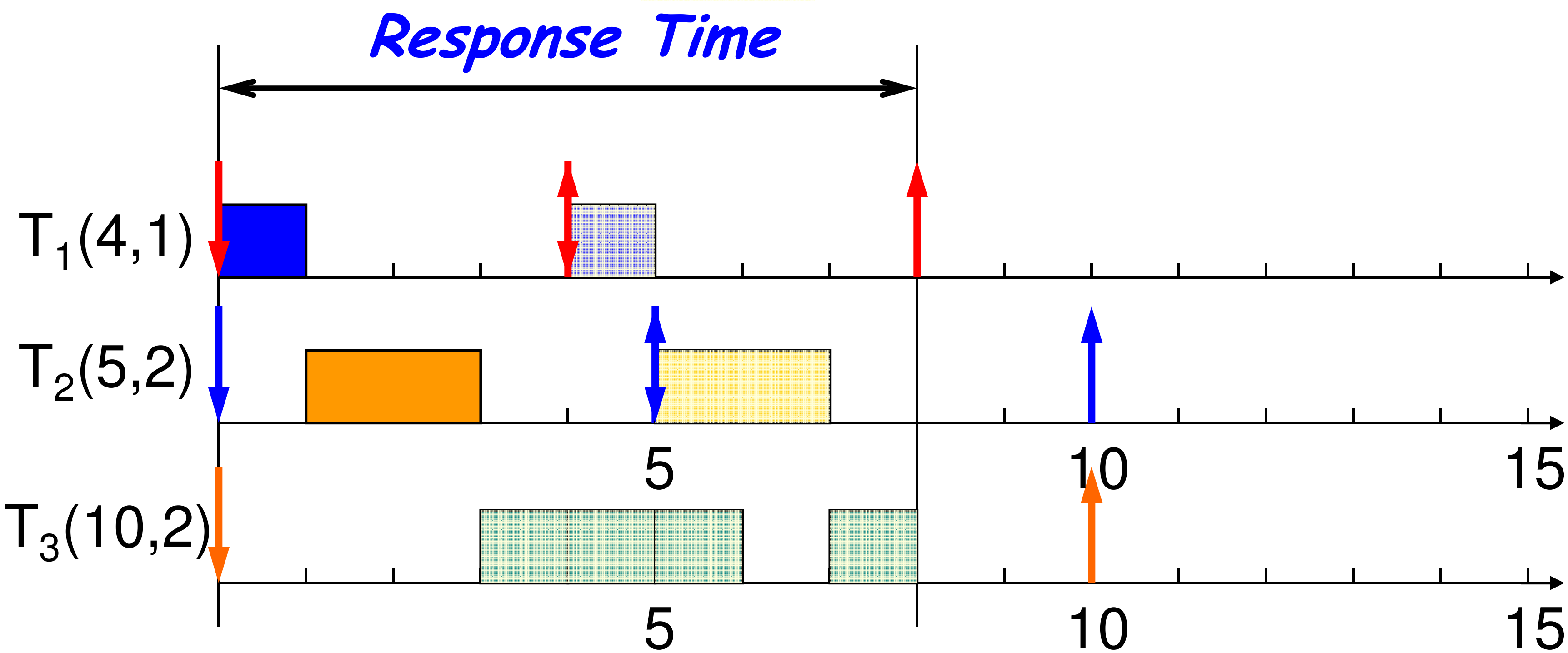
Response Time

- Response time
  - Duration from released time to finish time



Response Time

- Response time
  - Duration from released time to finish time

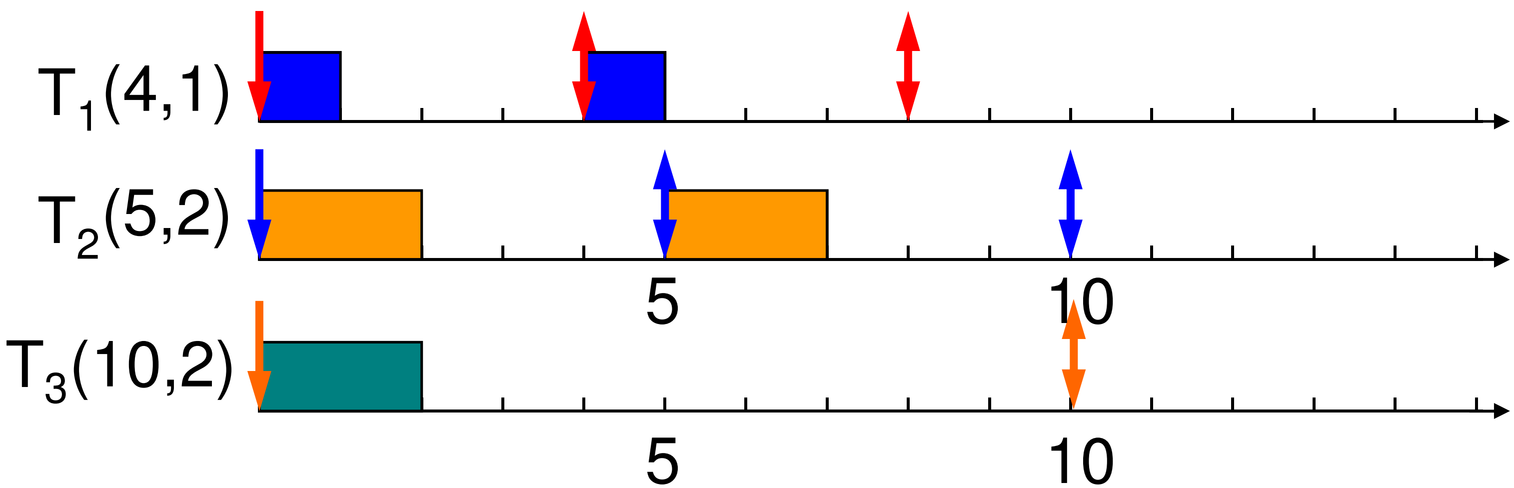


Response Time

- Response Time (r_i) [Audsley et al., 1993]

$$r_i = e_i + \sum_{T_k \in HP(T_i)} \left\lceil \frac{r_i}{p_k} \right\rceil \cdot e_k$$

- HP(T_i) : a set of higher-priority tasks than T_i



RM – Utilization Bound

- Real-time system is schedulable under RM if

$$\sum U_i \leq n\,(2^{1/n}-1)$$

Liu & Layland,

"Scheduling algorithms for multi-programming in a hard-real-time environment", Journal of ACM, 1973.

RM – Utilization Bound

- Real-time system is schedulable under RM if

$$\sum U_i \leq n\,(2^{1/n}-1)$$

- Example: $T_1(4,1)$, $T_2(5,1)$, $T_3(10,1)$,

$$\sum U_i = 1/4 + 1/5 + 1/10$$

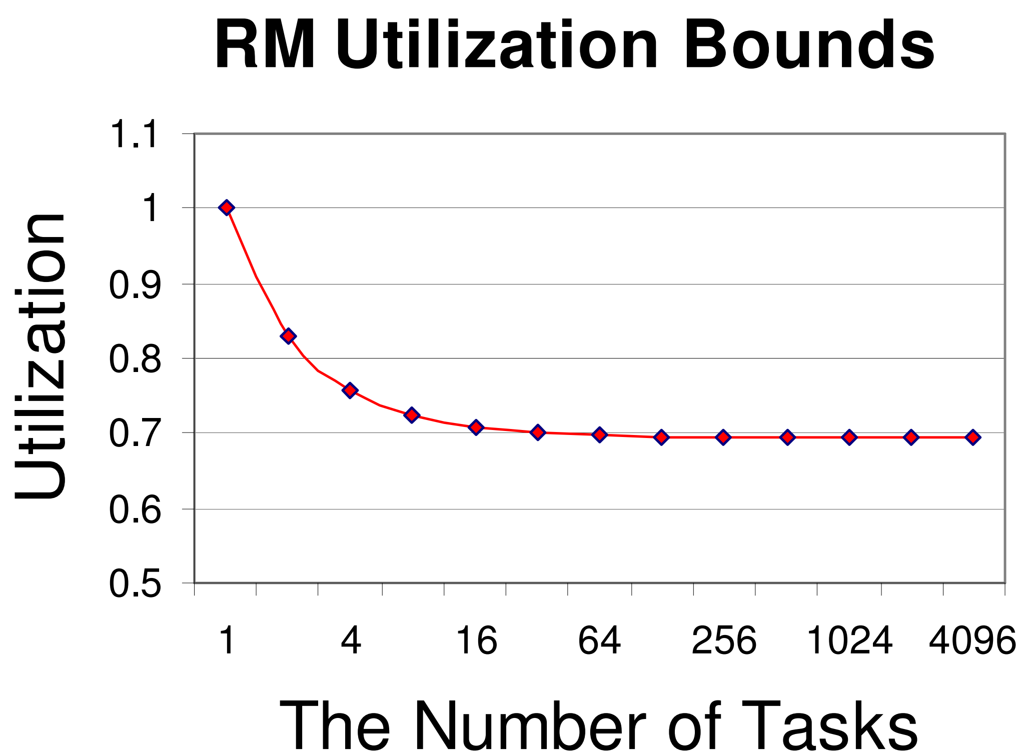
$$= 0.55$$

$$3\,(2^{1/3}-1) \approx 0.78$$

Thus, $\{T_1, T_2, T_3\}$ is schedulable under RM.

