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An Algorithm for Scheduling Certifiable Mixed-Criticality Sporadic Task Systems

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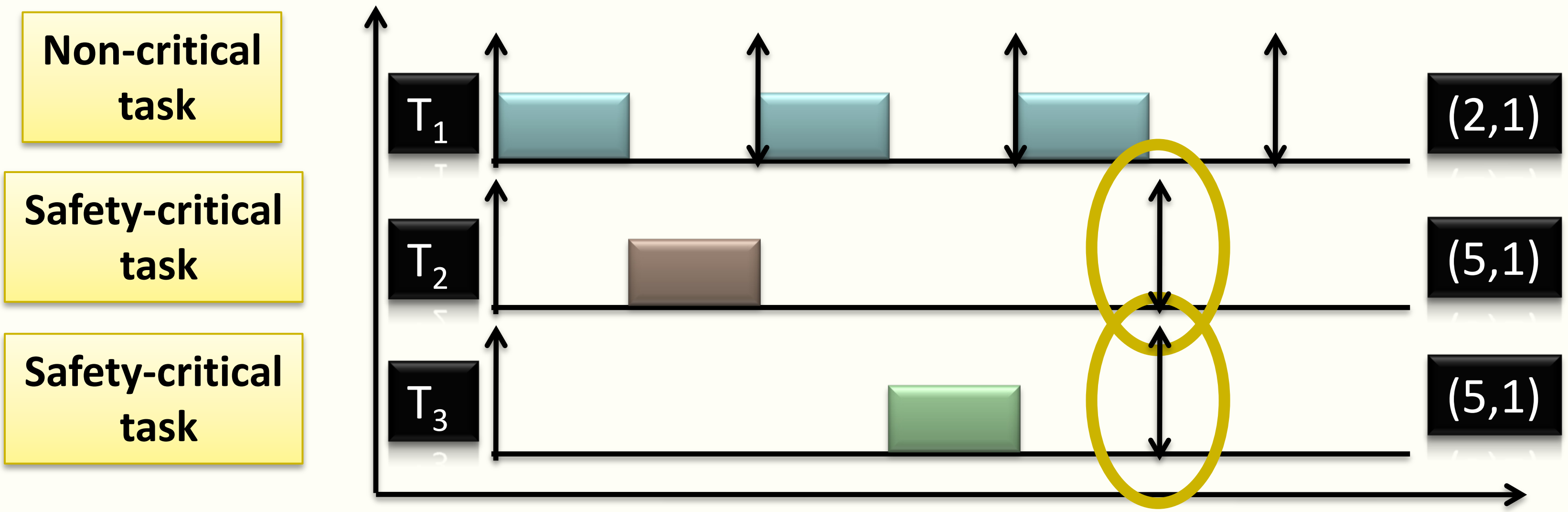
Motivation

- Tasks are in multiple criticality levels on safety-related embedded systems
- Certification is required for each criticality
- Classic real-time scheduling algorithms don't work efficiently

Motivation: An Example

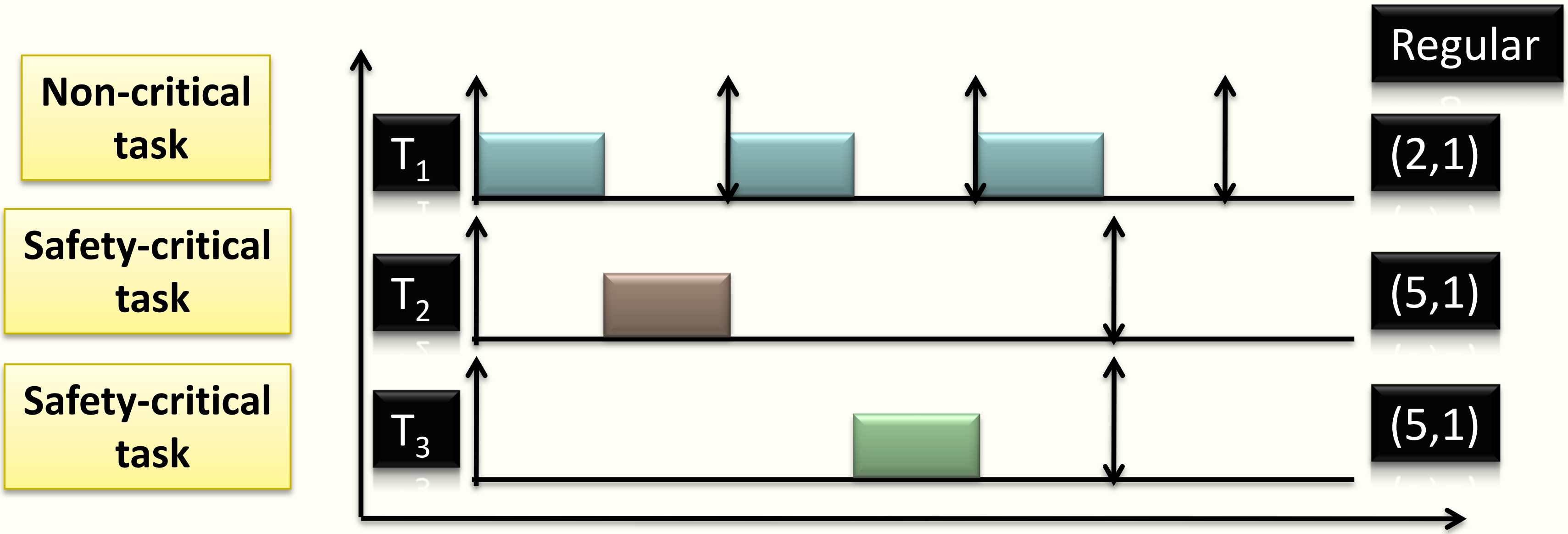
- Typical real-time system model

Certification:
Checking temporal correctness of safety-critical tasks



Motivation: An Example

- **The problem with certification**
  - The WCET is **estimated**
  - Schedulability relies on the **estimation**



Motivation: An Example

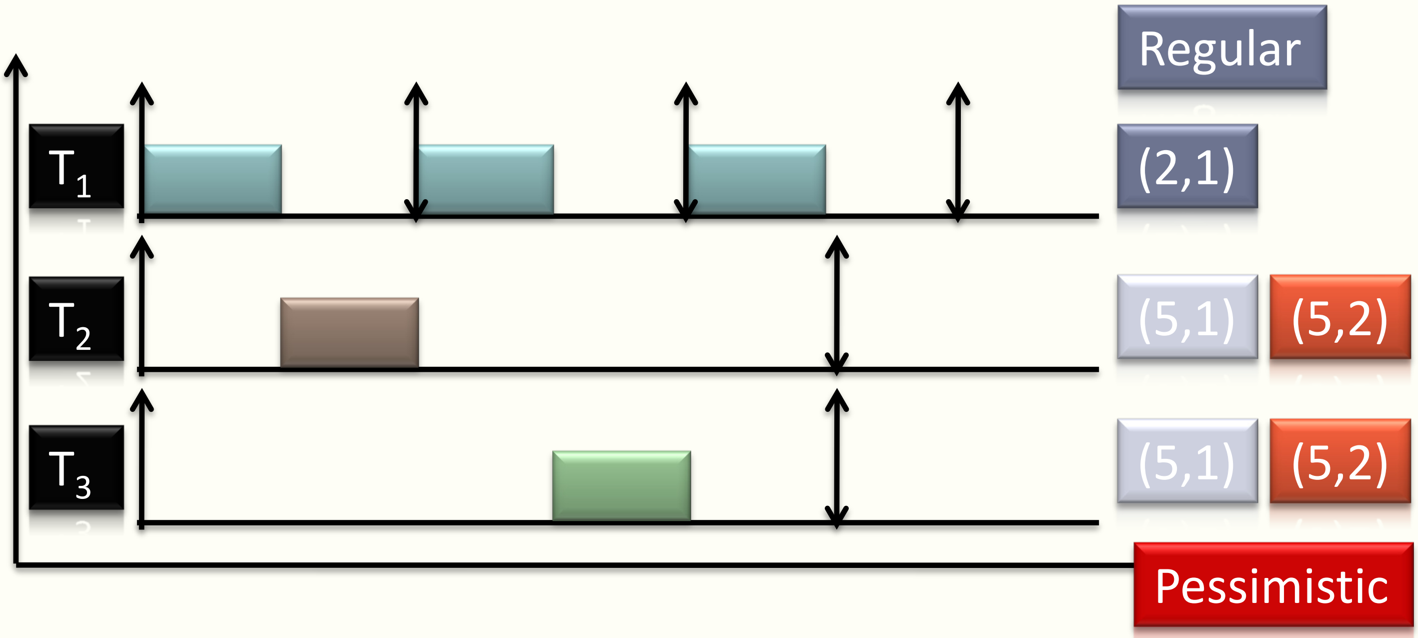
- The problem with certification

Certifiers may use
more pessimistic estimations

Non-critical task

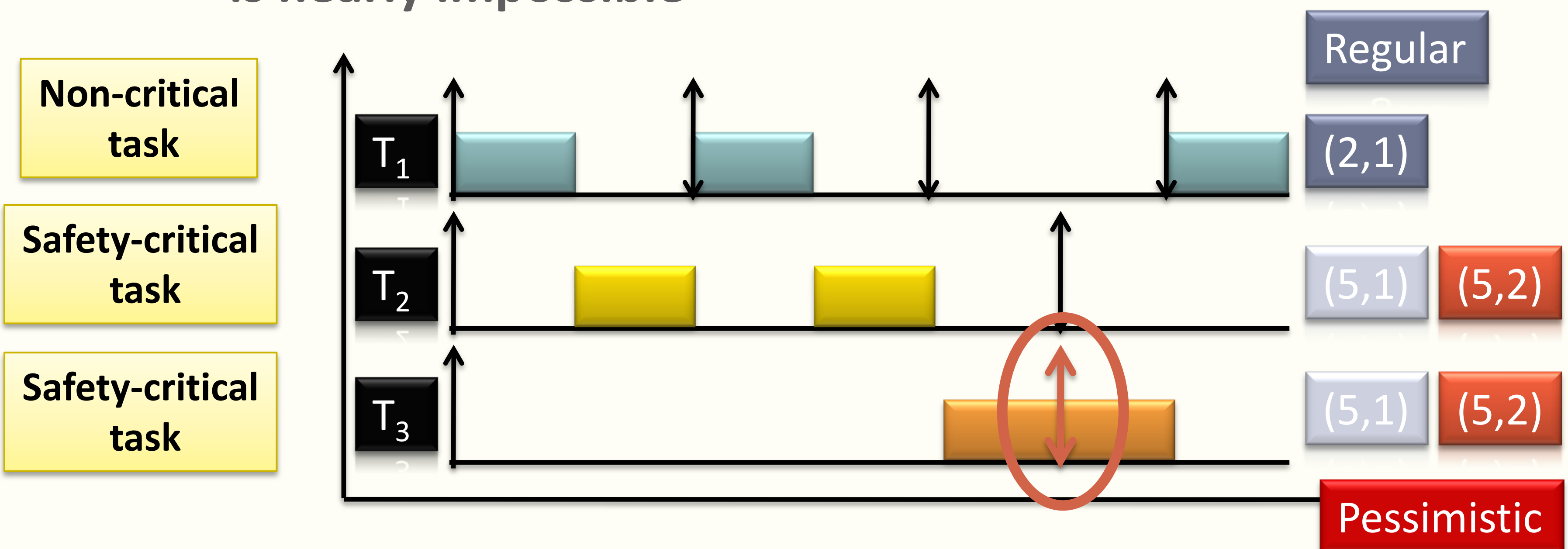
Safety-critical task

Safety-critical task



Motivation: An Example

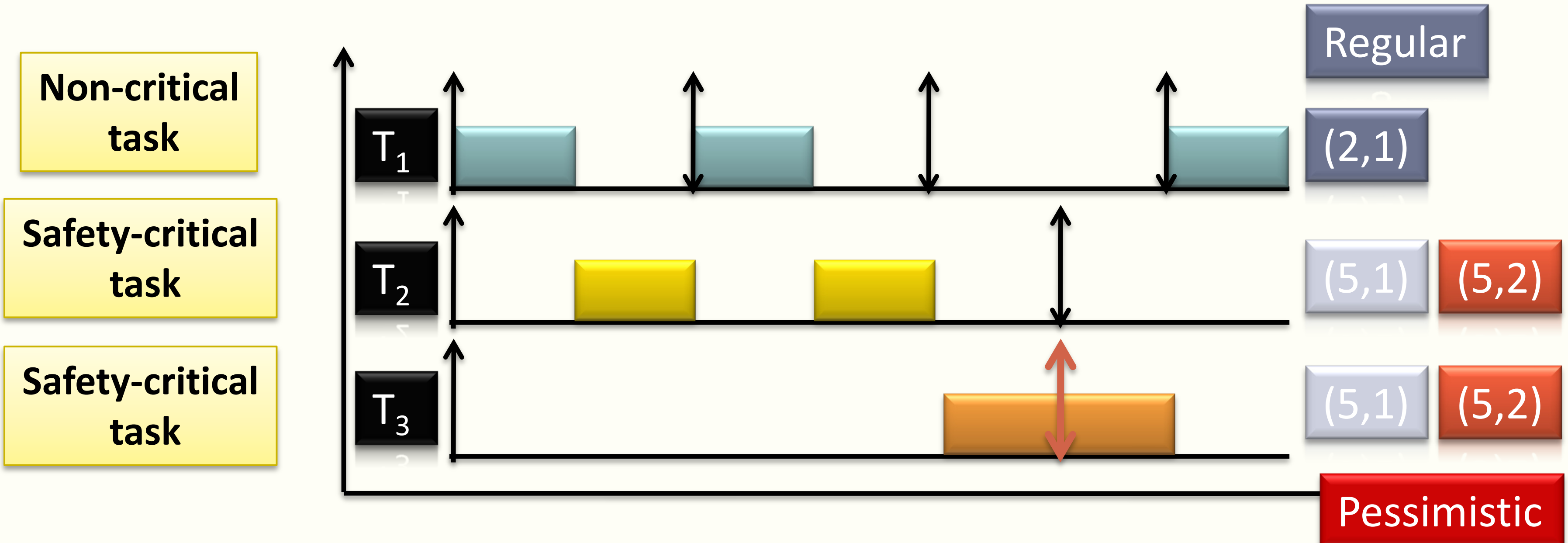
- **The problem with certification**
  - In this case, the system fails to pass certification
    - Though we know that T_2 and T_3's using so much time is nearly impossible



Motivation: An Example

- The problem with certification

We can use criticality monotonic to pass the certification



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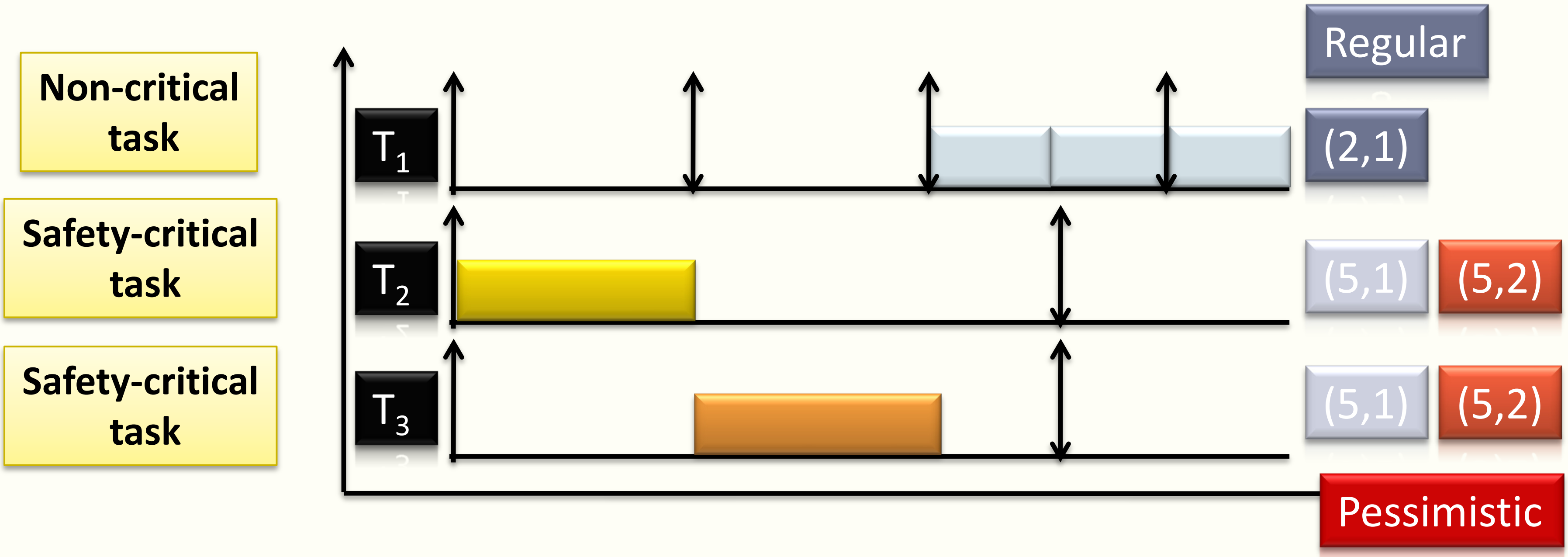