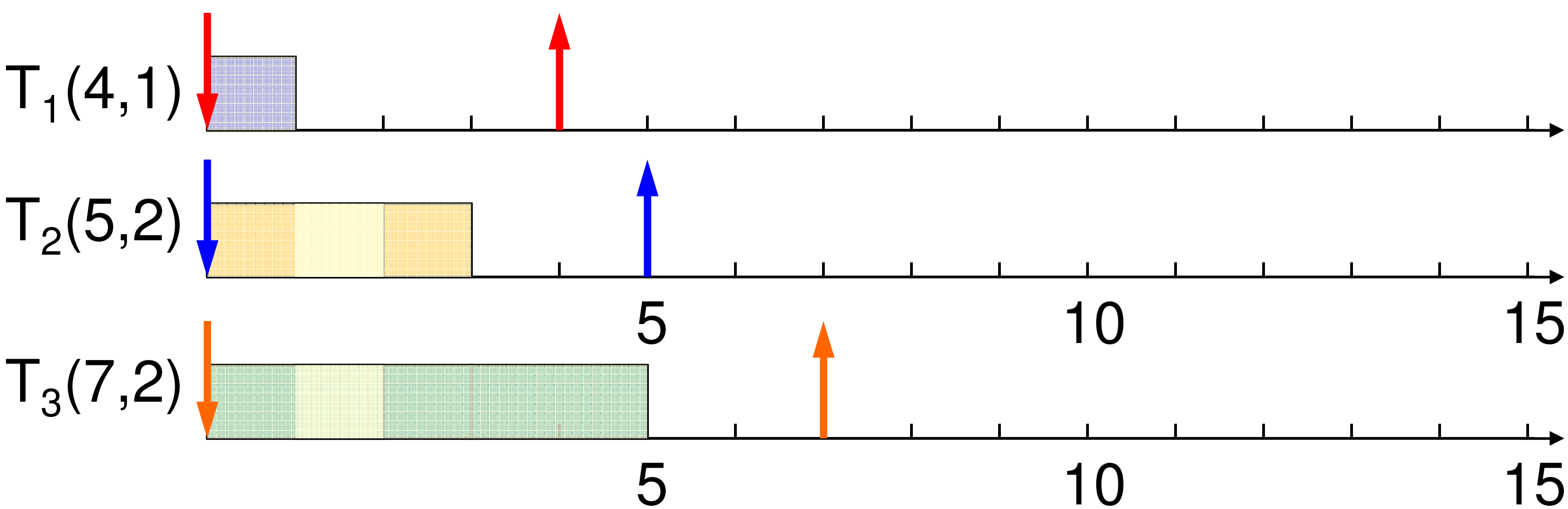
RM – Utilization Bound

- Real-time system is schedulable under RM if
  - $\sum U_i \leq n\,(2^{1/n}-1)$



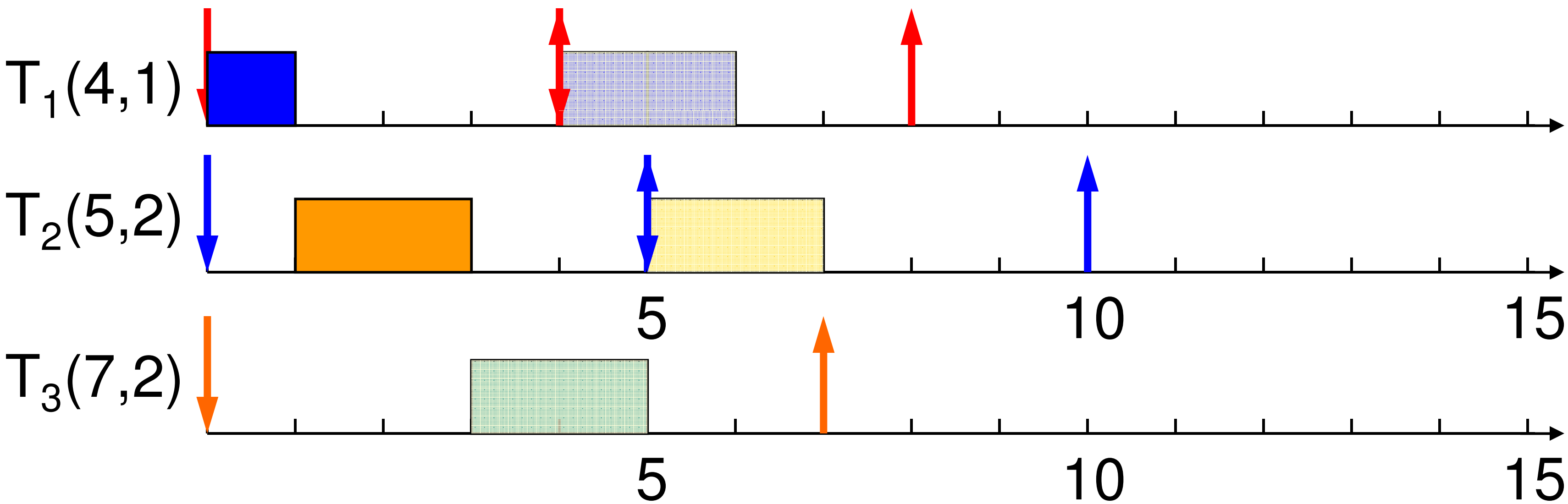
EDF (Earliest Deadline First)

- Optimal dynamic priority scheduling
- A task with a shorter deadline has a higher priority
- Executes a job with the earliest deadline



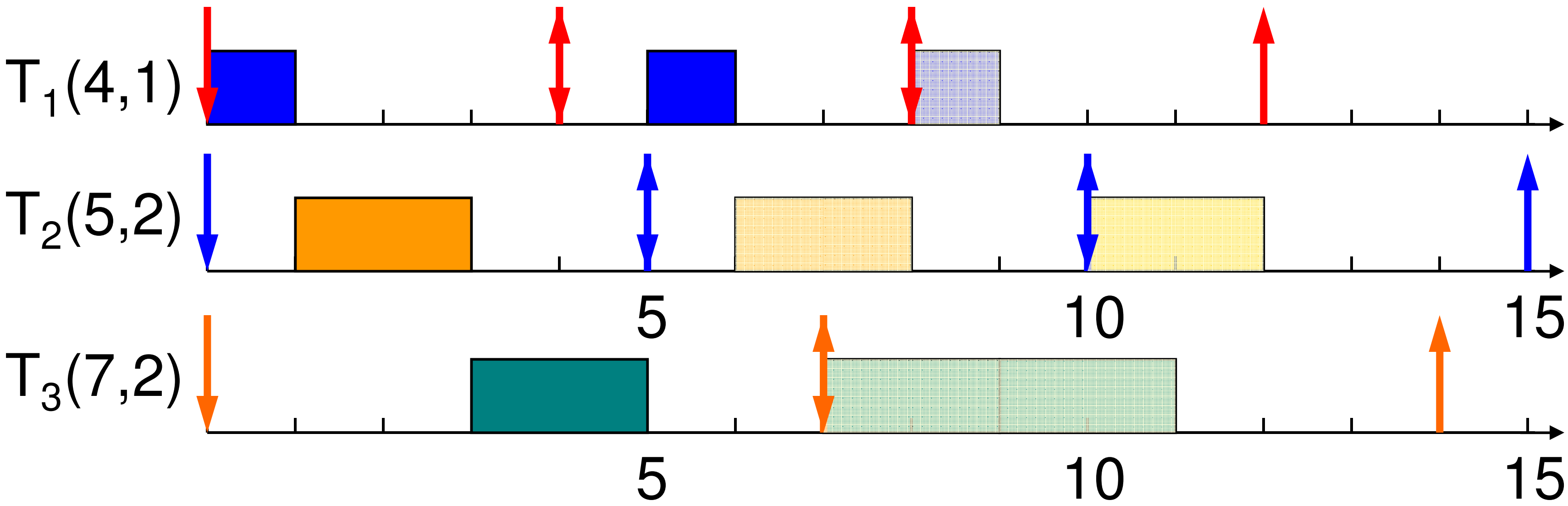
EDF (Earliest Deadline First)