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Motivation: An Example

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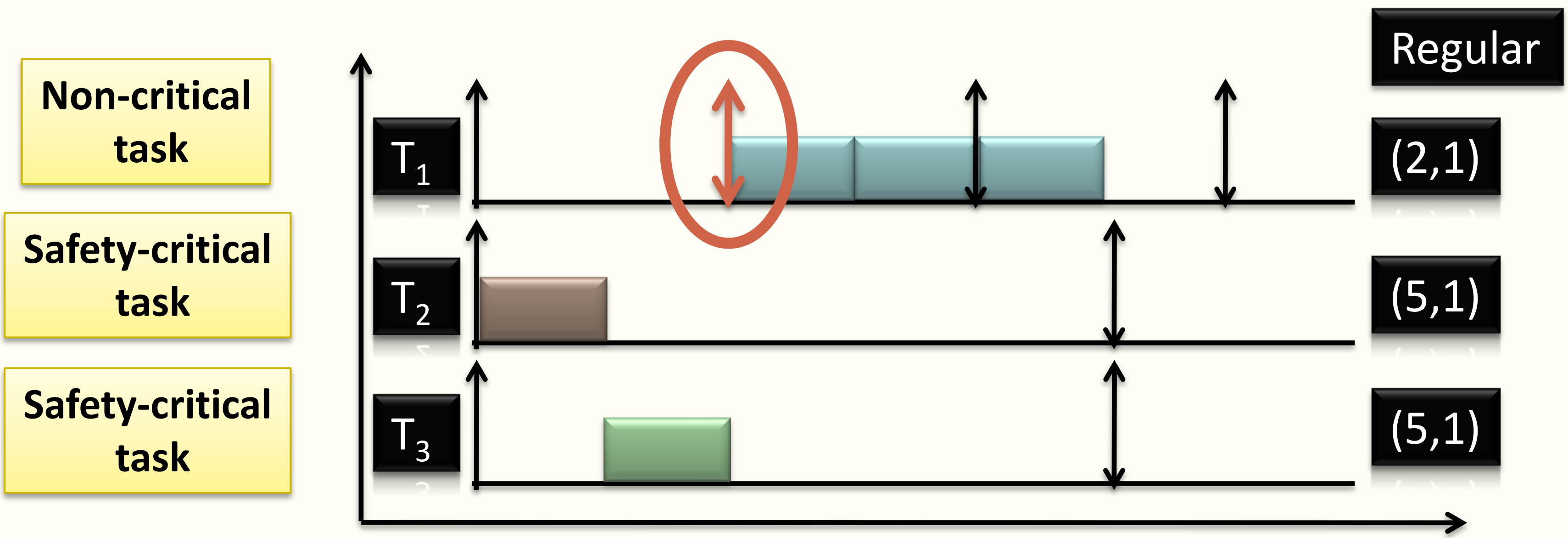
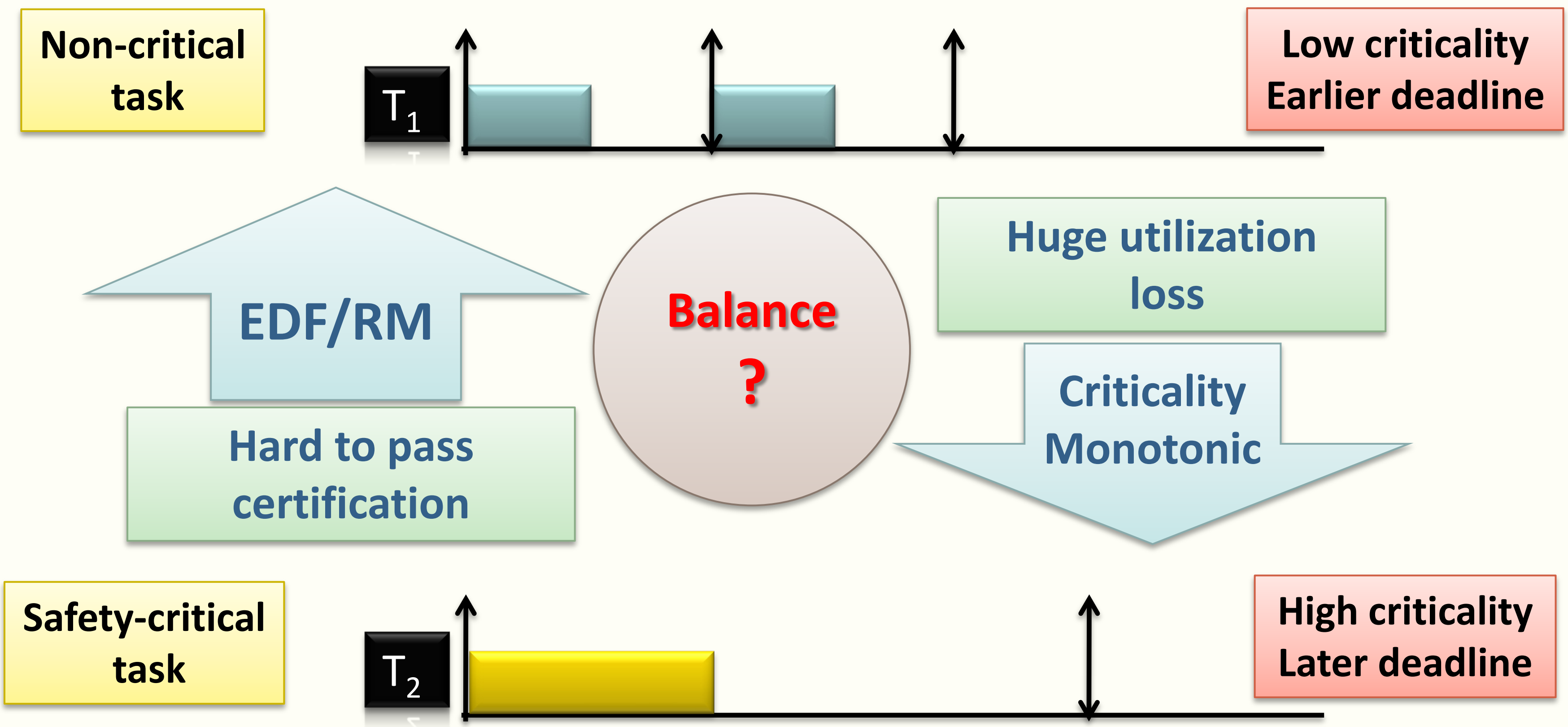


Motivation: Dilemma

- Urgency and importance may differ

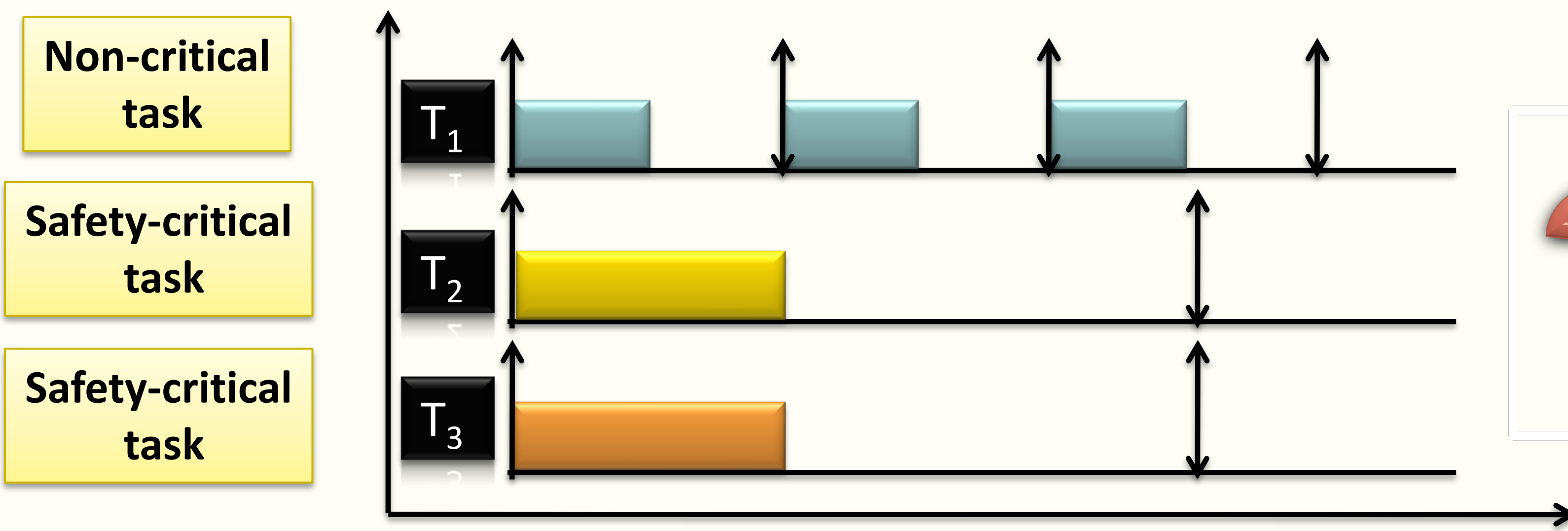


Motivation: Balance

Balanced Schedule:

With pessimistic estimations, it passes certification;

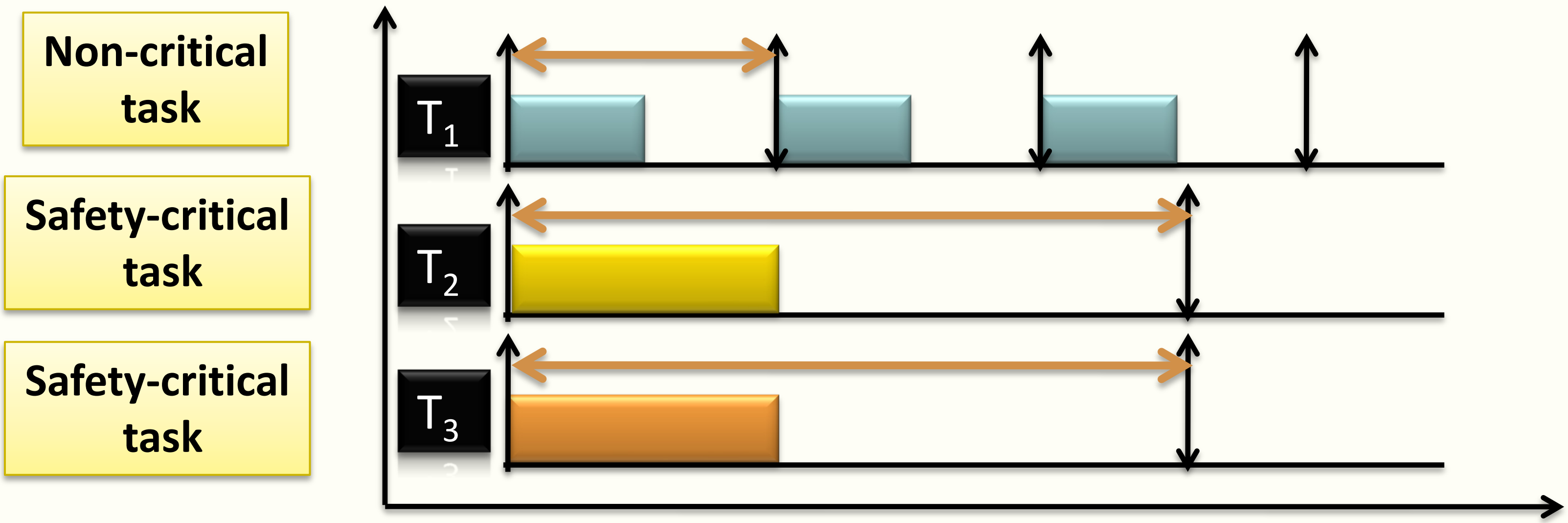
With normal estimations, it guarantees schedulability.



Model

- **Formal definition of the mixed-criticality sporadic task system**

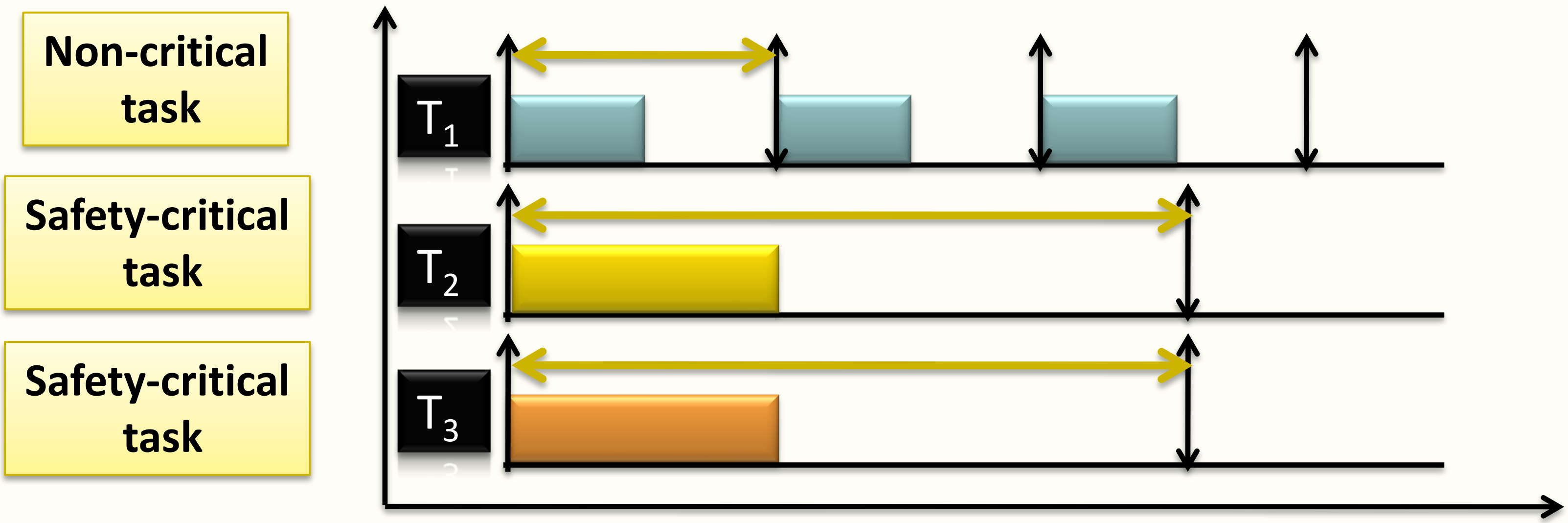
Period: T_i



Model

- Formal definition of the **mixed-criticality sporadic task system**

Deadline: D_i



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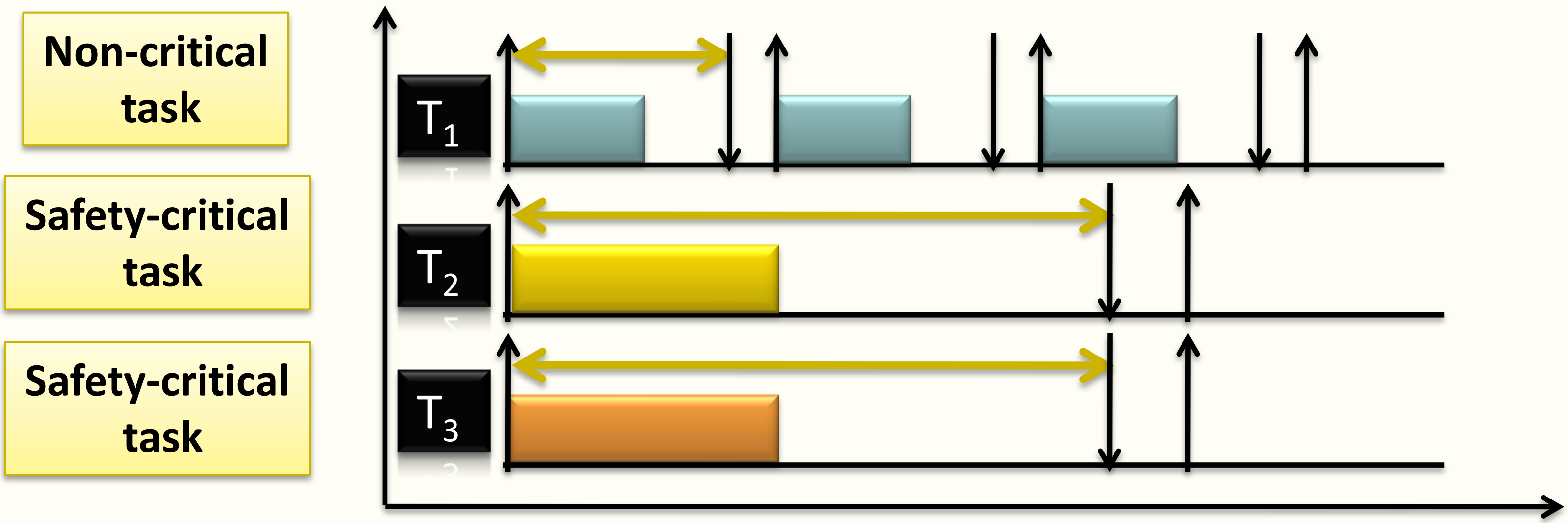
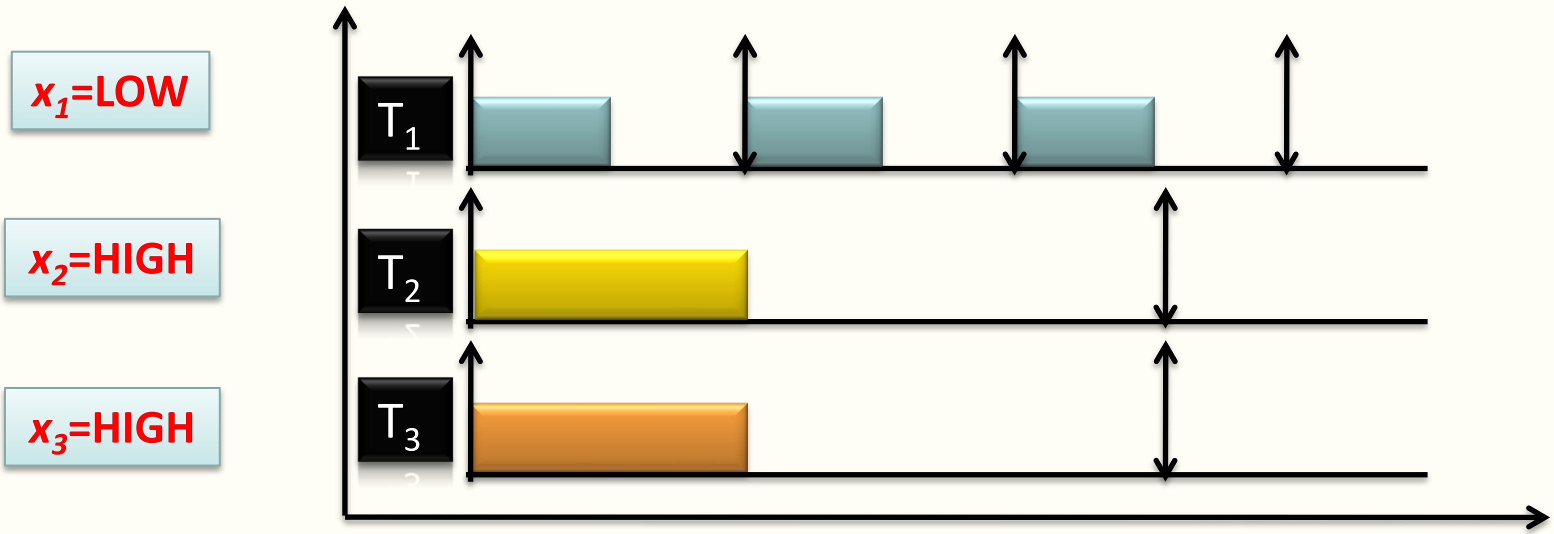


Model

- **Formal definition of the mixed-criticality sporadic task system**

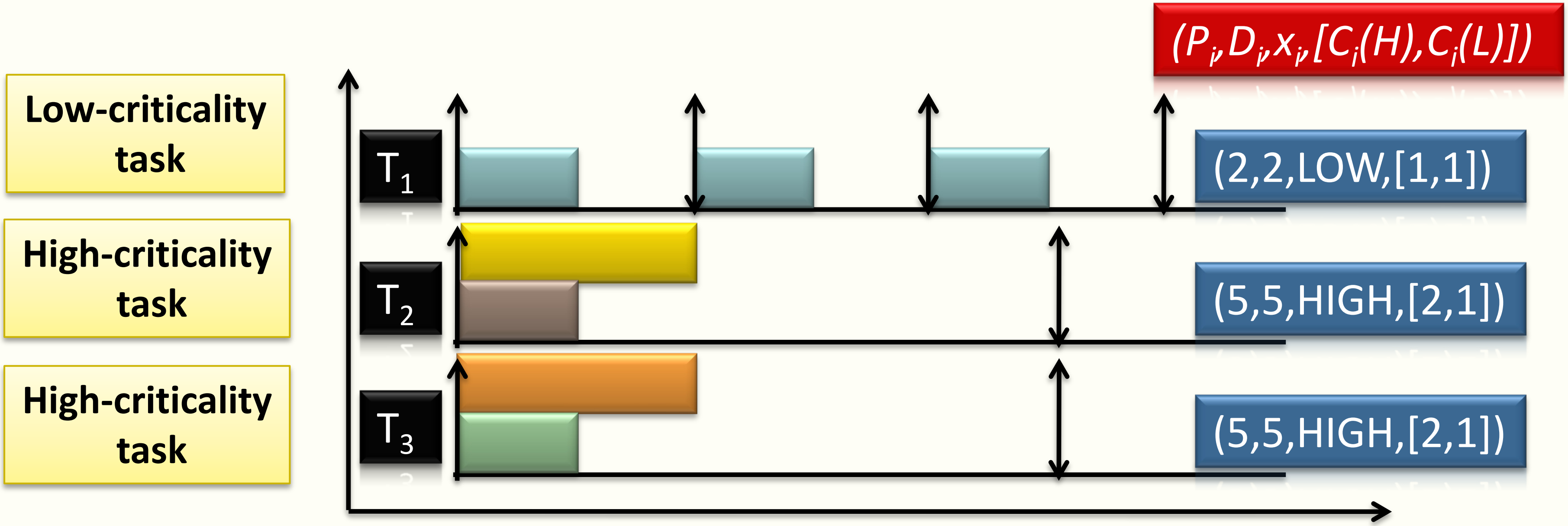
Criticality: x_i



Model

- The key idea is to specify **multiple WCETs** for different criticality levels

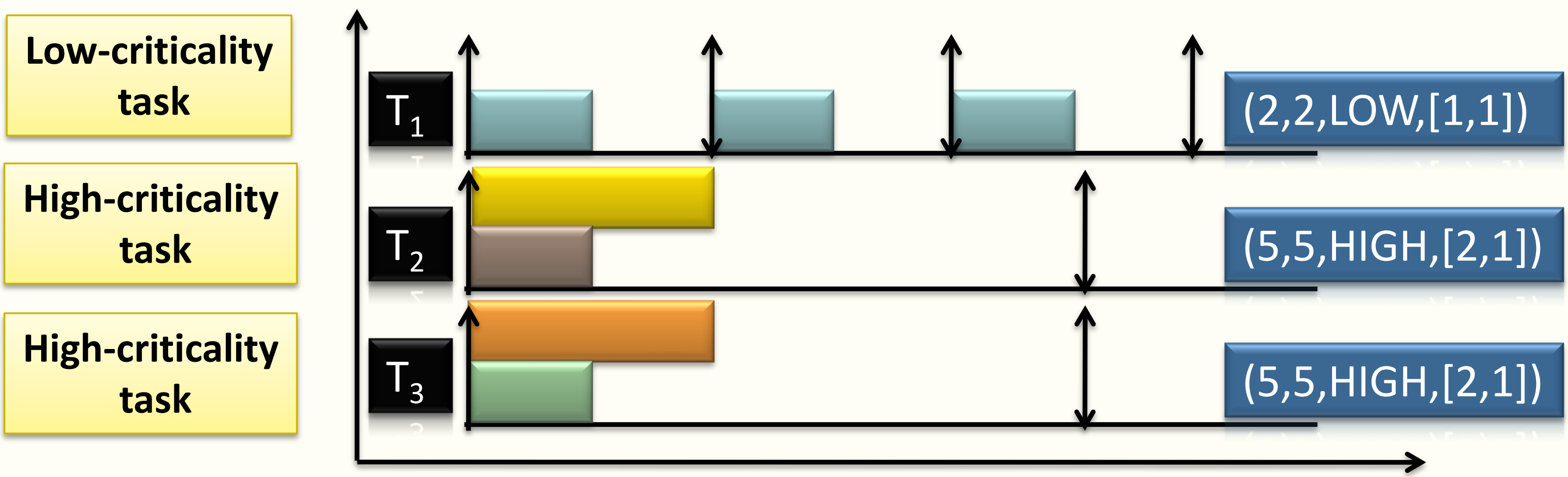
WCET at each criticality: *$[C_i(A), C_i(B), \ldots]$*



Model

- **Correctness of mixed-criticality schedule**

Temporal correctness of a schedule:
All tasks at level X and above should meet their deadlines if **no task exceeds its level-X WCET**



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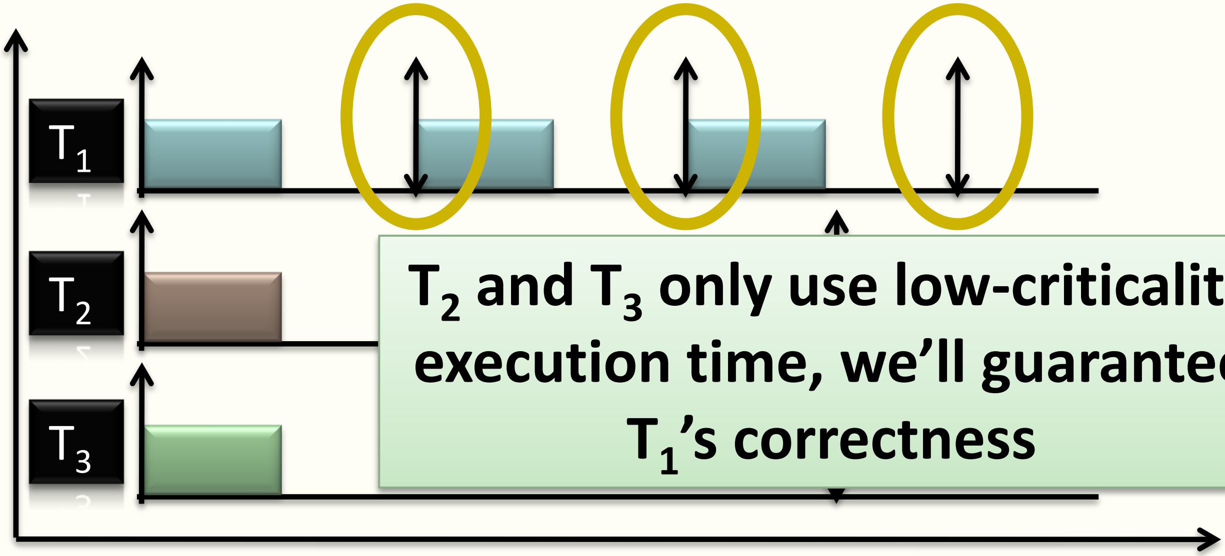
Low-criticality task

High-criticality task

High-criticality task



T_2 and T_3 only use low-criticality execution time, we'll guarantee T_1's correctness

Model

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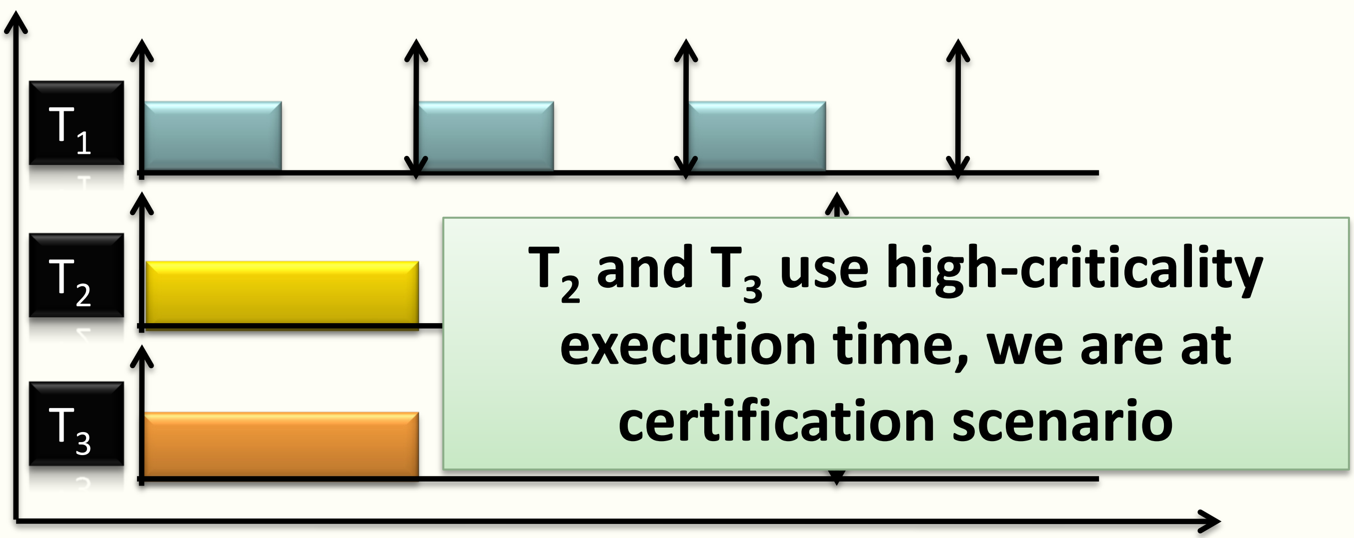

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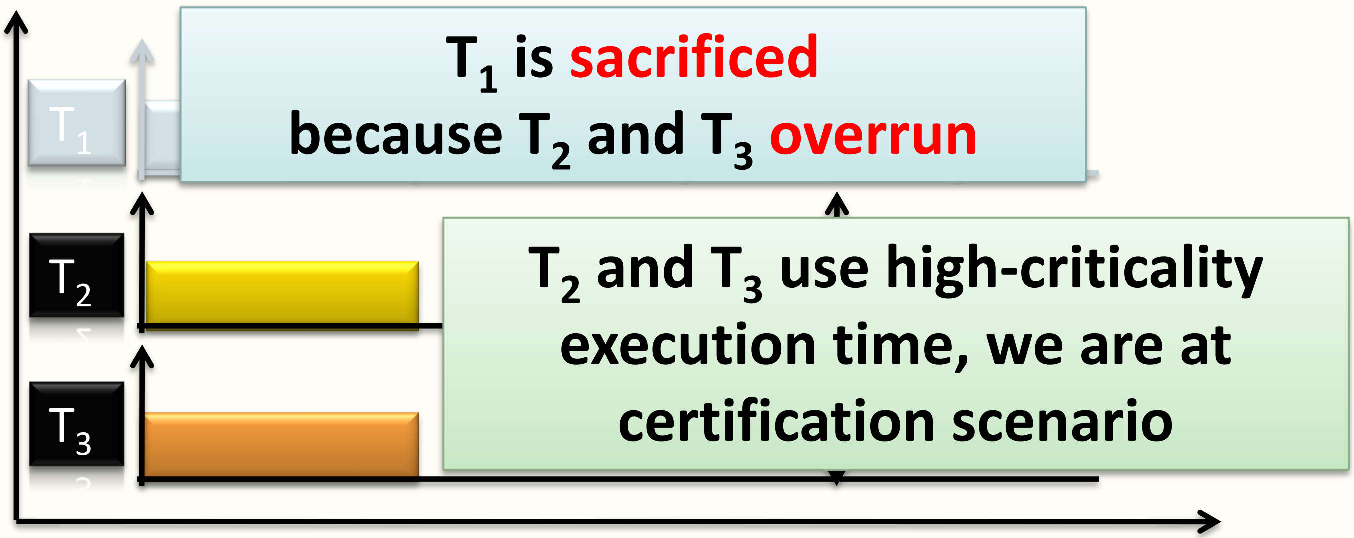

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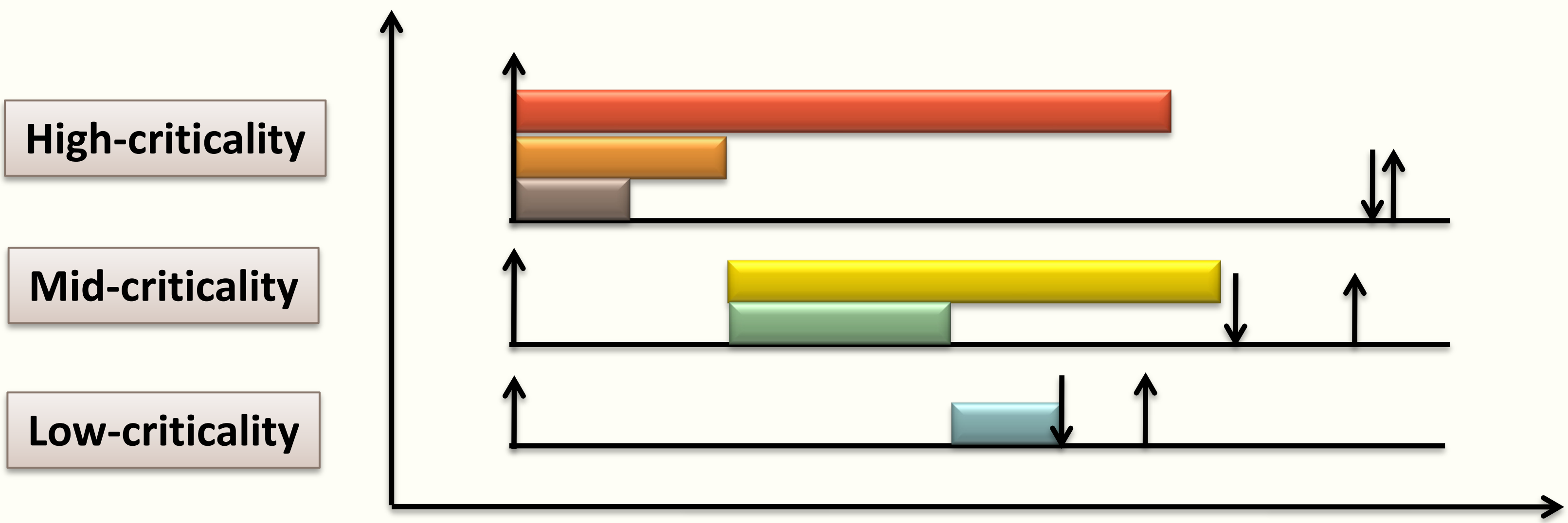