- Executes a job with the earliest deadline



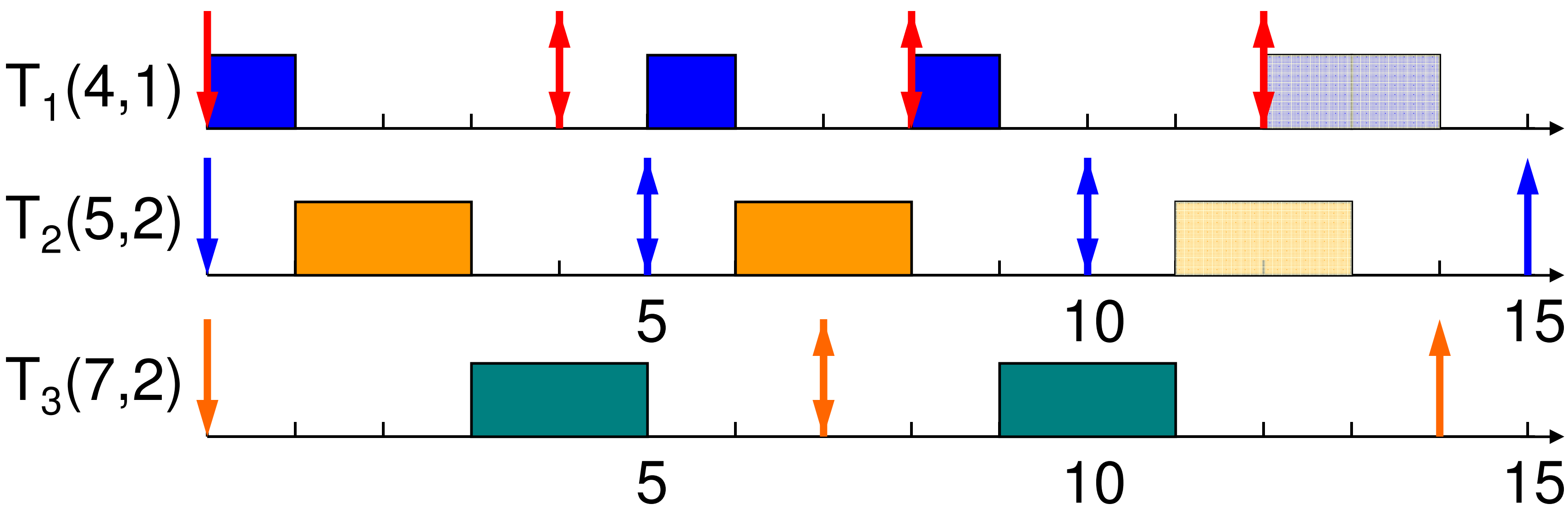
EDF (Earliest Deadline First)

- Executes a job with the earliest deadline



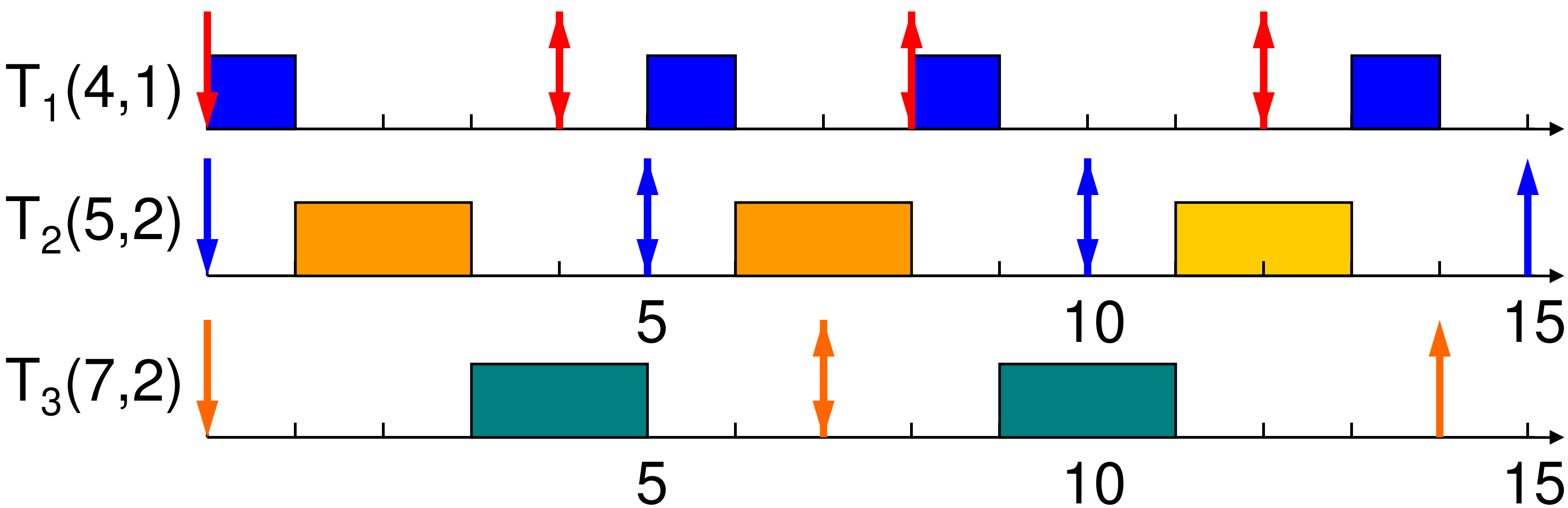
EDF (Earliest Deadline First)

- Executes a job with the earliest deadline



EDF (Earliest Deadline First)

- Optimal scheduling algorithm
  - if there is a schedule for a set of real-time tasks, EDF can schedule it.



EDF – Utilization Bound

- Real-time system is schedulable under EDF if and only if

$$\sum U_i \le 1$$

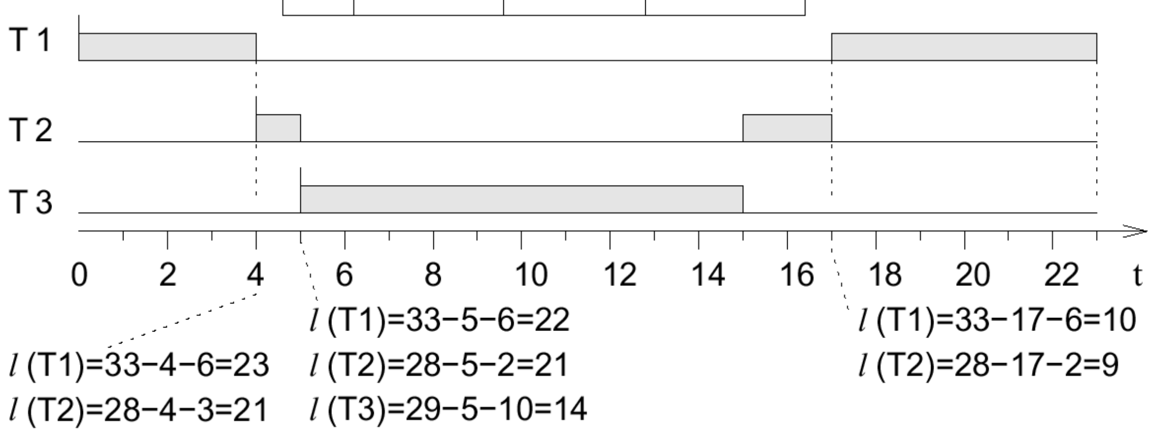
Liu & Layland,

"Scheduling algorithms for multi-programming in a hard-real-time environment", Journal of ACM, 1973.

Least Laxity First (LLF)

- Dispatch the task with the smallest laxity, which is the largest amount of time that a task can be delayed (some type of procrastination index)
- In a sense, it is similar to EDF, in that it runs the *most urgent* tasks in the set (the metric by which *urgency* is measured, differs though)

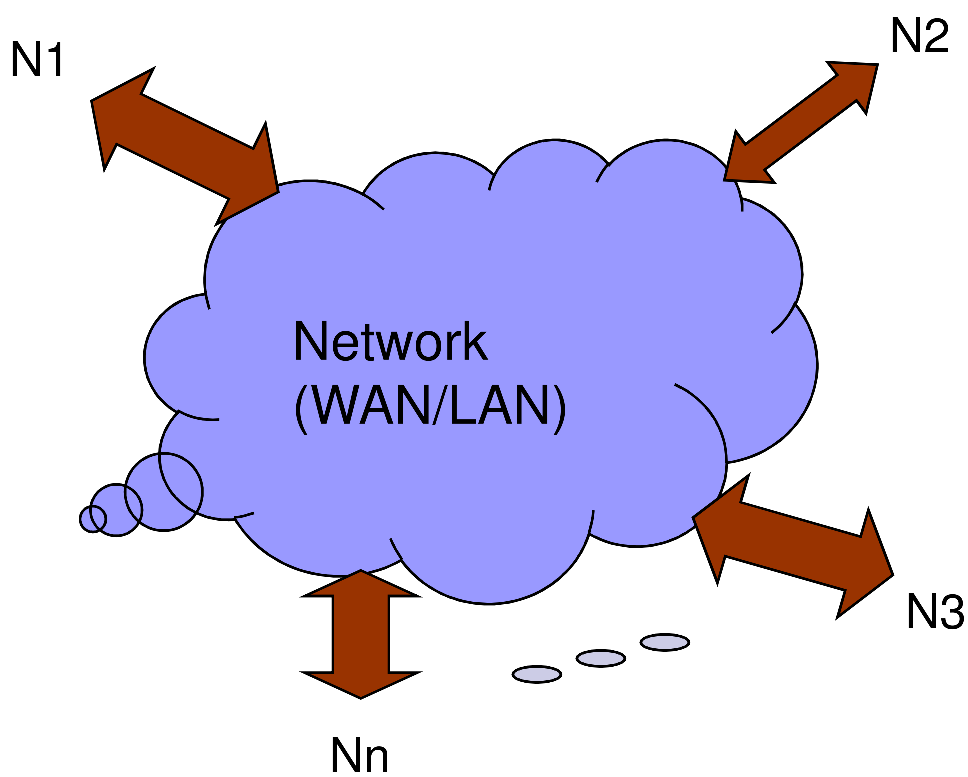
	arrival	duration	deadline
T 1	0	10	33
T 2	4	3	28
T 3	5	10	29



- Requires calling the scheduler periodically, and to re-compute the laxity - many calls of the scheduler
- When tasks have the same laxity - too many preemptions

What is a Distributed System?

- A set of nodes communicating through a network
- Network could be LAN or WAN
- Nodes could be homogeneous or heterogeneous



Why Distributed Systems?

- Applications themselves are distributed
  - E.g., command and control, air traffic control
- High performance
  - Better load balancing
- High availability (fault-tolerance)
  - No single point of failure

Problems with Distributed Systems

- Resource management is difficult
  - No global knowledge on workload
  - No global knowledge on resource allocation
- No synchronized clock (or clocks need to be synchronized)
- Communication related errors
  - Out of order delivery of packets, packet loss, etc.
- Difficult to distinguish network partition from node/link failures

Task Model

- Tasks can be periodic or non-periodic.
- Guaranteed Task – A task which may be assured to meet its deadline under all circumstances.
- A set (possibly null) of guaranteed periodic tasks exists at each node.
- Non-periodic tasks may arrive at any node at any time in the network.
- *The scheduling objective is to guarantee all periodic tasks and as many non-periodic tasks as possible, utilizing the resources of the entire network.*

Local Scheduler

- Each node in the network contains a *local* scheduler.

- When a new task arrives, an attempt is made to schedule the task at that node.
  - Calls *Guarantee routine*

- If guaranteed, the *Dispatcher* is invoked.
  - Dispatcher determines *which* among the guaranteed periodic and non-periodic tasks is to be executed next.
  - This selection depends on the *scheduling policy* used.
    - Example: EDF

Local Scheduler

- If the new task cannot be guaranteed, the scheduler tries to execute the task on some other node.

- The local scheduler interacts with other nodes to determine the node to which the task can be sent to be scheduled.
  - Uses techniques such as *bidding*, *focused addressing* etc.

- Upon arrival at the destination node, another attempt is made to schedule the task.

- Eventually, the task is either guaranteed and executed, or discarded.

Surplus

- The amount of *computation time* available on a node between the *arrival time* of a new unguaranteed task and its *deadline*.

- The new task can be guaranteed only if the surplus is greater than the execution time required for the task.

- A local task is guaranteed only if its *latest start time* is greater than its *arrival time*.

Latest Start Time (S)

- Arrange all guaranteed tasks in order of non-increasing deadlines

- If the 1st task has deadline D_1 and execution time e_1,
  - $S_1 = D_1 - e_1$
- Let the 2nd task has deadline D_2 and execution time e_2,
  - If $D_2 > S_1$, $S_2 = S_1 - e_2$
  - Otherwise, $S_2 = D_2 - e_2$

- *S values of all other tasks are similarly calculated.*

Time Overhead Considerations

- Time spent on scheduling is important in real-time systems.
- Dispatcher's execution time must be included in every task's computation time.
  - *Invoked each time any task (including the local scheduler and bidder tasks) completes execution and relinquishes the CPU*
- Newly arriving non-periodic tasks must be examined soon after they arrive.
  - *But interrupting a running task to guarantee a newly arriving task could cause the running task to miss its deadline!*

Time Overhead Considerations

- **A possible solution:**
  - After dispatcher chooses next task to run, check its *surplus* to verify that running the bidder task / local scheduler in between will not cause deadline misses of guaranteed tasks.

- This solution cannot be used if the running task is non-preemptive. **Solution:**
  - Run the bidder and the local scheduler tasks as periodic tasks on a processor separate from the CPU on which tasks are scheduled.

- **A logical extension:** Allocate a separate processor with limited processing capabilities for scheduling.

Communication Related Overheads

- If a new task cannot be guaranteed locally, it becomes a candidate for remote execution.

- Communication delays depend on the pairs of processes involved
  - The distance separating them
  - The communication protocol used
  - The communication from other nodes in the system to the two nodes.

Communication Delay Estimation

- Every communication is time-stamped by the sending node.
- The receiving node computes delay by subtracting the time-stamp from the time of receipt.
- Subsequent delays may be estimated based on a linear relationship between message length and communication delay.
- *In this talk, we assume that the clocks on different nodes are synchronized.*

Focused Addressing

- The scheduler with a task which cannot be guaranteed locally, first attempts to execute it on another node through *focused addressing*.

- Focused addressing works as follows:
  - Estimate the arrival time *AT* of the task (say *T*) at a node *N*.
  - If estimated surplus at *N*, between *AT* and deadline *D* of *T* is greater than its execution time *e* by *FP%*, the task is sent to the node.

  - The receiving node uses the *guarantee routine* to check whether it can guarantee the arriving task.
  - *FP* is an adaptive parameter.

Bidding

- If there is no node with a significant surplus, a more expensive bidding procedure is invoked.

- The main functions of the bidder are:
  - For a task that cannot be guaranteed locally, the *bidder* sends out a *request for bids* (*RFBs*) to nodes with surplus processing power.
  - Evaluating bids.
  - Responding to the request for bids from other nodes.

Request for Bids (RFB)

- A request for bid (RFB) message is broadcast to all nodes.

- A RFB message contains the following information:
  - Execution time of the task: *e*, Deadline: *D*, Size of the task: *S*, the time *t* at which the message is being sent and a deadline for responses: *R*.

- *R* is the time after which the requesting process will examine the bids to choose the best bidder.

Request for Bids (RFB)

- The deadline for responses *R* should be such that after *R* there is sufficient time:
  - for the requesting process to evaluate the bids,
  - for the task to reach the best bidder node,
  - for the best bidder to guarantee and schedule the task,
  - once scheduled, for the task to complete computations and meet its deadline.

Request for Bids (RFB)

- R = D – (P + E + W + e)
  - *P*: period of the task that evaluates bids (*the maximum waiting time before bids are recognized*)
  - *E*: expected time taken for the task to reach the best bidder
  - *W* : estimated time after arrival that the task may begin computation.
- If R is insufficient, the bidder may again resort to *focused addressing*.
  - *FP* is adjusted to augment chances of finding a node with surplus.
- If a node with surplus still cannot be found, the task cannot be guaranteed.

Request for Bids (RFB)

- A possible improvement:
  - *Do not broadcast RFBs*
  - Send RFBs only to nodes whose estimated surplus matches the requirements of the task to be guaranteed - ***Buddies***
    - *avoids potentially unnecessary communication*

- Drawbacks of the approach:
  - Requires time to check the node-surplus information to determine potential bidders
  - Can prevent bidding by nodes with surplus, if the available information was inaccurate.

Making Bids

- This is carried out in response to an RFB
- The bidder first checks and proceeds only if its response will reach the requestor before the response deadline *R*.
  - This time includes: time of response + transit time of response
- Once a node decides to respond, it first computes *AT*, the estimated arrival time of the task if, indeed, it is awarded the task.

Making Bids

- *AT* takes into account the following:
  - The fact that bids at the requesting node are evaluated after the response deadline *R*
  - The average delay in evaluating bids (estimated to be one half the bidding period)
  - The estimated time for the task to arrive at the bidder's node.
- Whether the bidder can execute the new task is determined by the surplus *SATD* at the bidder's node between *AT* and deadline *D*.

Making Bids

- *SATD* takes into account:
  - Future instances of periodic tasks
  - Processing time for tasks that may arrive as a result of previous bids
    - *PNB*: % of CPU time used by non-periodic tasks arriving as a result of bidding
  - Processing time needed for non-periodic tasks that may arrive locally in the future
    - *PNL*: % of CPU time used by non-periodic tasks arriving locally

- SATD = S – (PNB + PNL) x (D - AT)
  - S = Surplus between AT and D

Making Bids

- Possible Improvements:
  - A node receiving an RFB, determines that another node has a higher probability of being awarded the task.
    - *Do not respond to the RFB*
  - Saves communication and computation costs incurred in bidding
  - The accuracy of this decision would depend on the accuracy about other nodes' surpluses

Evaluating Bids

- Bids are processed by the node that originally sent RFBs
- Queues all bids until the response deadline *R*
- Calculates Estimated Arrival Time (*EAT*) at each bidder's node.
- For each bidder it estimates *SEATD*, the surplus between ETA and D
  - SEATD = SATD x ((D - EAT) / (D - AT))
- *The node with the greatest SEATD becomes the best bidder.*
  - *Identity of the 2nd best bidder may also be sent to the best bidder*

Evaluating Bids

- Intimates to all *but* the best bidder that their bids were not accepted.
  - An alternative: *Bidders may time-out after a predetermined time*.
    - (RFBs may also contain similar time bounds within which bids must be received)

- Surplus information sent on bids may be used for *focused addressing* and selection of *buddies* while sending RFBs

Response to Task Award

- Awardee node treats it as a task that has arrived locally
  - Takes action to guarantee it.
- If the task cannot be guaranteed,
  - Determine if some other node has the surplus to guarantee it.
  - Instead of a broadcast, send the task to the second-best bidder.
- Otherwise, the task is rejected.
- *The environment that submitted the task will be responsible for appropriate action if a task is not guaranteed.*
  - Resubmit task with a later deadline.

Handling Precedence Constraints

- The bidding algorithm can be extended to handle tasks with precedence constraints.