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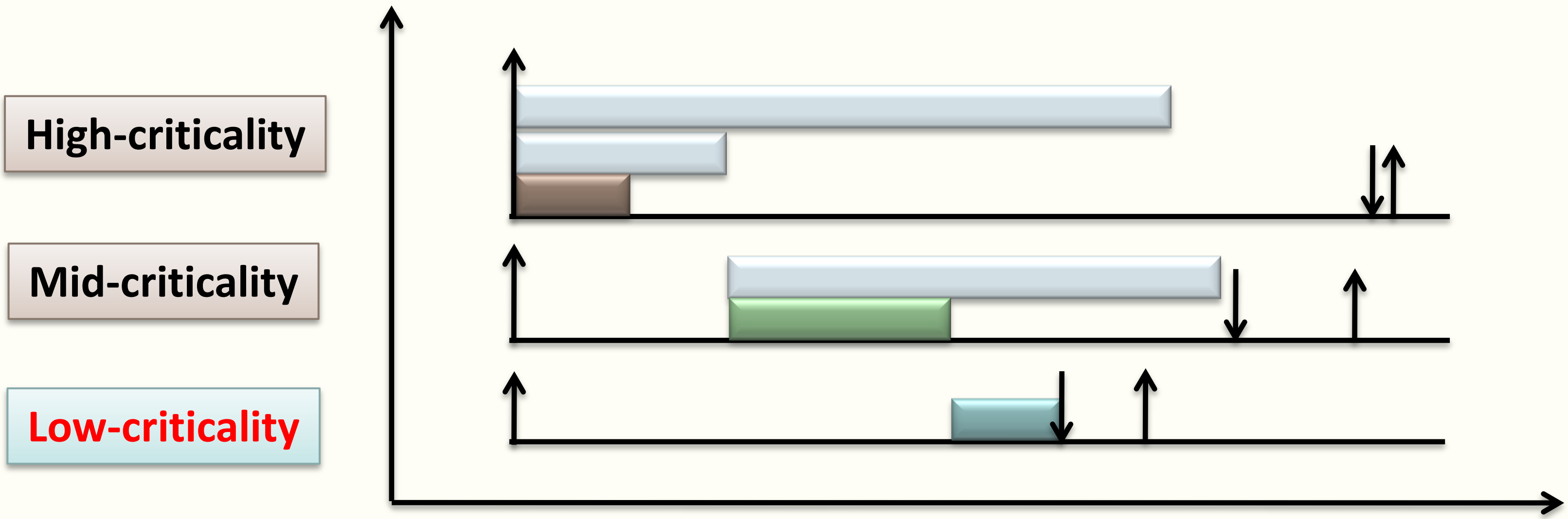

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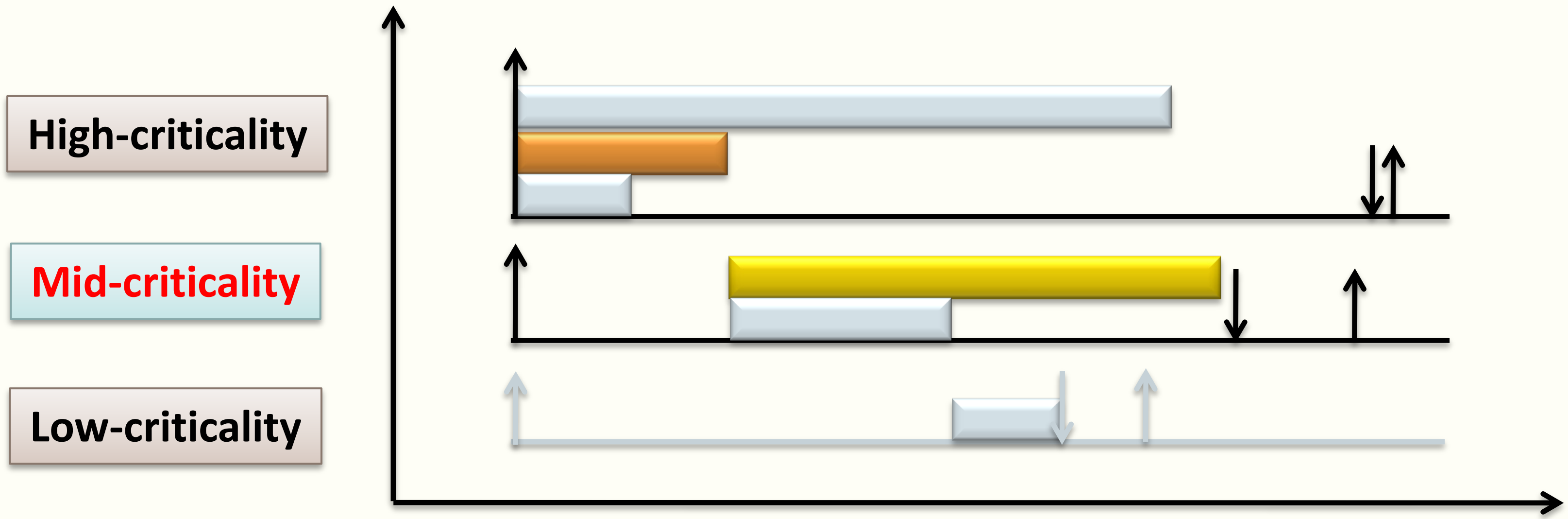

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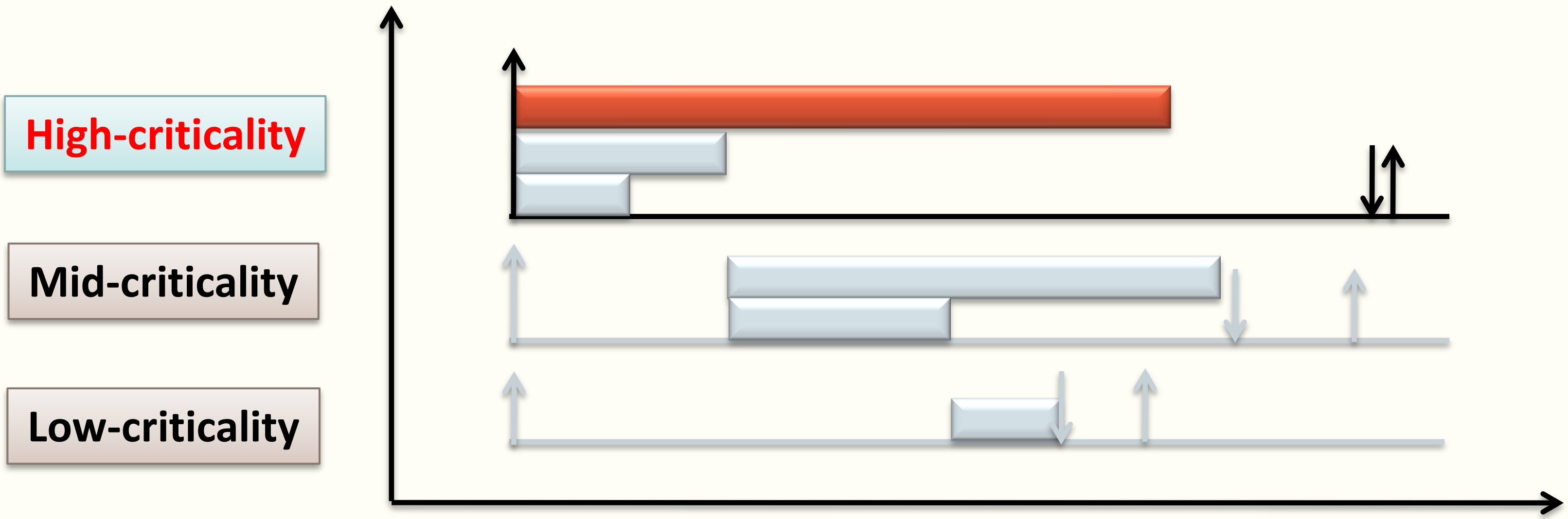
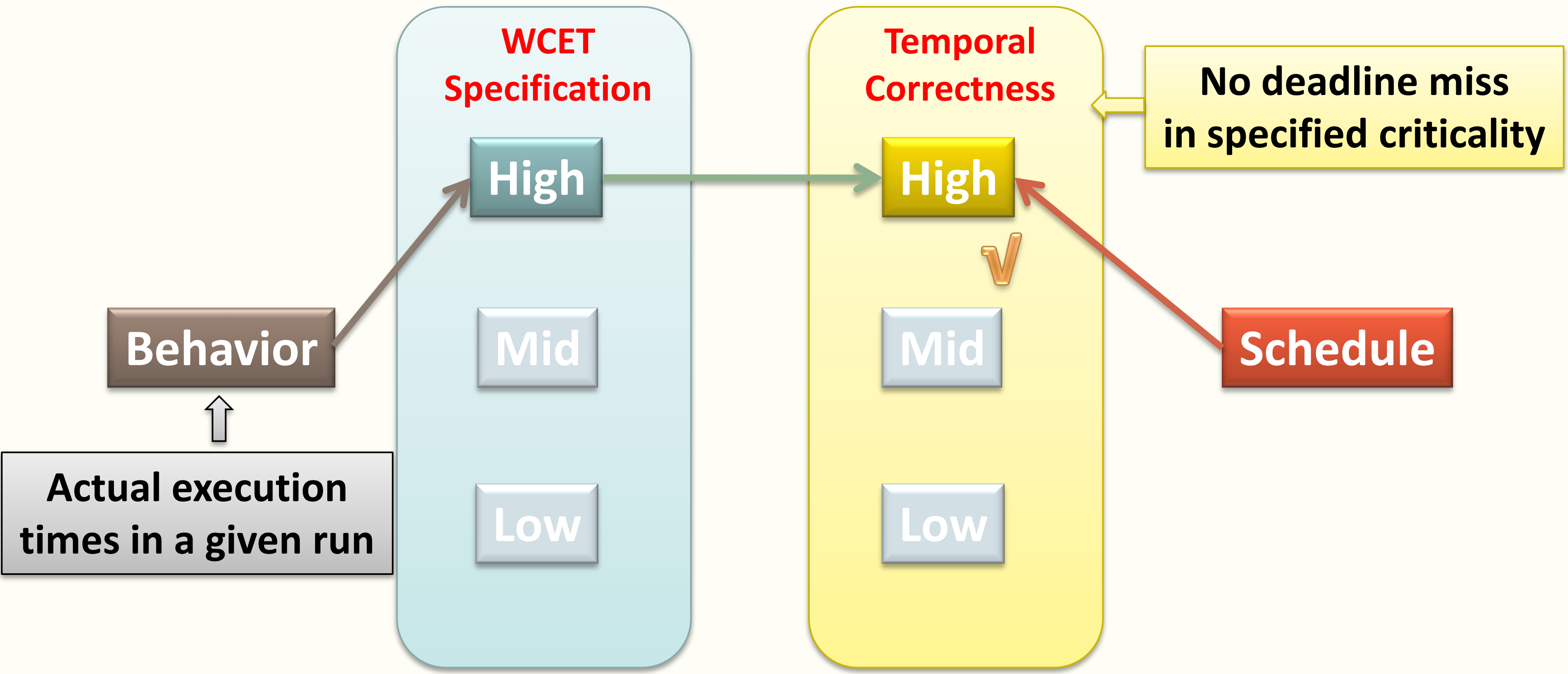


Model

- Informal interpretation of correctness



Model

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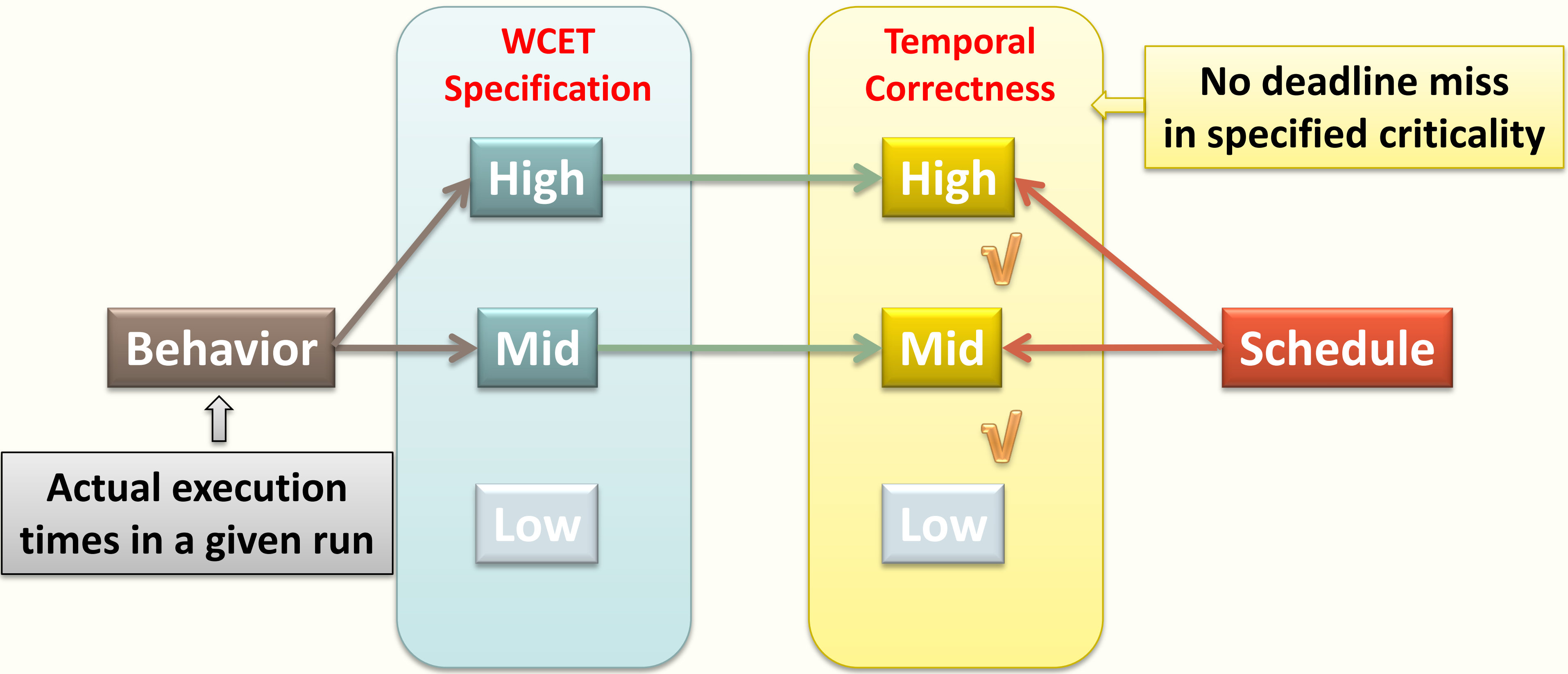

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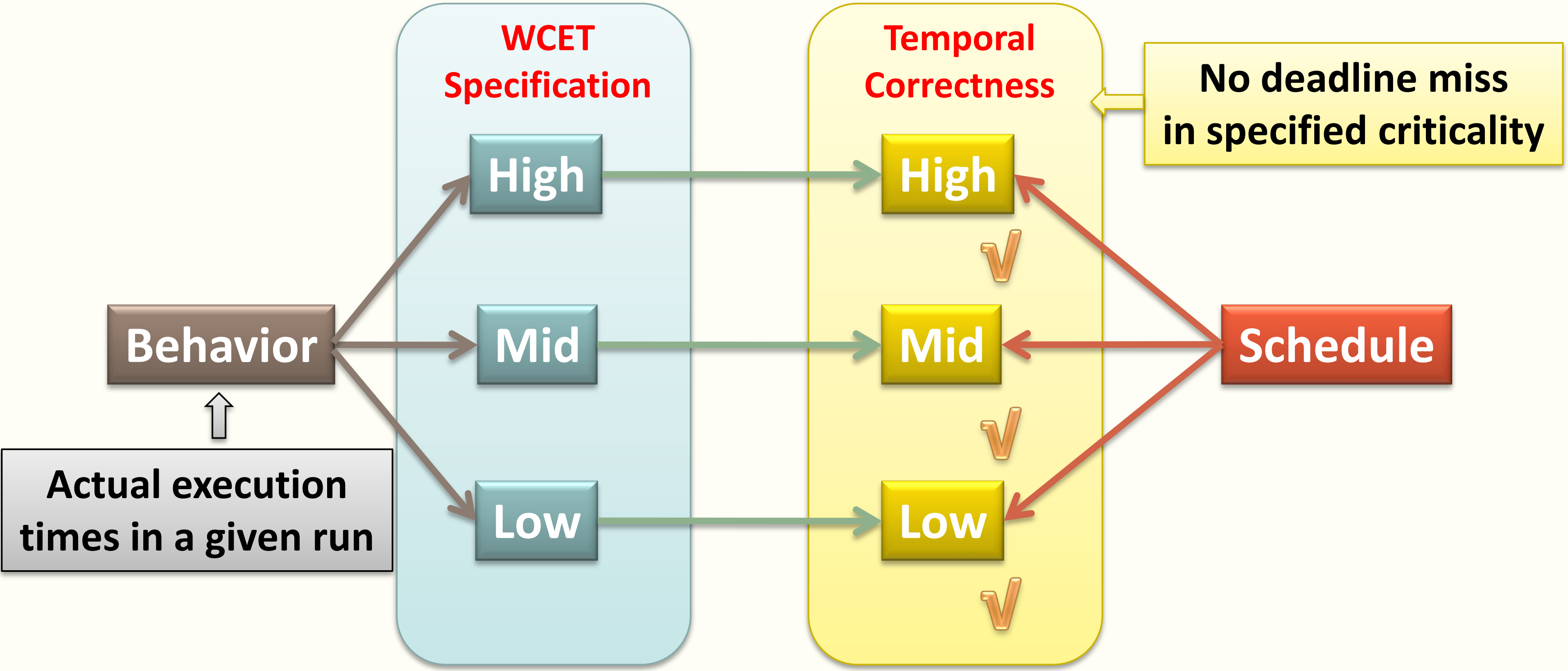


Previous Results

- The problem of scheduling mixed-criticality independent jobs has been solved
  - *Baruah, Li, and Stougie*. RTAS 2010
  - *Li and Baruah*. EMSOFT 2010
- We call our solution "OCBP algorithm"
  - Own Criticality-Based Priority algorithm

Previous Results

- OCBP algorithm generates a **static priority list** for a set of mixed-criticality **independent jobs**
  - It requires **specified release-time** and **deadline** for each job
  - It guarantees mixed-criticality correctness
  - It has a ***speedup factor*** 1.618 for two-criticality job sets
    - More criticality levels has higher speedup factor
    - Scheduling optimally is NP-hard in the strong sense
  - It runs in $O(n \log n)$ time in the number of jobs

Main Contribution

- **In this paper, we apply OCBP algorithm to the mixed-criticality sporadic task systems**
  - Speedup factors are maintained
  - A sufficient load-based schedulability test is also maintained

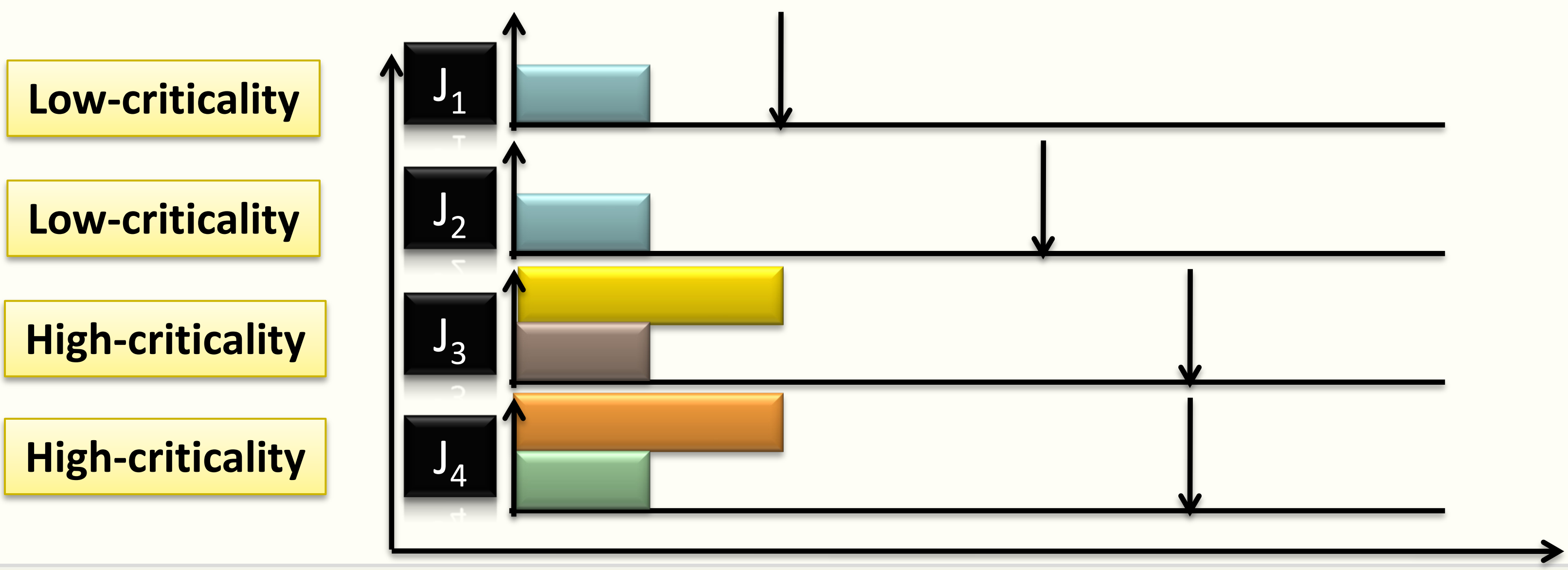
OCBP Algorithm on Jobs

- The principle of OCBP algorithm is to recursively find the lowest-priority job
  - Very similar to "Audsley's Approach"
  - If a level-X job would meet its deadline as the lowest-priority job, when all jobs execute at their level-X WCETs, then this job can be assigned lowest priority
    - Repeat this procedure to get a full priority list
    - When such lowest-priority job can not be found, claim the job set unschedulable

OCBP Algorithm on Jobs

- The principle of OCBP algorithm is to recursively find the lowest-priority job

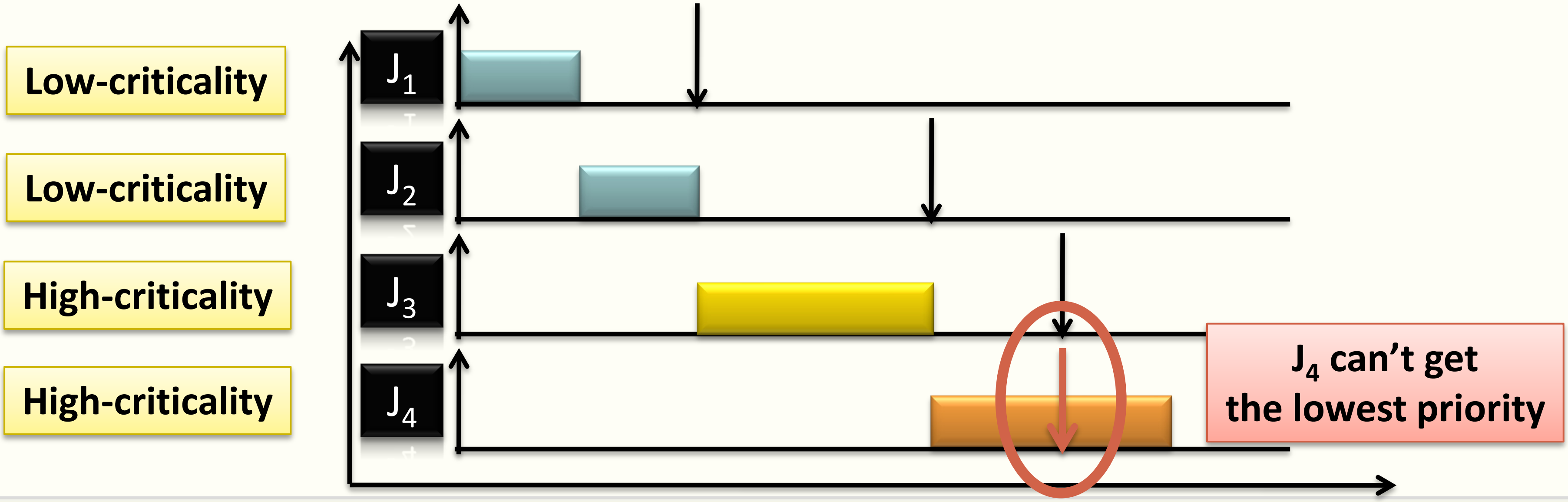
Determine if a job can get the lowest priority:
Compute ***maximum time demand*** in its criticality



OCBP Algorithm on Jobs

- The principle of OCBP algorithm is to recursively find the **lowest-priority** job

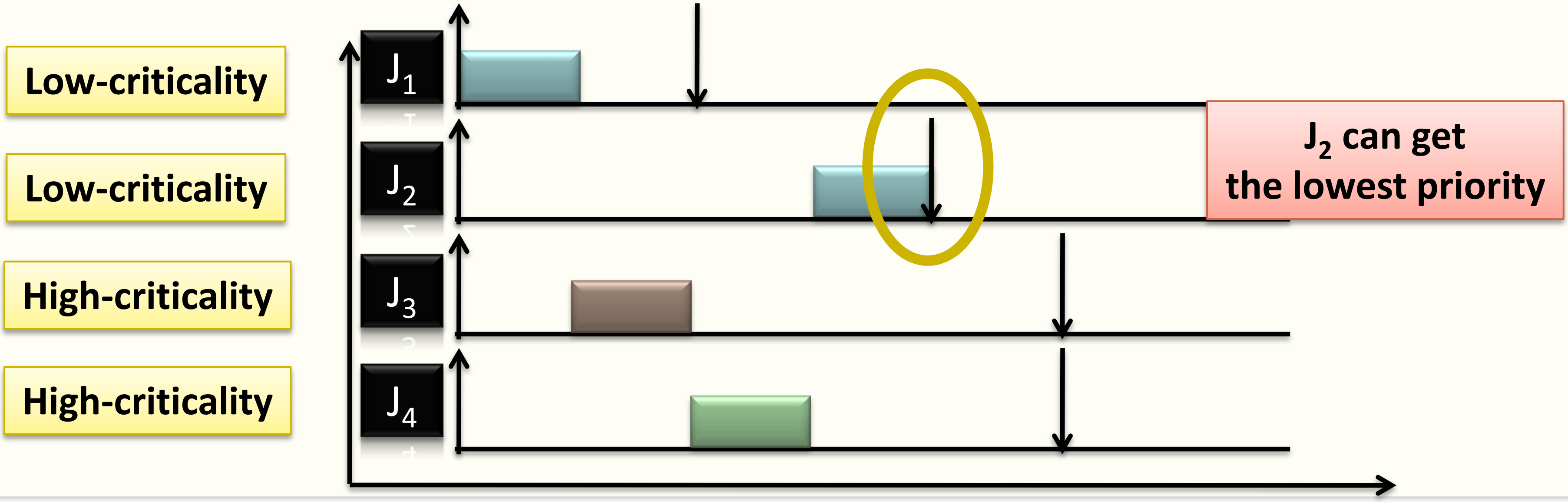
For J_4, the maximum possible time demand (in the worst case) exceeds its deadline



OCBP Algorithm on Jobs

- The principle of OCBP algorithm is to recursively find the lowest-priority job

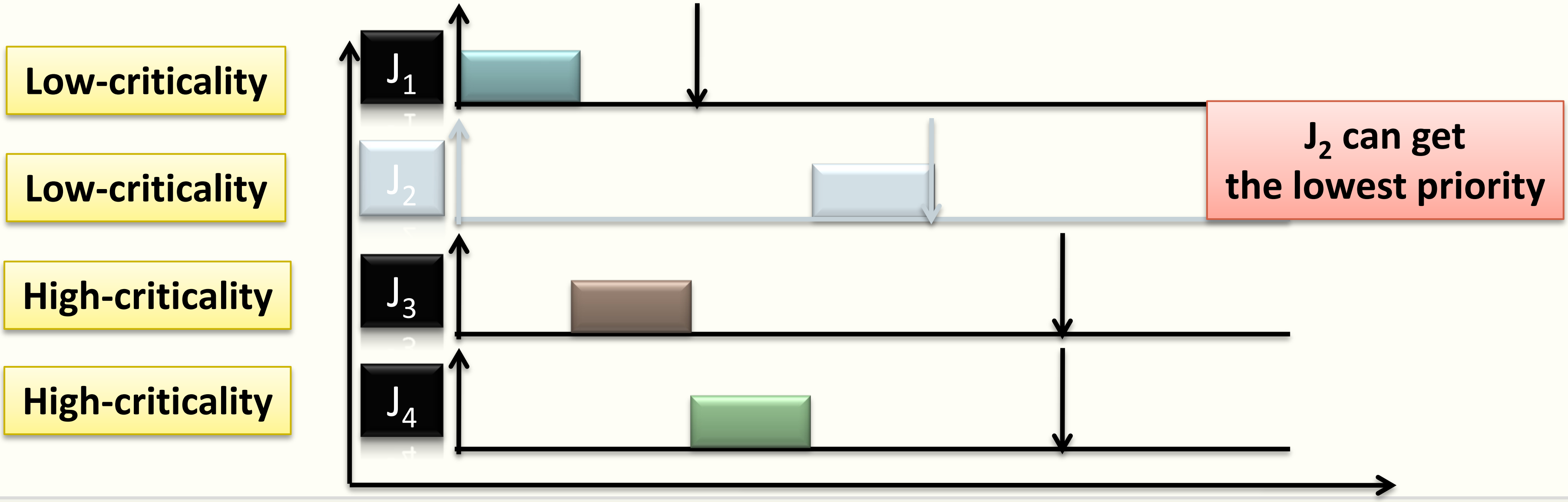
For J_2, the maximum time demand is smaller (if J_3 or J_4 overruns, J_2 can miss its deadline)



OCBP Algorithm on Jobs

- The principle of OCBP algorithm is to recursively find the lowest-priority job

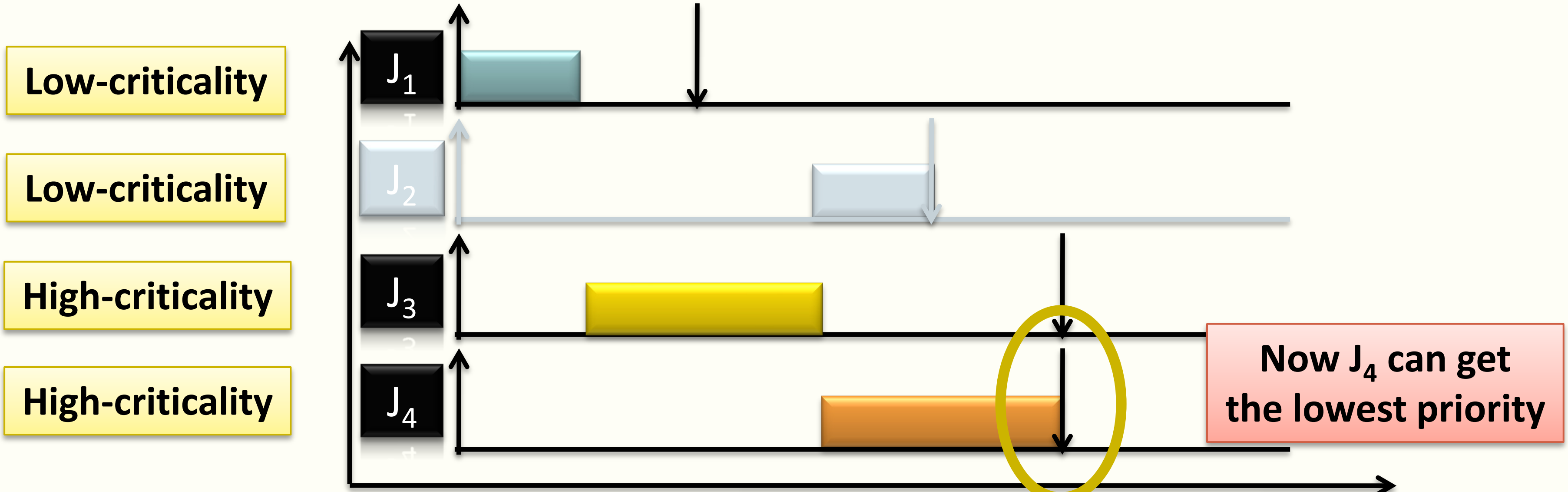
Assign J_2 the lowest priority,
and delete it from the job set



OCBP Algorithm on Jobs

- The principle of OCBP algorithm is to recursively find the **lowest-priority** job

Now the maximum time demand for J_4 decreases (J_2 won't affect J_4 now)



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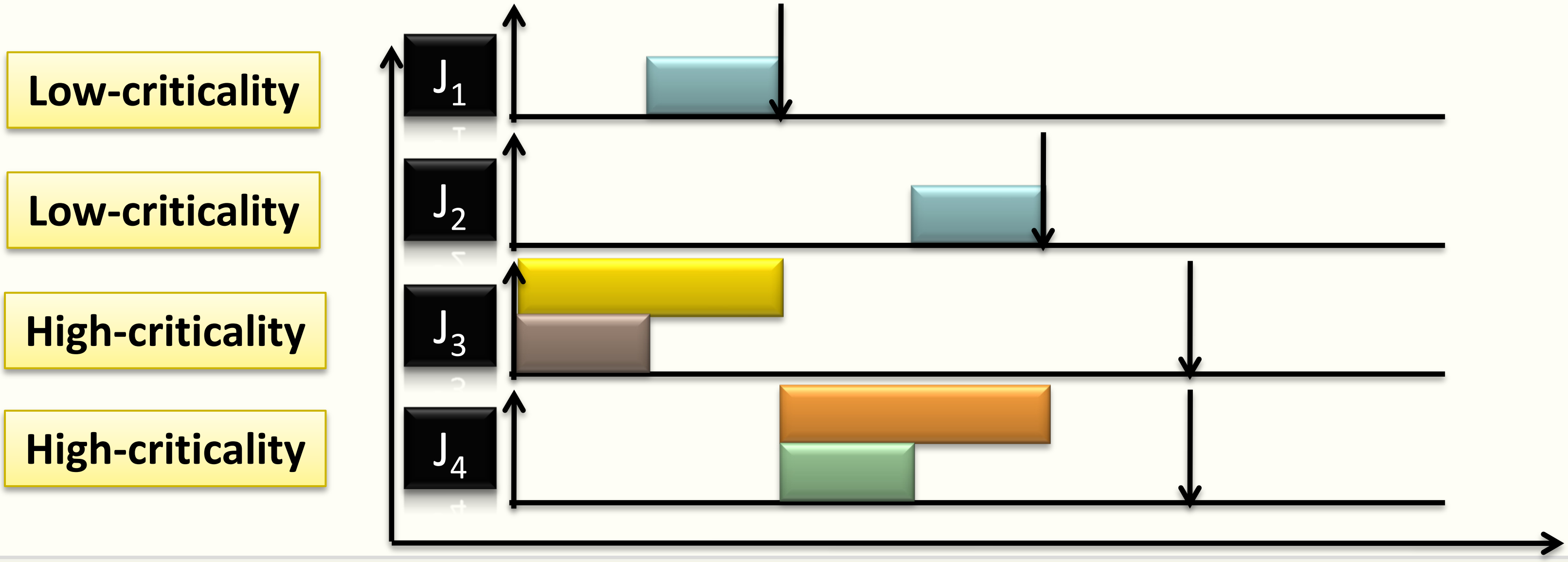
OCBP Algorithm on Jobs

- The principle of OCBP algorithm is to recursively find the lowest-priority job

Repeat the procedure, we can get a priority list:

$J_3 < J_1 < J_4 < J_2$



From Jobs to Sporadic Tasks

- Sporadic tasks have infinite jobs
  - But the processor can't be infinitely busy
    - We assume that the processor isn't fully utilized
- To apply the job-oriented OCBP algorithm, we consider jobs in the longest busy interval
  - The number of jobs in the longest busy interval is bounded
    - The number of jobs is pseudo-polynomial to the number of tasks