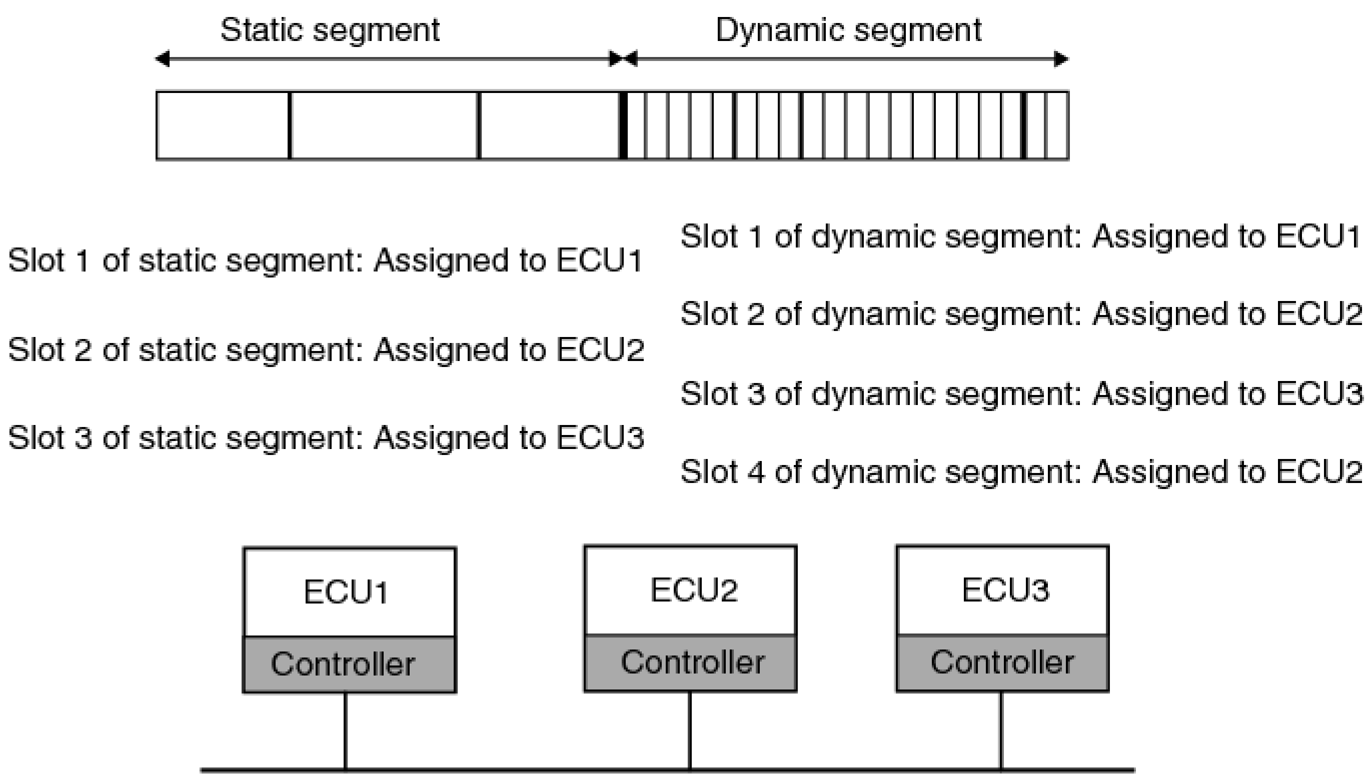
- Consider the following scenario:
  - Task A has been guaranteed on node 1, B on node 2, C on node 3
  - A and B should precede C
  - Assume $D_A < D_B$

- Try to guarantee C at node 3, with start time of $D_B + T$
  - *T*: Max time required for A and B's outputs to reach C

Handling Precedence Constraints

- If C cannot be guaranteed at node 3,
  - Send C to node 2 (containing preceding task with latest deadline)
  - Broadcast an RFB to be returned to node 2
- Attempt to guarantee task at node 2.
- If this is not successful, try to *modify* D_B to D'_B such that,
  - $D'_B < D_B$ and $D_A < D'_B$
  - B remains guaranteed
  - C can be guaranteed
  - A possible extension: *Recursively apply the above method*.
- If C is still not guaranteed,
  - Send C to the best bidder in a normal bidding process

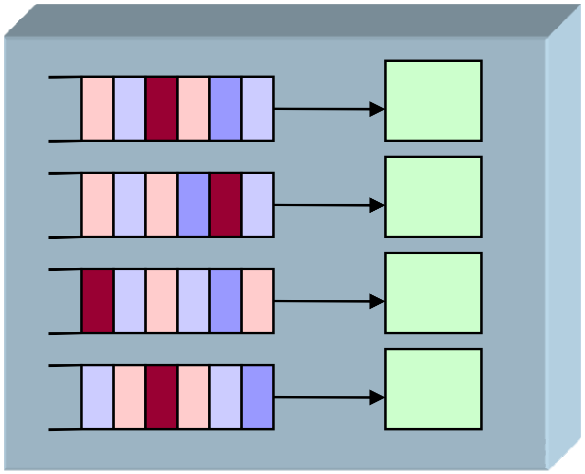
Time triggered Bus: Flexray



Multiprocessor Scheduling - Partitioning

- Partition tasks so that each task always runs on the same processor

- Steps:
  - Assign tasks to processors (bin packing)
  - Schedule tasks on each processor using uniprocessor algorithms like EDF or LLF.



Partitioning

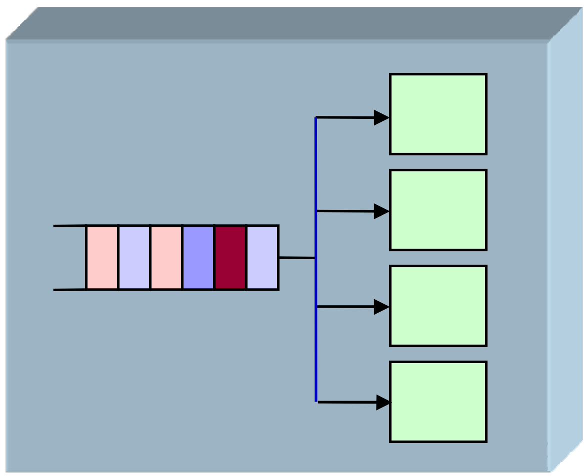
- Assignments of tasks to processors
  - Bin-packing problem (NP-hard problem)
  - Typically done using heuristics

- Proposed heuristics
  - First Fit (FF)
  - Best Fit (BF)
  - Worst Fit (WF)
  - First Fit Decreasing (FFD), etc.

Global Scheduling

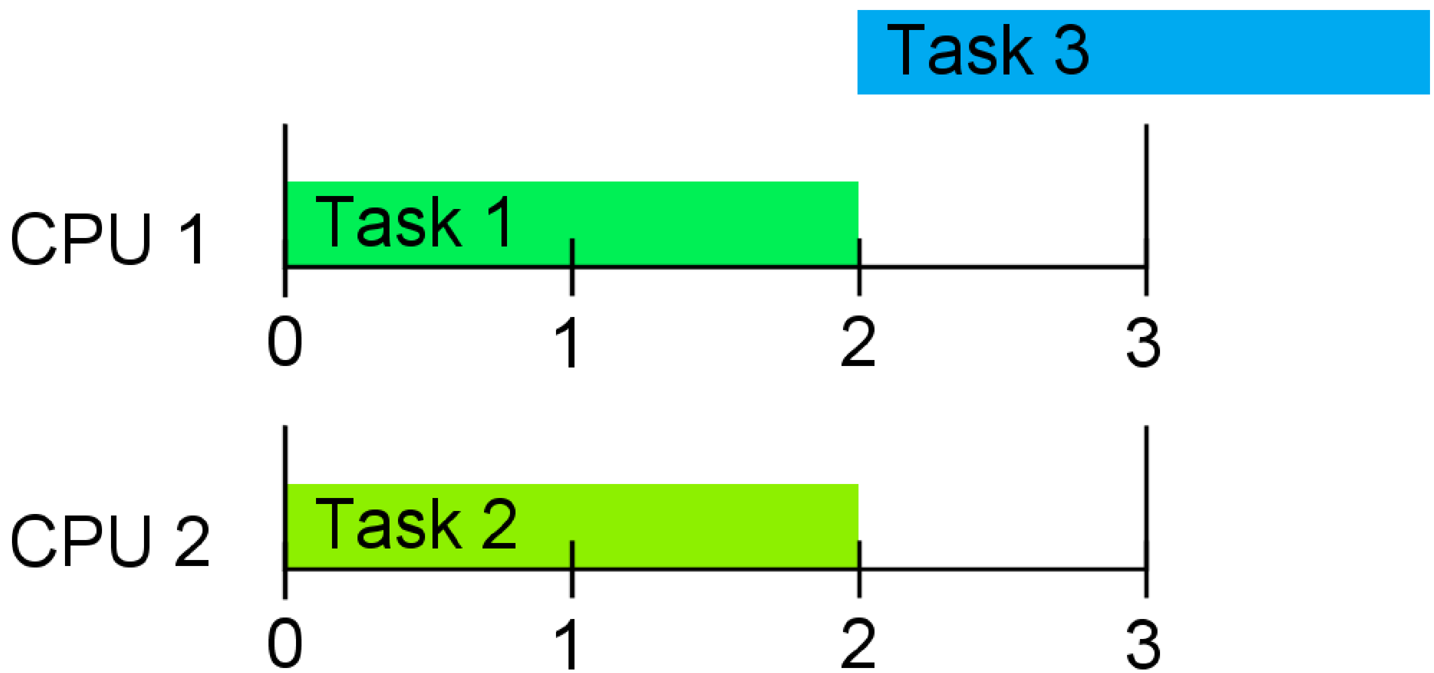
- A single scheduling algorithm is used that schedules all tasks