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From Jobs to Sporadic Tasks

- We run OCBP algorithm in the beginning of the longest busy interval
  - We specify every job to get **the earliest possible** release-time and deadline
    - Assuming that the sporadic tasks run periodically
- A priority list for all jobs in the longest busy interval will be generated
  - This priority list may be eventually erroneous
    - Because jobs are **not** released immediately

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From Jobs to Sporadic Tasks

- **We proved that the priority list can be erroneous only after the following two violations:**
  - **When the processor is idle**
  - **When a high-priority job is released, and preempts a low-priority job**

From Jobs to Sporadic Tasks

- We proved that the priority list can be erroneous only after the following two violations
- We also proved that when the violation happens, we can re-compute the priority list
  - Use OCBP algorithm again
  - The re-computation will always generate a valid priority list

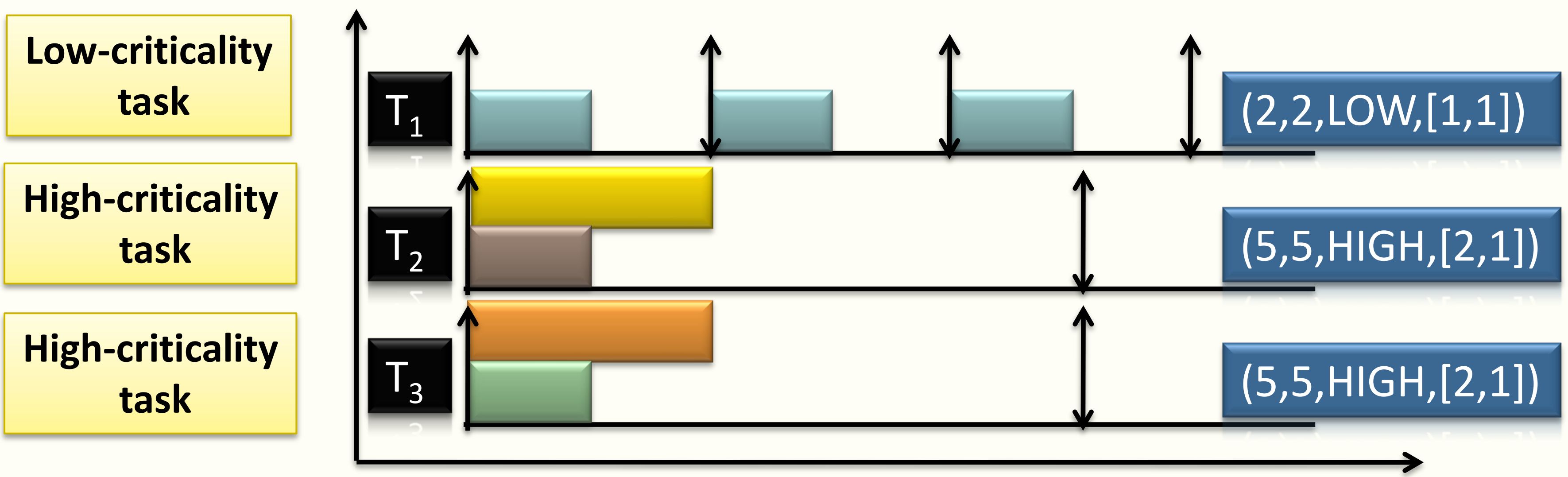
From Jobs to Sporadic Tasks

- We proved that the priority list can be erroneous only after the following two violations
- We also proved that when the violation happens, we can re-compute the priority list

Inductively, we've proved that:
For a mixed-criticality sporadic system,
if OCBP algorithm succeeds in the beginning,
there exists a correct scheduling algorithm

OCBP Algorithm on Tasks

- An example of running OCBP algorithm on mixed-criticality sporadic tasks

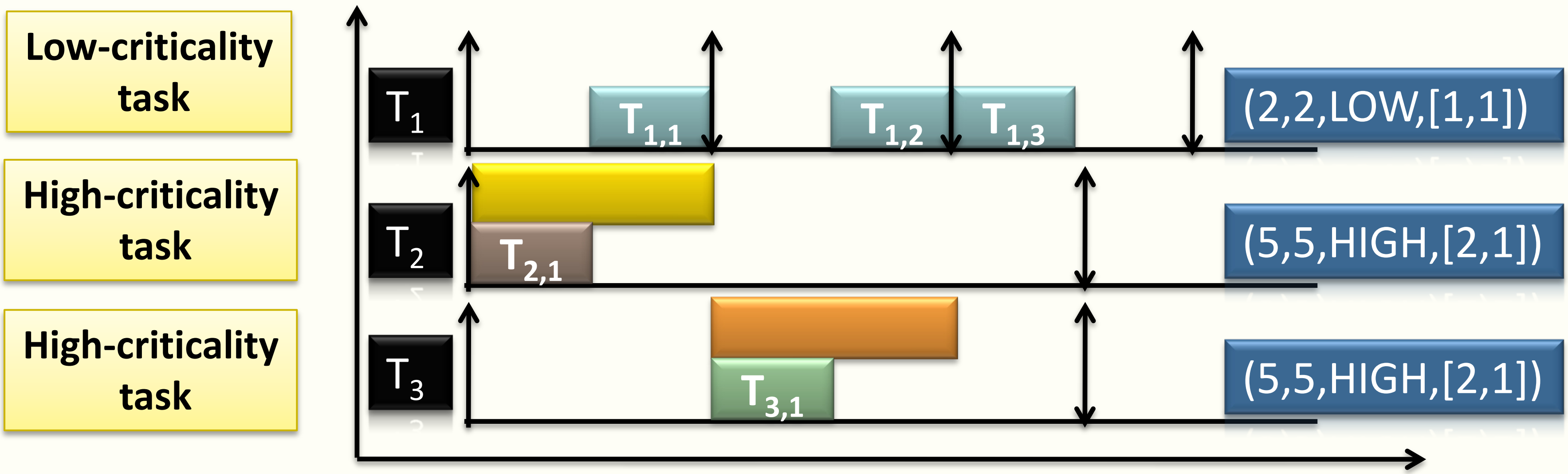


OCBP Algorithm on Tasks

- Example of running OCBP algorithm in the beginning

A priority list (in the beginning):

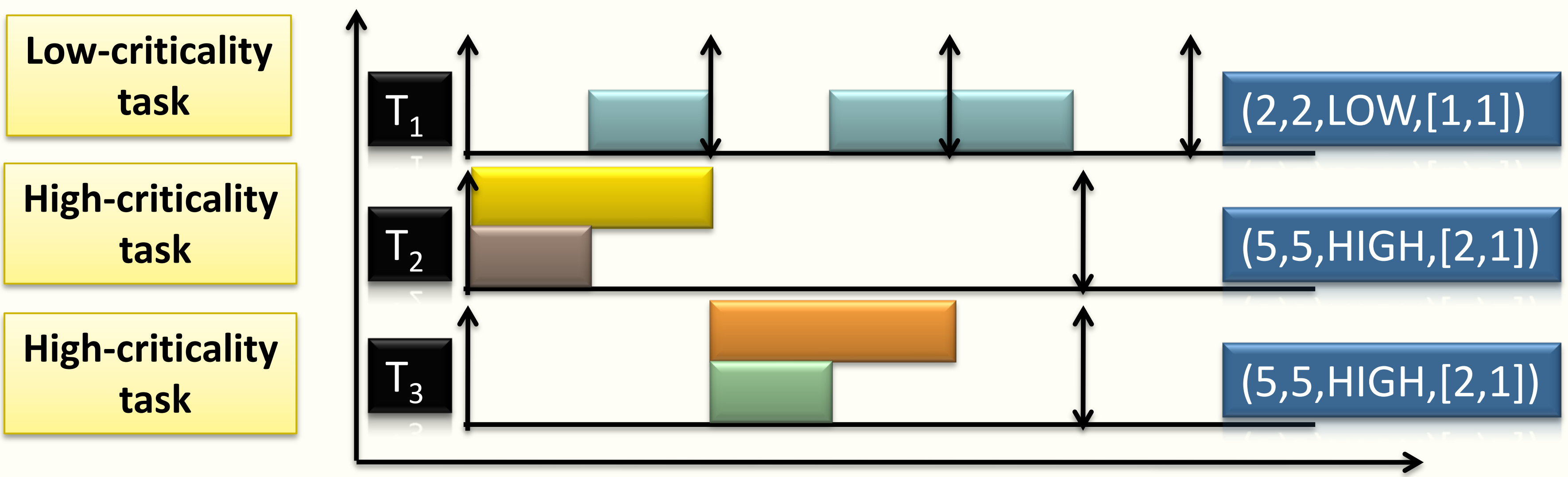
$T_{2,1} < T_{1,1} < T_{3,1} < T_{1,2} < T_{1,3}$



OCBP Algorithm on Tasks

- Example of executing tasks following the OCBP priority list

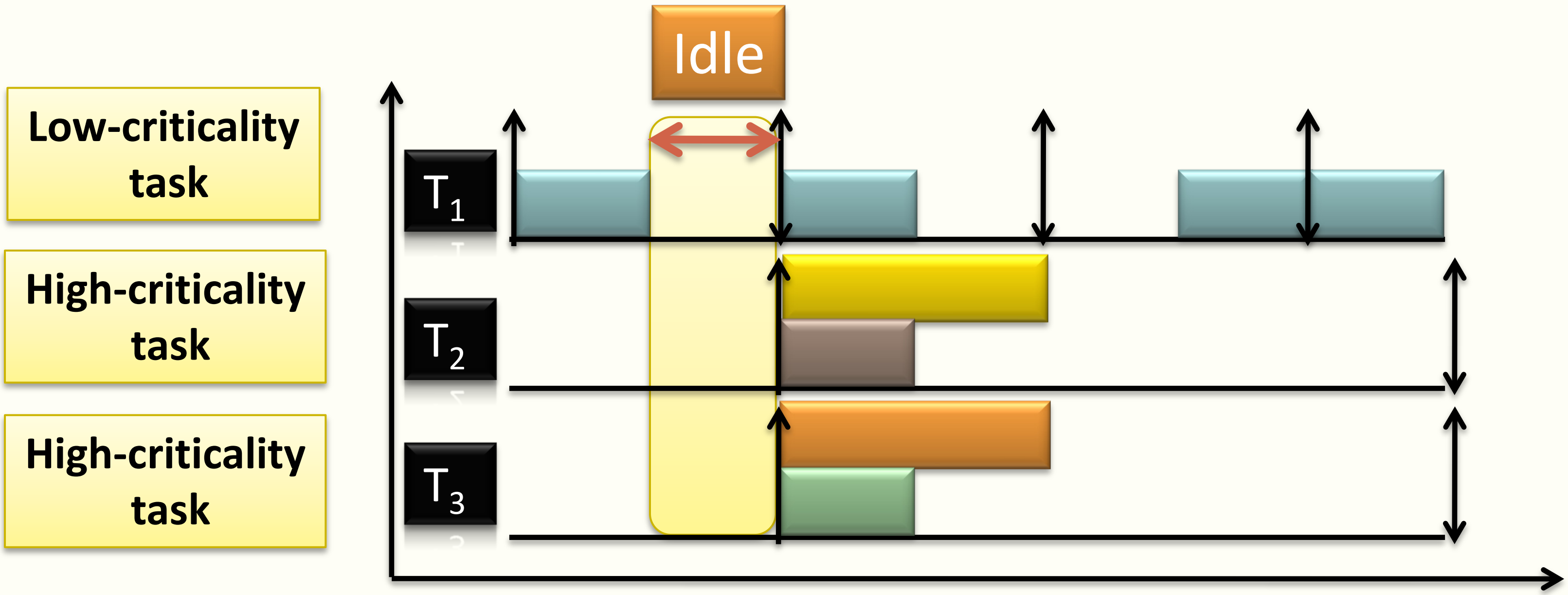
When **no violation happens**,
follow $T_{2,1} < T_{1,1} < T_{3,1} < T_{1,2} < T_{1,3}$



OCBP Algorithm on Tasks

- Example showing when a violation happens

Violation: When the processor is idle



OCBP Algorithm on Tasks

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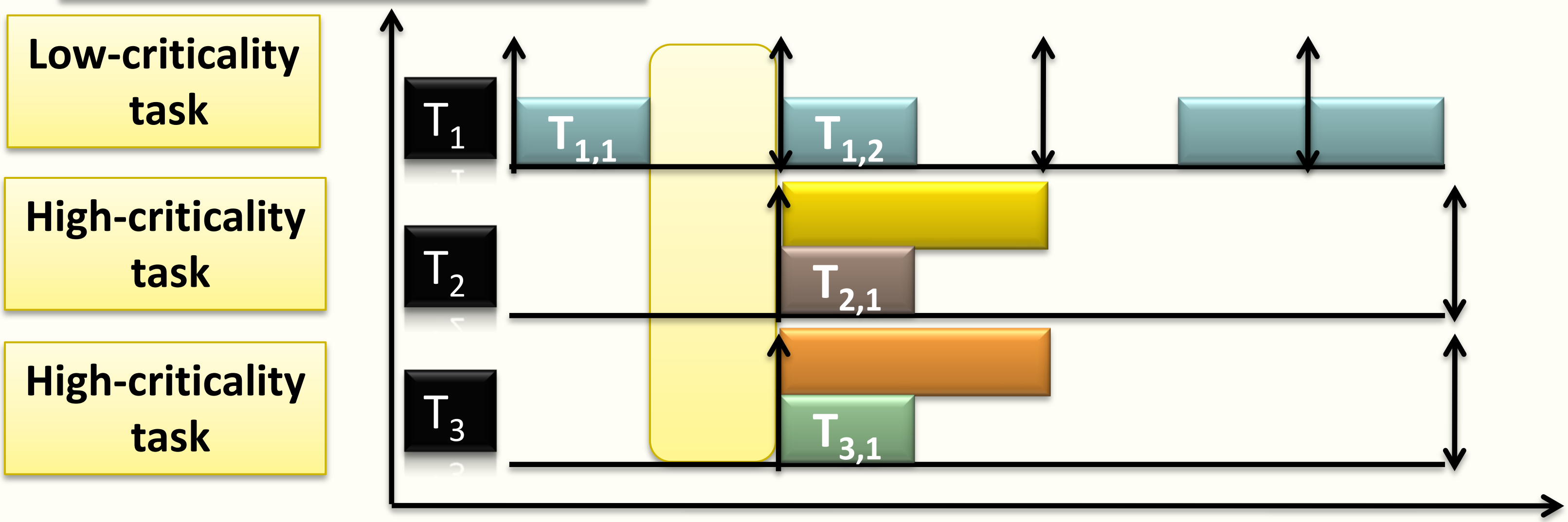

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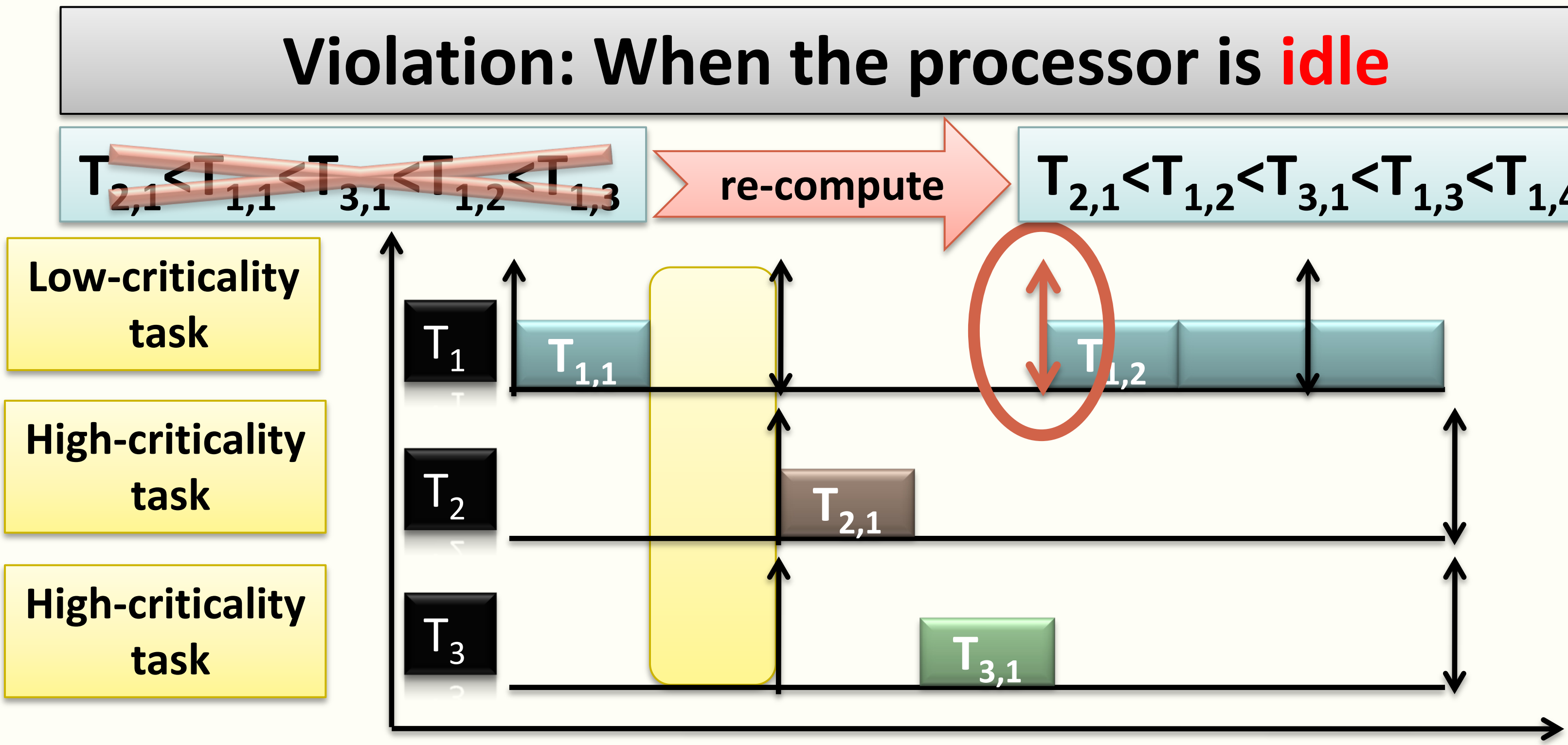