- Important difference:
  - Task may migrate among the processors



Partitioned Schedulers ≠ Optimal

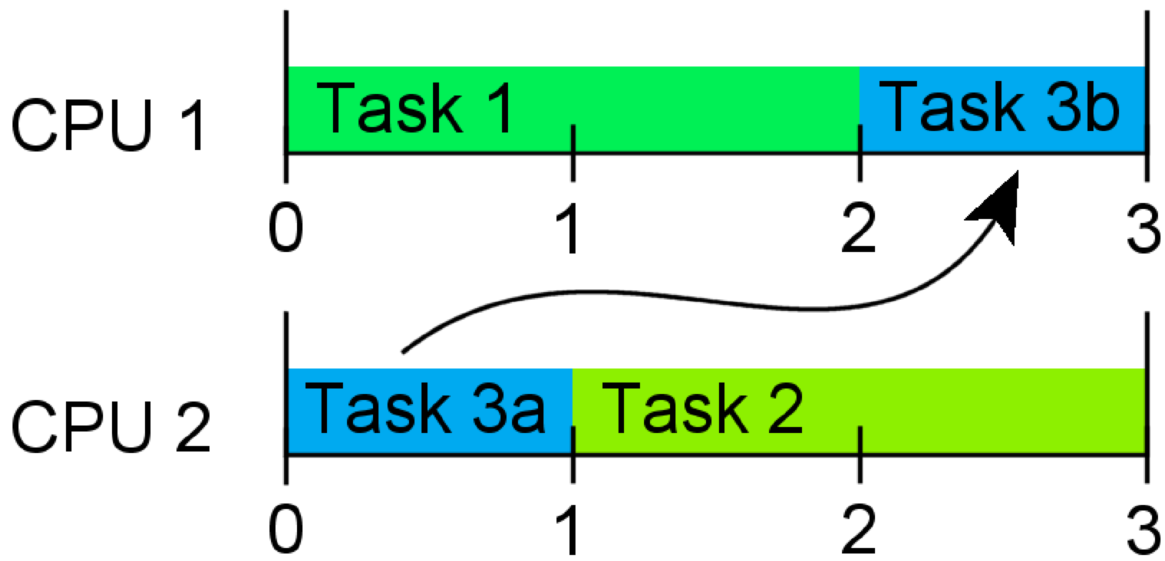
- Example: 2 processors; 3 tasks, each with 2 units of work required every 3 time units



Global Schedulers Succeed

- Example: 2 processors; 3 tasks, each with 2 units of work required every 3 time units

Task 3 *migrates* between processors



Problem Classification Methods

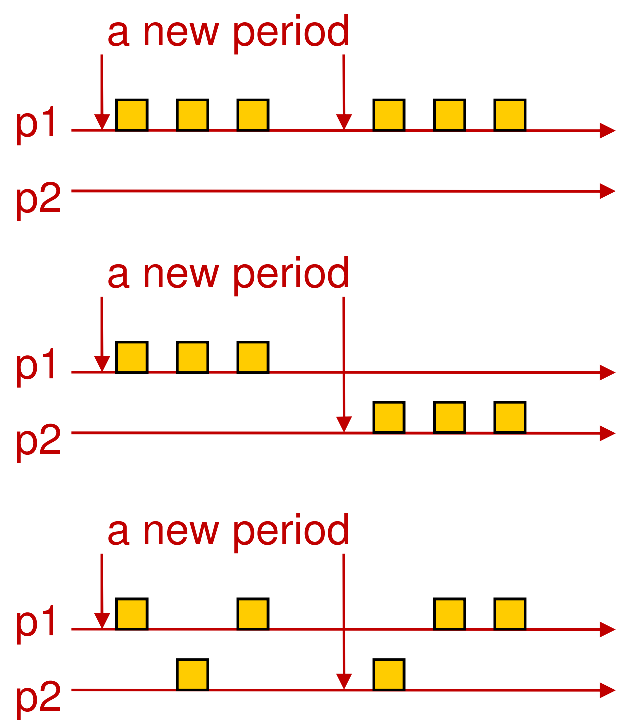
- Migration-based Classification
  - No migration
  - Restricted migration
  - Full migration
- Priority-based Classification
  - Static priorities
  - Job-level dynamic priorities
  - Unrestricted dynamic priorities

Global Scheduling Vs. Partitioning

- Trade-off between the two approaches
  - Global scheduling (= no restriction on migration)
    - Good: high utilization
    - Bad: high migration cost (also cache misses)
  - Partitioned scheduling (= strict restriction on migration)
    - Good: no migration cost
    - Bad: low utilization
- Generally, if we restrict more,
  - the run-time overhead is reduced but
  - the schedulability (e.g., utilization bound) is also reduced.

Migration-based Classification

- No Migration (Partitioned)
  - Task can not migrate
  - Job can not migrate
- Restricted Migration
  - Task can migrate
  - Job can not migrate
- Full Migration
  - Task can migrate
  - Job can migrate



Migration-based Classification

- Task migration and / or cache misses become very harmful when
  - CPUs are connected via bus or network
  - Each CPU has its own memory
  - Shared global memory not enough to hold states of all tasks
- For CPU cores on a single chip
  - CPUs are connected via a high-speed on-chip network
  - CPUs share large global memories and caches.
  - → Lower migration costs

The Big Goal #1

- Design of optimal scheduling algorithms
  - Intuitively speaking, any task set, whose utilization is less than or equal to the number of processors, is schedulable by some ***(3,3)-restricted*** algorithm

- Pfair (1996), ERfair (2000), PD^2 (2003), Bfair (2003), EKG (2006), LLREF (2006), SERF* (2011), POES* (2011), DP-Fair (2011), ESSM* etc. are examples of (3,3)-restricted algorithms.
  - Optimal real-time scheduling methodologies on multiprocessors.

Greedy Algorithms Fail on Multiprocessors

- At each scheduling point, a *greedy algorithm* will regularly select the *m* “best” jobs and run those
  - Earliest Deadline First (EDF)
  - Least Laxity First (LLF)
- EDF and LLF are optimal on a single processor ; neither is optimal on a multiprocessor
  - Such greedy approaches generally fail on multiprocessors

Greedy Algorithms Fail on Multiprocessors

- Example *(n* = 3 tasks, *m* = 2 processors) *:*

Task 1 : Work = 9 , Period = 10

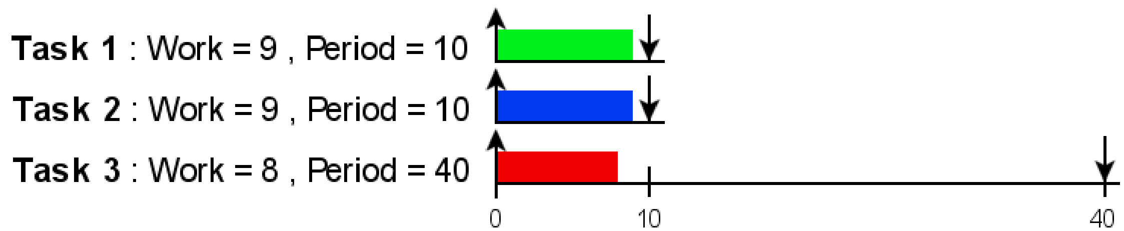
Task 2 : Work = 9 , Period = 10

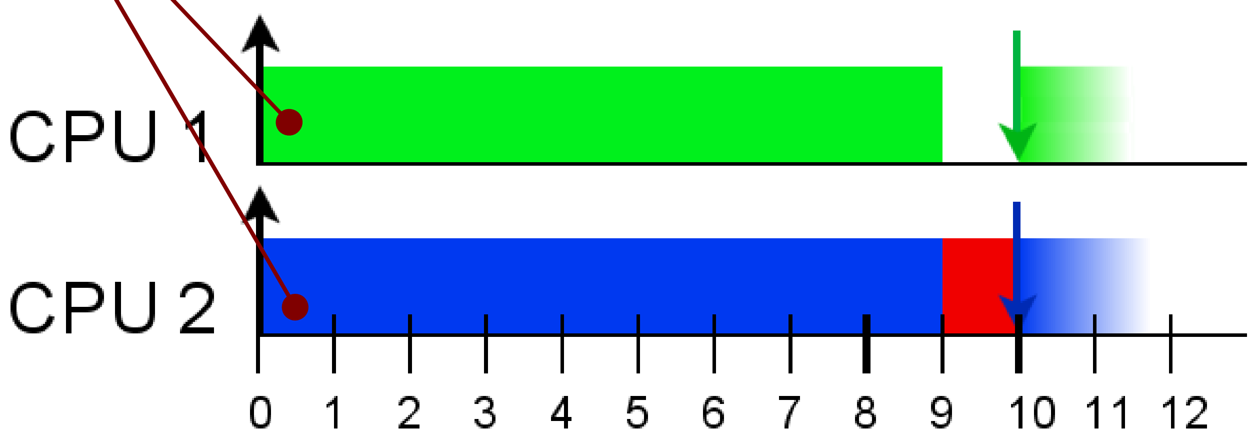
Task 3 : Work = 8 , Period = 40

Utilization: 9/10 + 9/10 + 8/40 = 2

Event-Driven Algorithms Fail on Multiprocessors

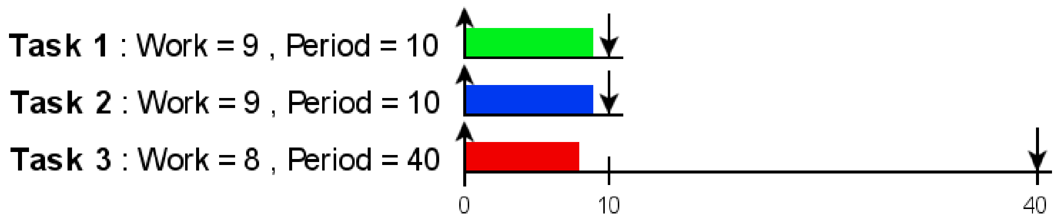
At time t = 0, Tasks 1 and 2 are the obvious greedy choices