OCBP Algorithm on Tasks

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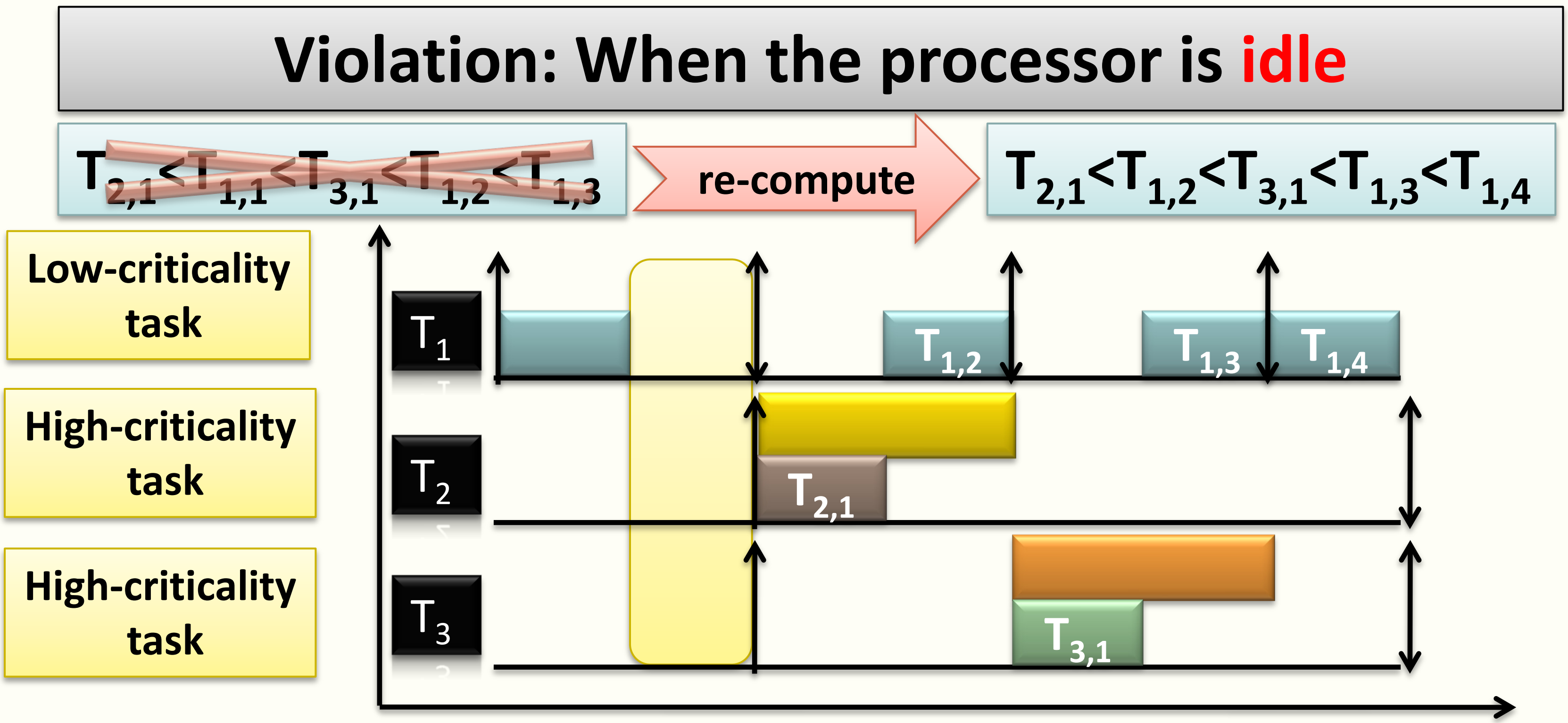
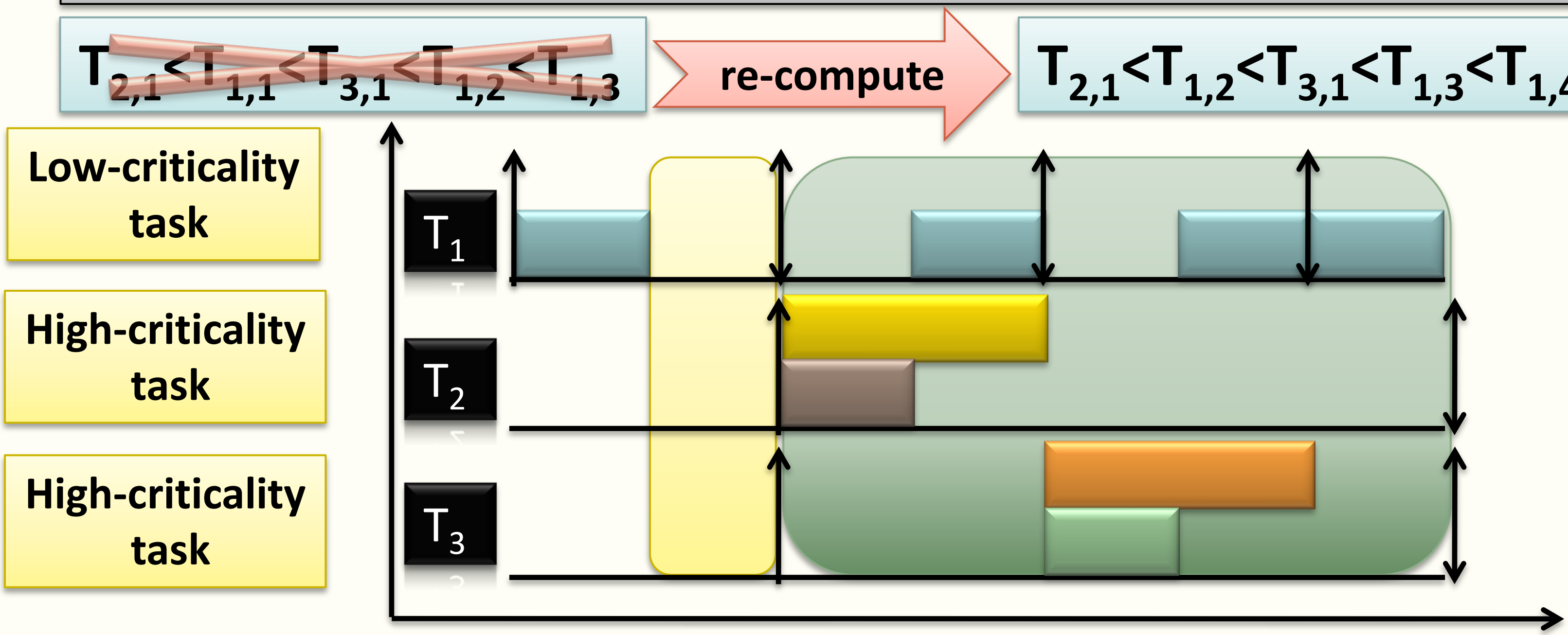


OCBP Algorithm on Tasks

- The re-computation is valid

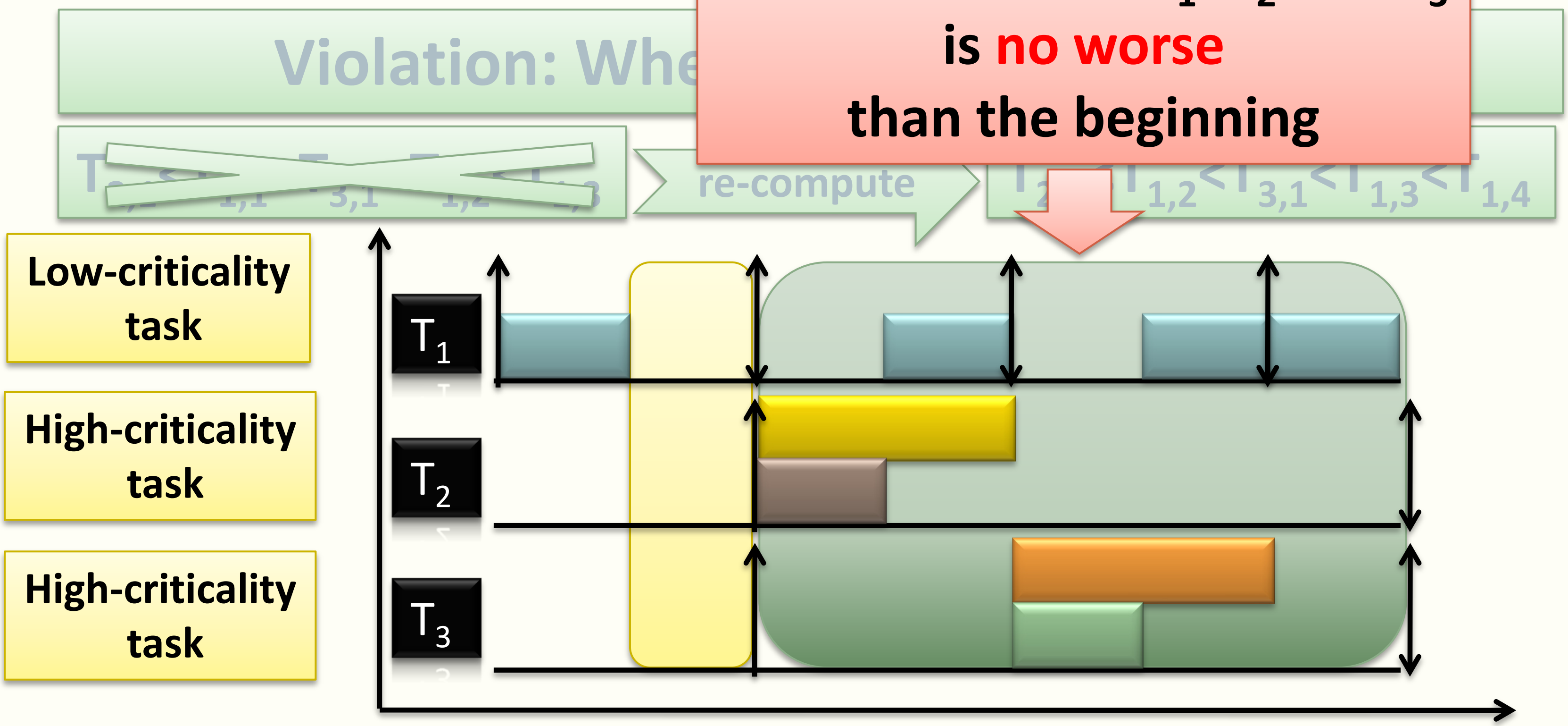
Violation: When the processor is idle



OCBP Algorithm on Tasks

- The re-computation is **valid**

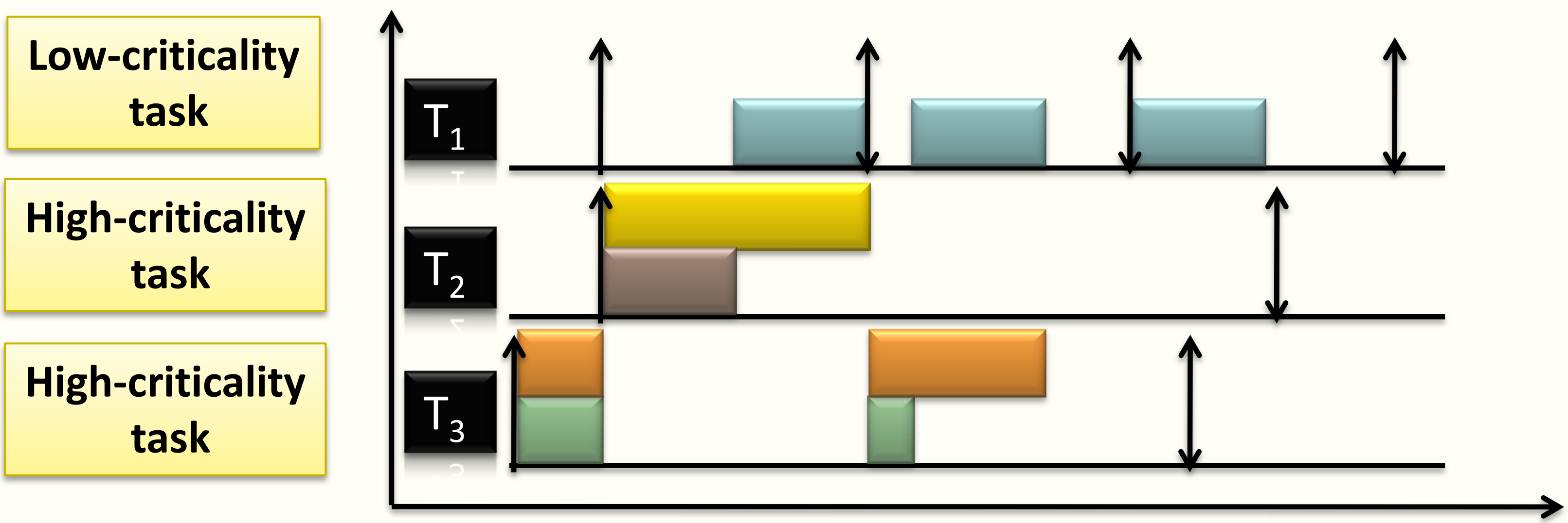
The situation for T_1, T_2 and T_3 is no worse than the beginning



OCBP Algorithm on Tasks

- Example showing when a violation happens

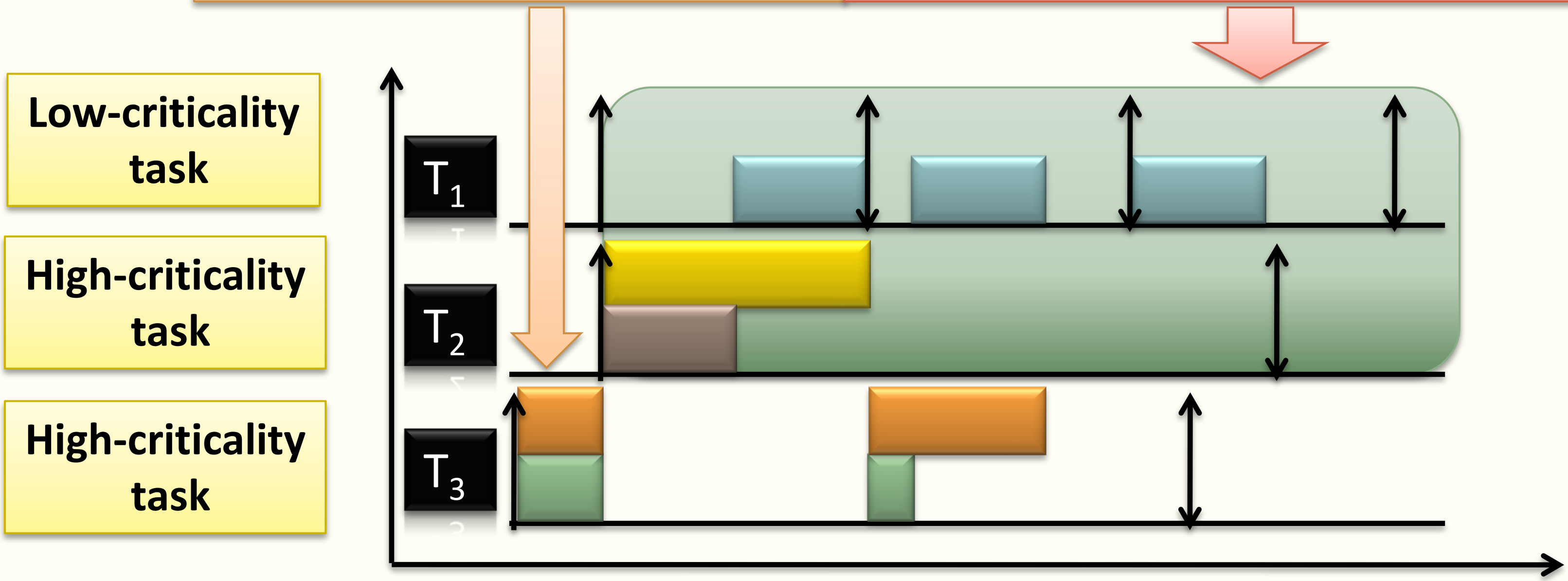
Violation: When a high-priority job is released, and preempts a low-priority job



OCBP Algorithm on Tasks

- The re-computation is also valid

$T_{3,1}$ is guaranteed to meet its deadline when $T_{1,1}$ and $T_{2,1}$ preempt it	The situation for $T_{1,1}$ and $T_{2,1}$ is no worse than the beginning



Final Solution

- Our scheduling algorithm for mixed-criticality sporadic task system
  - Attempt to compute a priority list for jobs in the longest busy interval using OCBP algorithm
    - The schedulability will be determined

Offline

  - Execute jobs according to the priority list
  - If any following violations happens, re-compute the priority list using OCBP algorithm
    - When the processor is idle
    - When a high-priority job preempts a low-priority job

Run-time

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Performance Measurement

- Speedup factor
  - *Φ=1.618* for OCBP algorithm with two criticalities
    - *Φ=2* for EDF with two criticalities
    - *Φ=∞* for criticality-monotonic
  - The result for multiple criticalities is available at
    - *Baruah et al*. MFCS 2010