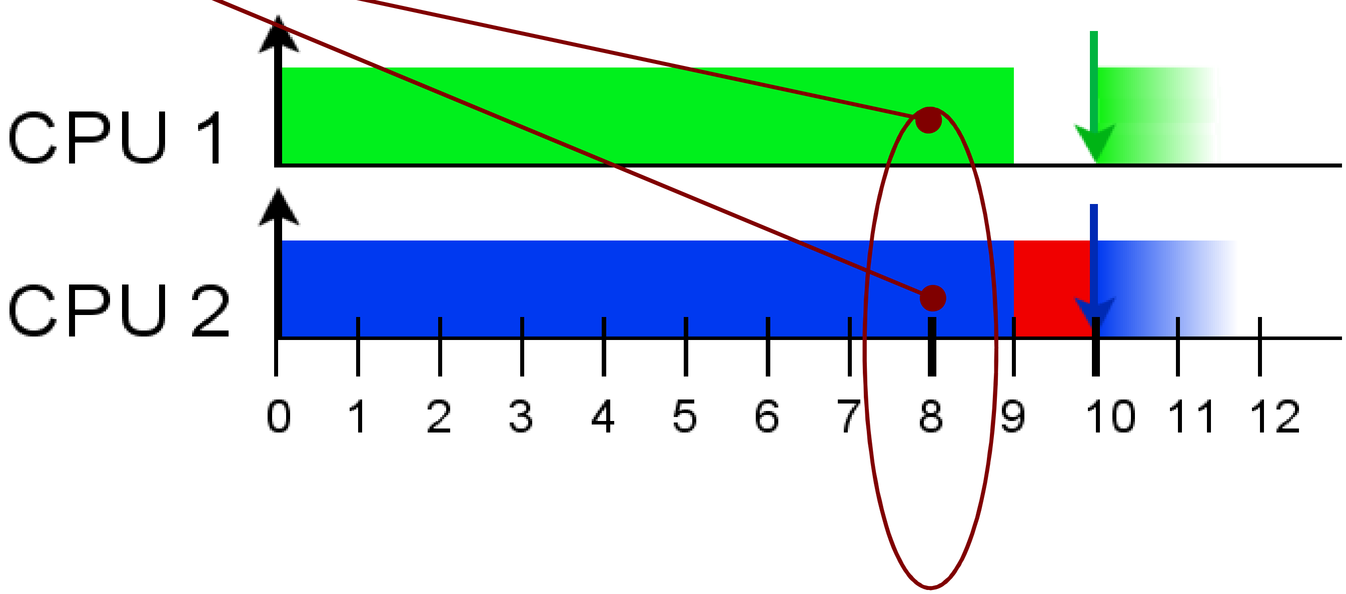




Greedy Algorithms Fail on Multiprocessors

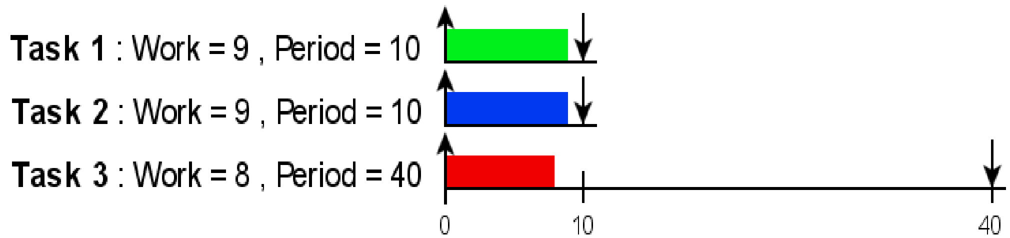
Even at t = 8, Tasks 1 and 2 are the only “reasonable” greedy choices

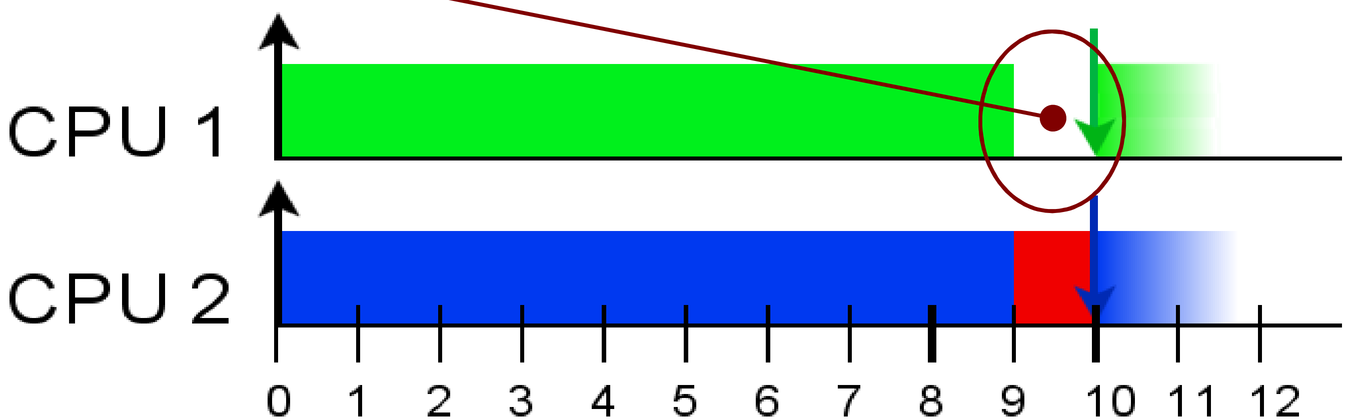




Greedy Algorithms Fail on Multiprocessors

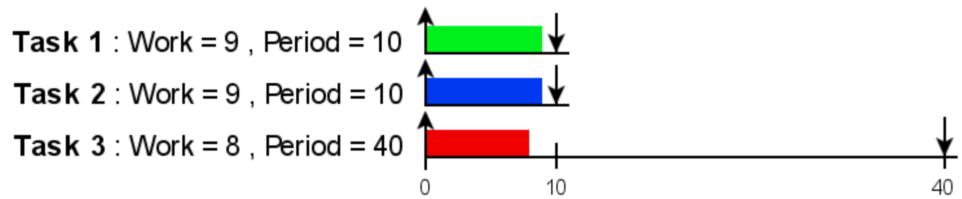
Yet if Task 3 isn't started by t = 8, the resultant idle time eventually causes a deadline miss

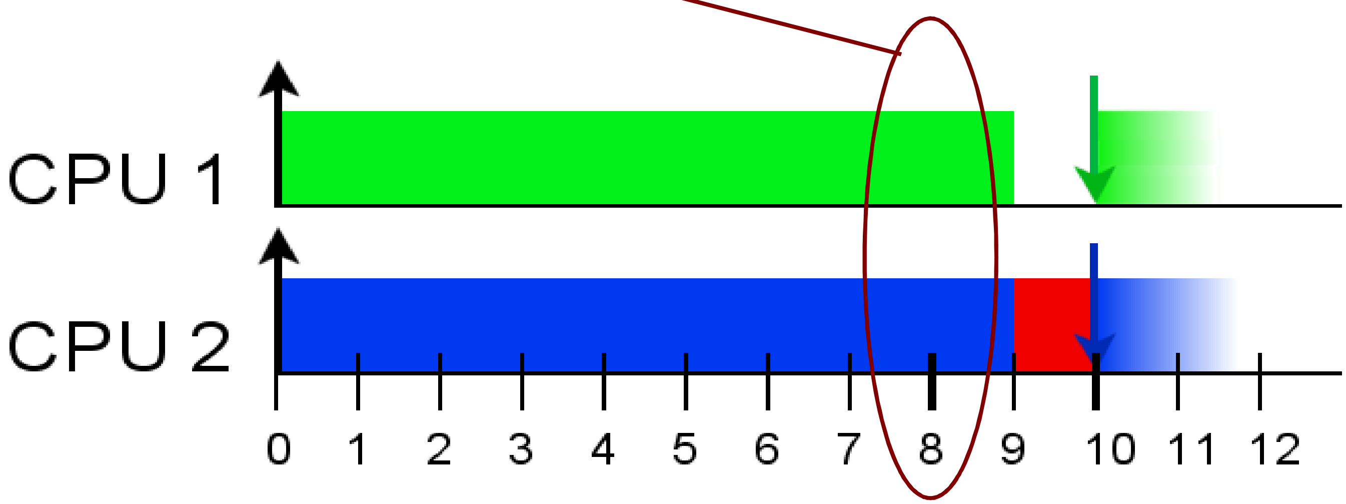




Event-Driven Algorithms Fail on Multiprocessors

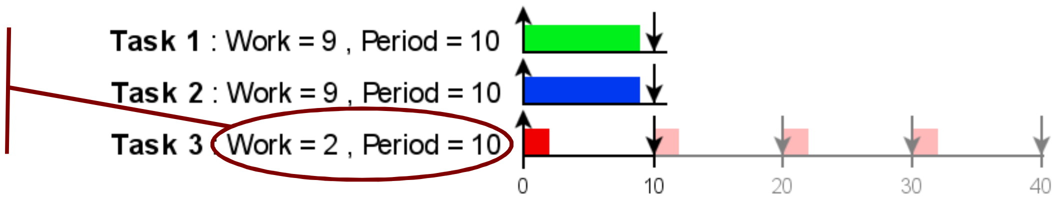
How can we "see" this critical event at t = 8?

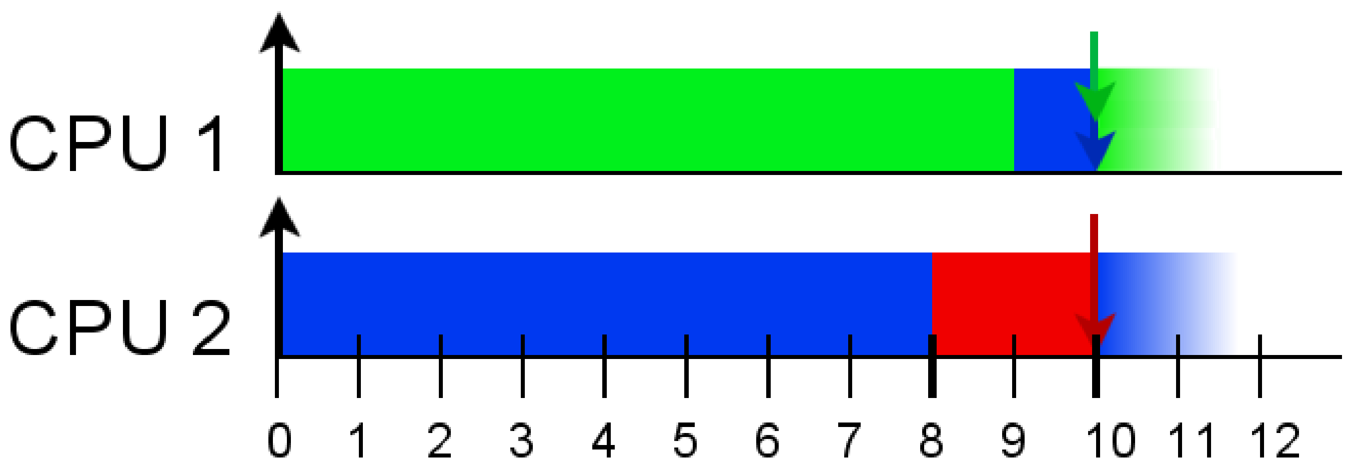




Proportioned Algorithms Succeed

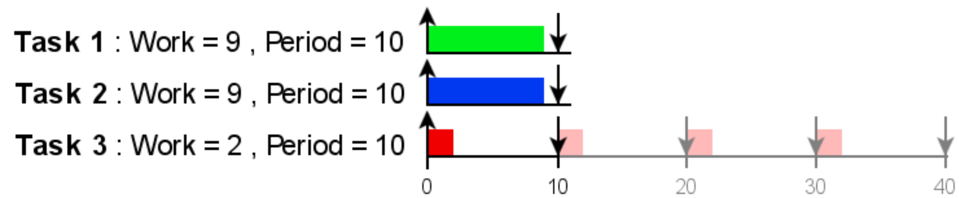
Subdivide Task 3 with a period of 10

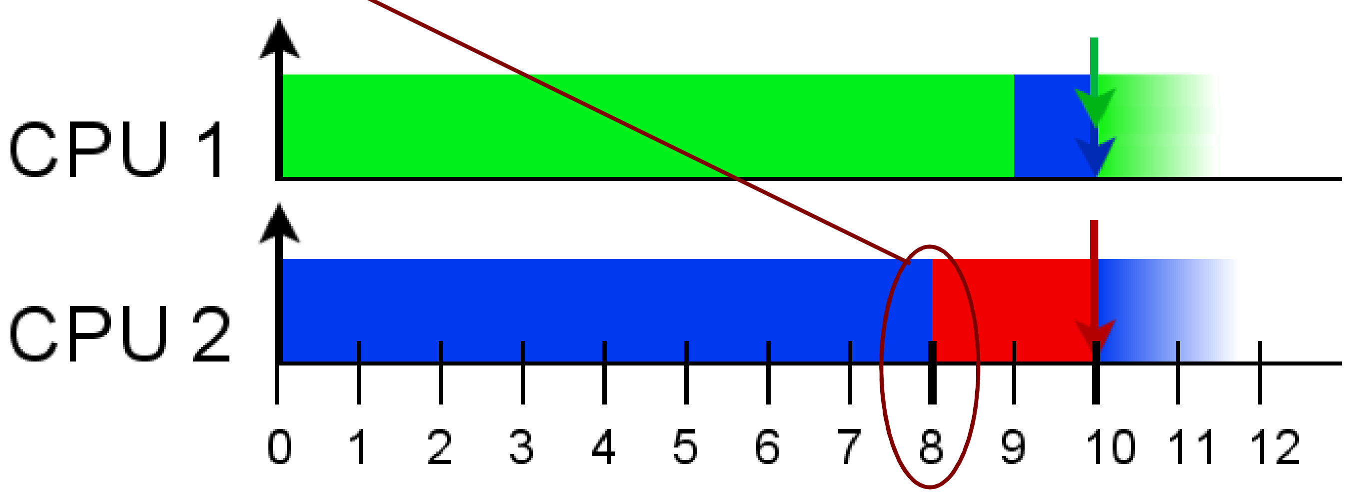




Proportioned Algorithms Succeed

Now Task 3 has a *zero laxity* event at time t = 8





The Other Big Goals

- Big Goal #2: *Proportional Fairness*
  - Jobs having equal priority (same utilization) are said to be scheduled with equal fairness if their rates of execution progress are same.

- Big Goal #3: *Low Overheads*
  - Task migration and Context Switches
  - Scheduling Complexity

Current State of the Art

- Pfair, ERfair, PD^2 satisfy goals #1 and #2
- Bfair, EKG, LLREF, DP-Fair satisfy goals #1 and #3
- POFBFS*, POES*, SERF*, ESSM* satisfy goals #1, #2 and #3
- There are other algorithms like EDF-fm (2005) which trades-off goal #1 to achieve goal #3.

ERFair Scheduling

- A work-conserving global multi-processor scheduling methodology for hard real-time repetitive tasks sets with fully dynamic priorities.
- Divides tasks into unit length sub-tasks; schedules the most urgent sub-tasks at each time-slot to ensure fairness.
- ***Early Release fair (ERfair) Scheduling*****:** At the end of any time-slot t, at least ($wt_i * t$) time-slots of execution of each task T_i must complete.

ERfair Scheduling - Idea

- Early Release fair (ERfair):
  - Given the task weights, finds pseudo-deadline d_i^j of the j^{th} sub-task of task I as :

$$d_i^j = \left\lceil \frac{j * p_i}{e_i} \right\rceil - 1$$

- Algorithm:
  - Schedule task with earliest pseudo-deadline first.
    - Arrange tasks in a min heap.
    - Extract the task at the root and execute.
    - Calculate pseudo-deadline of next sub-task.
    - Insert the task into the heap and re-heapify.
  - Ties between multiple tasks having same pseudo-deadline is broken using tie-breaking rules.
  - Complexity: O(log n) per time-slot per processor.

Strengths

- **Schedulability: Optimal**
- **Quality of Service (QoS):** Guarantees QoS : *reserve X time units for task A out of every Y time units.*
- **Temporal Isolation:** Provides temporal isolation to each client task from the ill-effects of other "misbehaving" tasks attempting to execute for more than their prescribed processor shares.
  - Makes it applicable in a wide range of domains – CPU, networks, embedded systems
- Graceful degradation for all tasks in times of overload.
- Efficient handling of dynamic task arrivals and departure

Weaknesses

- **Scheduling Overheads**
  - **High Scheduling Complexity:** Uses a min-heap to determine the most urgent operation deadlines of sub-tasks at each time-slot. Hence, for *n* given tasks, they suffer a high scheduling complexity of $O(lg\ n)$ per time-slot per task.
  - **Unrestricted Migrations and Preemptions:** A direct consequence of global scheduling and ignorance of affinities:
    - of tasks towards the processor where it executed last
    - of processor caches towards tasks it executed recently.

- Dearth of techniques to incorporate practical and emerging design metrics like power, overload management, fault tolerance, etc.

Thank You