Performance Measurement

- Schedulability test
  - OCBP algorithm is itself a schedulability test
    - It runs in pseudo-polynomial time to number of tasks
  - We also proved that for any two-criticality system

$$l_{LO}^2 + l_{HI} \leq 1$$

  is a sufficient schedulability test
    - This schedulability test dominates currently known EDF schedulability test for mixed-criticality systems

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Performance Measurement

- Run-time performance
  - Every time a new job arrives, re-computation may happen
  - The re-computation could require pseudopolynomial time in the worst case

Future Work

- Scheduling algorithm with better run-time performance
- Multiprocessor scheduling
- Non-preemptions

Thank you

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Load-Based Schedulability Test

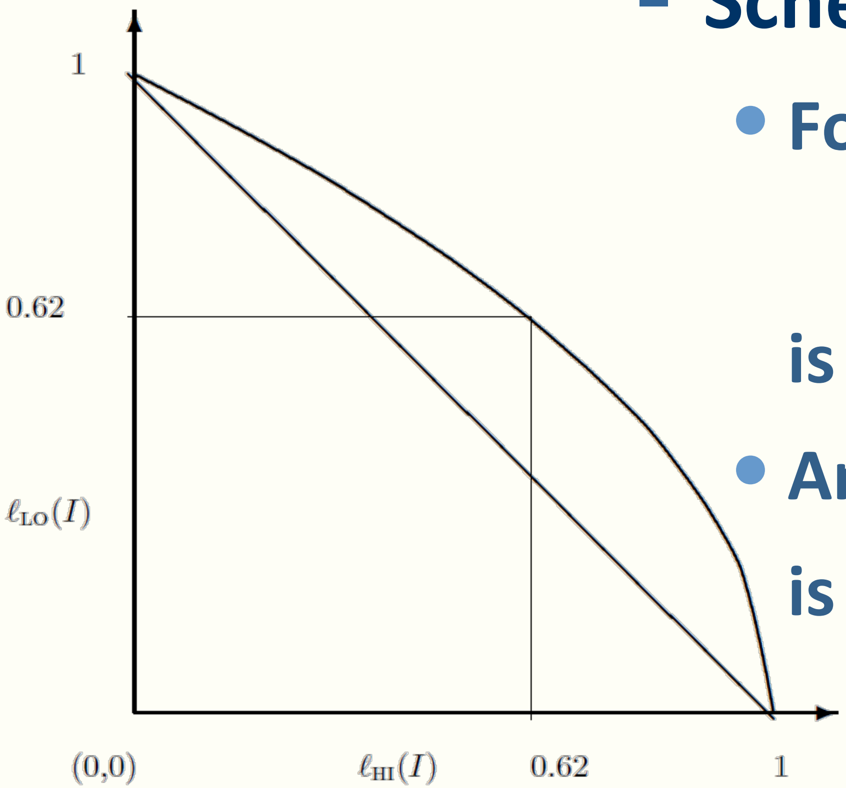


Figure 1: Bound on the LO-criticality load (ℓ_{LO}) as a function of HI-criticality load (ℓ_{HI}).

- **Schedulability test**
  - For any two-criticality system

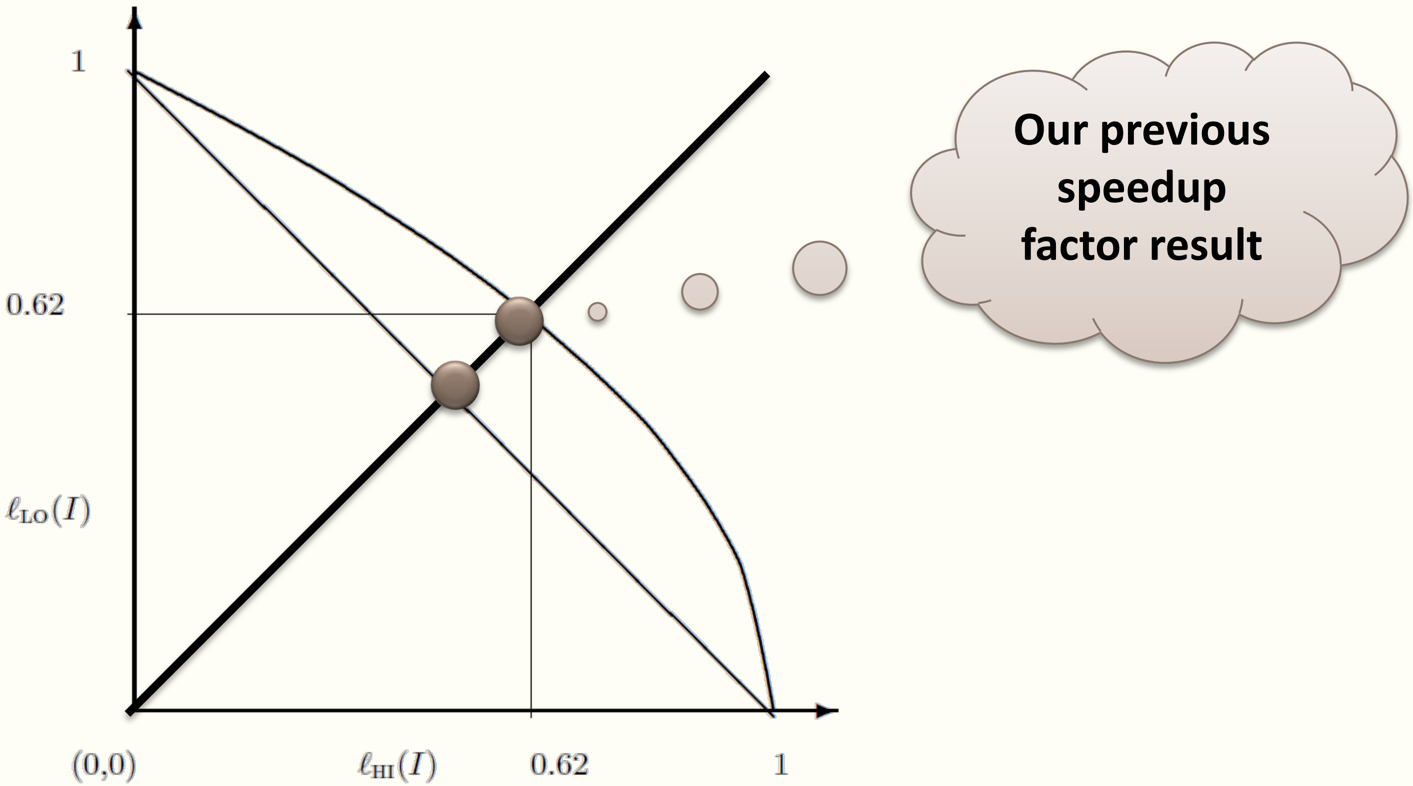
$$l_{LO}^2 + l_{HI} \leq 1$$

  is schedulability test for OCBP

  - And $l_{LO} + l_{HI} \leq 1$

  is schedulability test for EDF

Load-Based Schedulability Test



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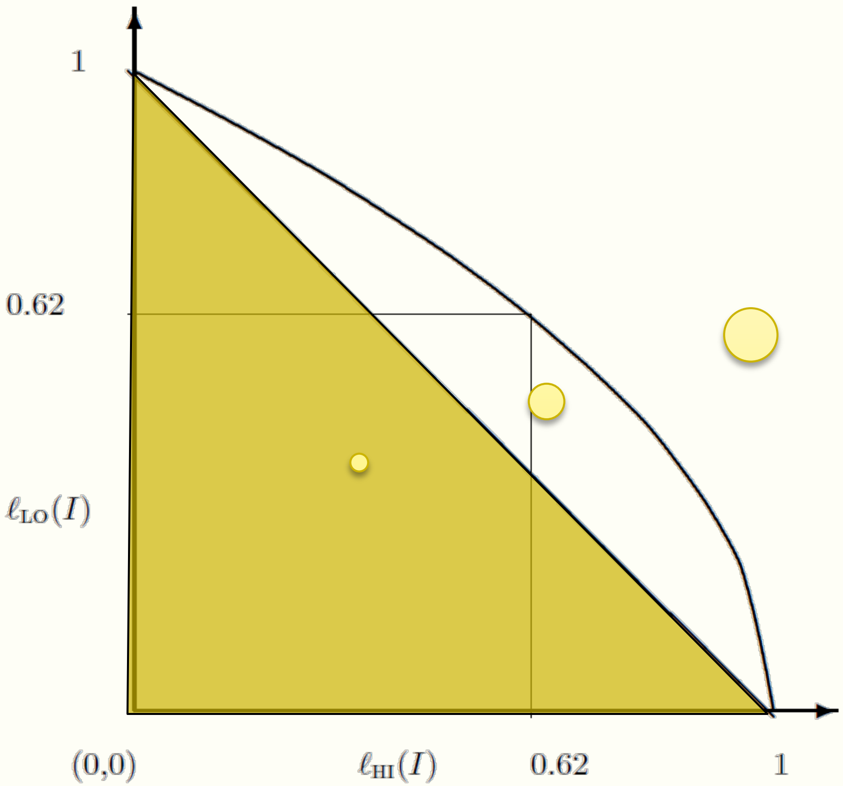

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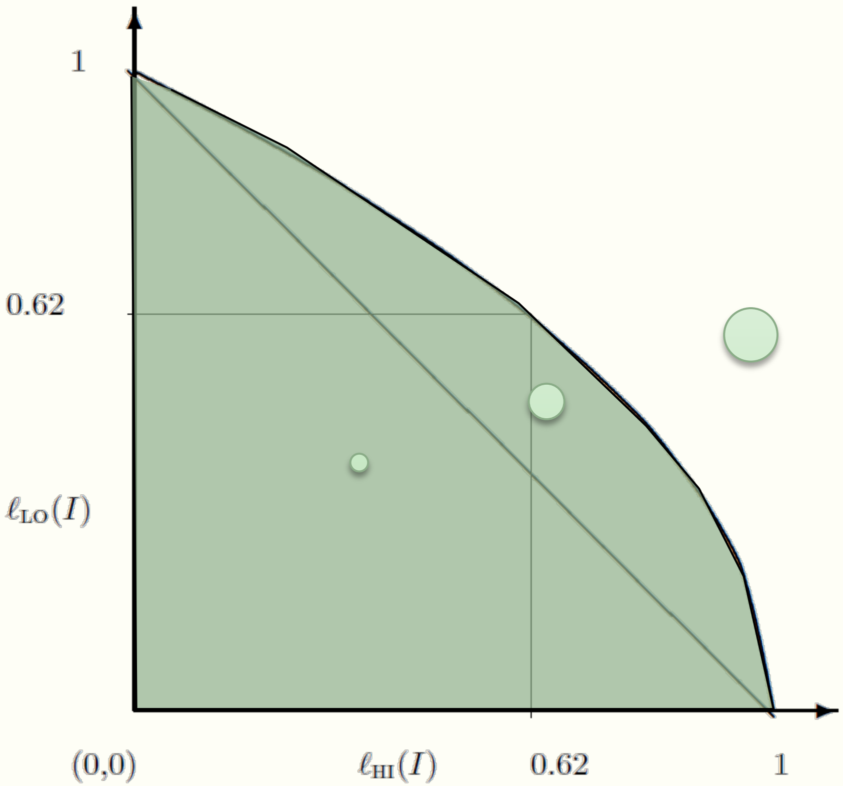
Load-Based Schedulability Test



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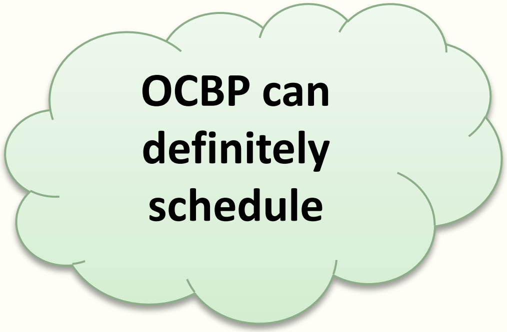
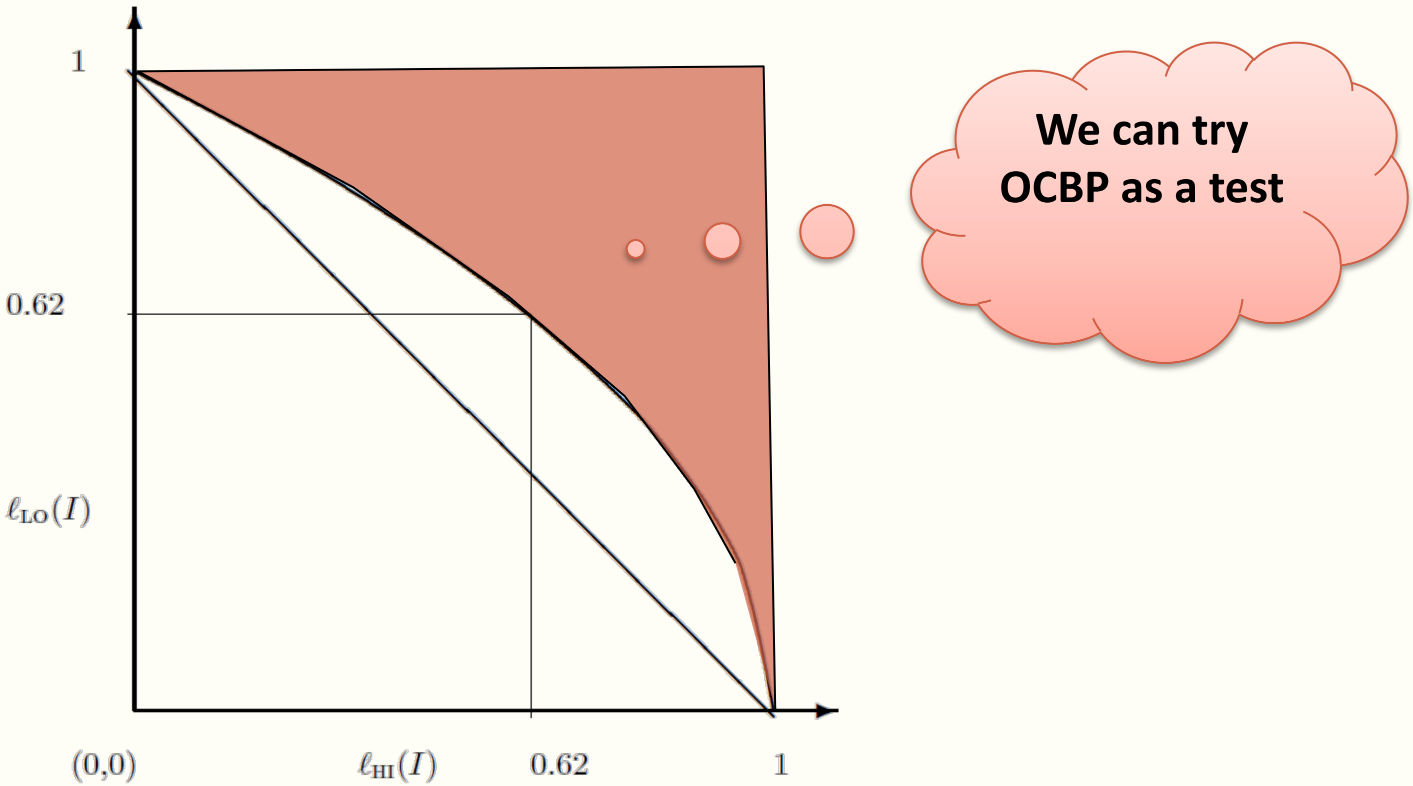


Load-Based Schedulability Test



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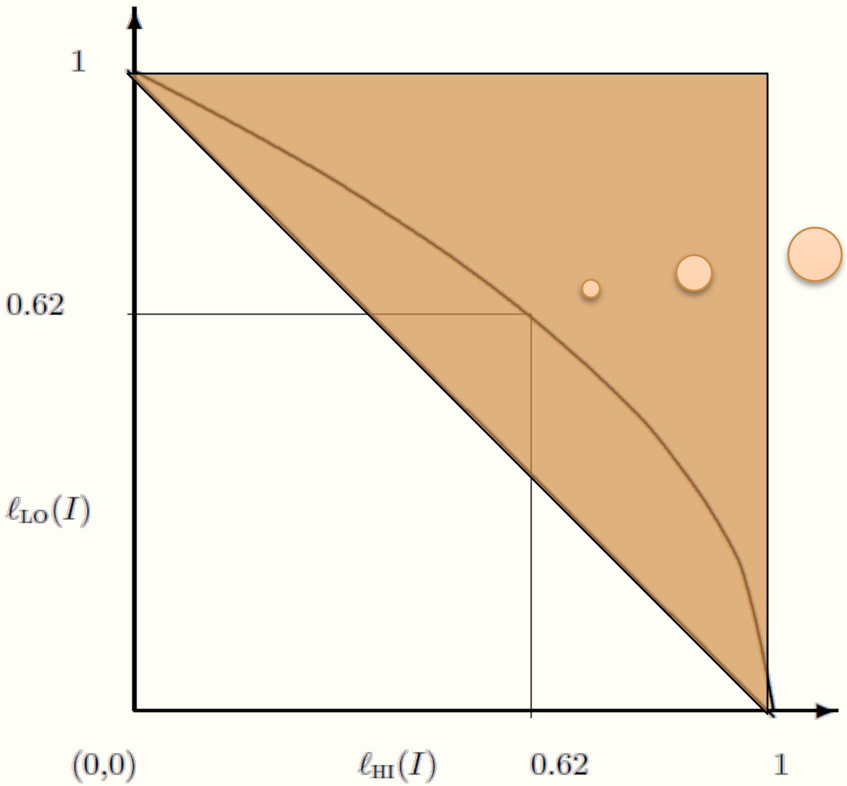
Load-Based Schedulability Test



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No known test exists for EDF