THE UNIVERSITY of NORTH CAROLINA at CHAPEL HILL

Friday, April 26th, 2013

Haohan Li

Scheduling Mixed-Criticality Real-Time Systems

Doctoral Dissertation Defense

Under the Direction of Prof. Sanjoy K. Baruah

Outline

- Motivation
- Thesis statement
- Background
- Dissertation research
  - Models
  - Algorithms
- Other contributions and future work

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Cyber-Physical: The Next Revolution?

- **Classic computer systems**
  - **Process information**

- **Cyber-physical systems**
  - **Interact with physical world**
    - Collect data
    - Make decisions intelligently
    - Perform actions

Real-Time: Essential to Cyber-Physical

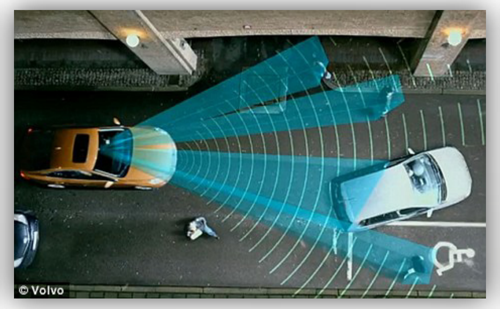
- **Not only the right move**

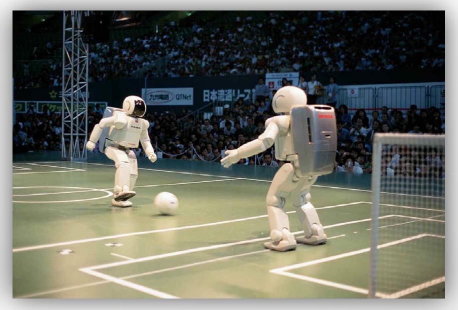
- **The right move at a good time**

Real-Time Systems

- Systems that provide both logical and temporal correctness
  - Predictability is more important than performance
    - Provably guarantee responses within strict time constraints (deadlines)







Real-Time == Real-Fast?

- **Not true for multitasking systems**

  - **A good scheduling policy is the key to prompt responses**

Motivation: Mixed-Criticality Systems

- **Northrop Grumman X-47B**
  - **Unnamed aerial vehicle**



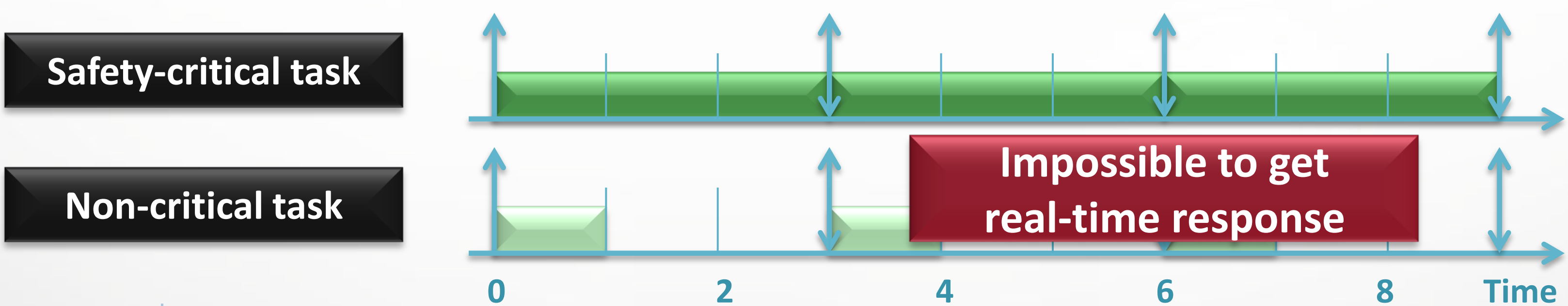
    - Motion plan, route plan, recon and combat
    - Integrated, intelligent and computational-intensive
  - **The flight control tasks are safety-critical**
  - **The mission-related tasks are non-safety-critical**

Motivation: Mixed-Criticality Systems

- Conflicting requirements
  - Safety-critical tasks may never fail
    - Reserving large amount of resources
  - Non-critical tasks should be intelligent
    - Using as many resources as possible
- Traditional real-time systems face challenges
  - Computational resource waste due to pessimism

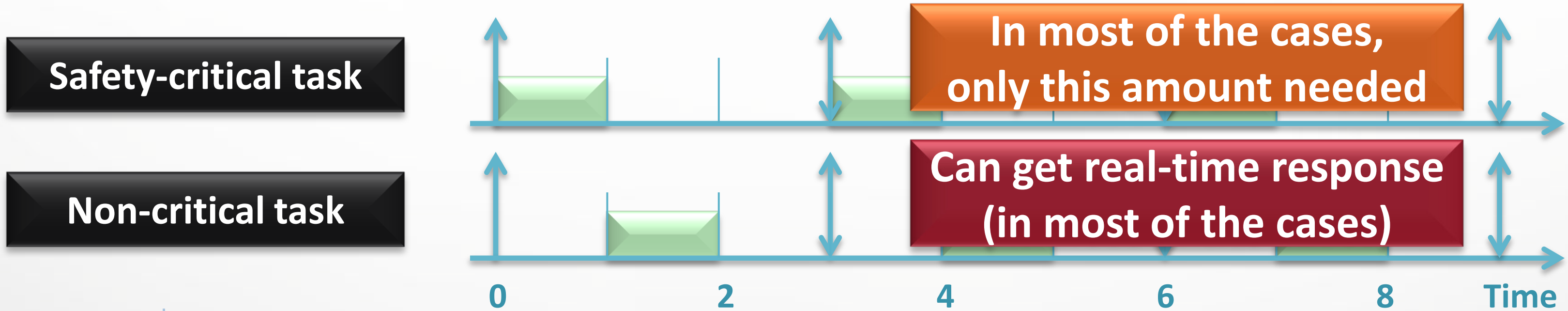
Motivation: Mixed-Criticality Systems

- Pessimism in traditional methods
  - Scheduling based on execution-time estimations
  - Safety-critical tasks require very pessimistic execution-time estimations
  - Non-critical tasks suffer from pessimistic estimations



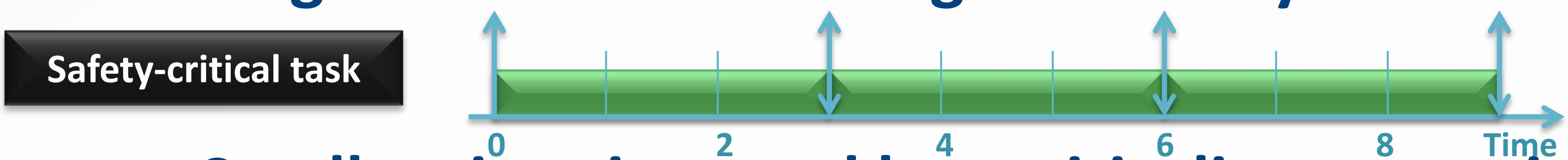
Motivation: Mixed-Criticality Systems

- **Pessimism in traditional methods**
  - Non-critical tasks don't have to assume such pessimistic estimations
    - Can assume smaller estimations and make guarantees
    - These guarantees are invalid only in the very worst case

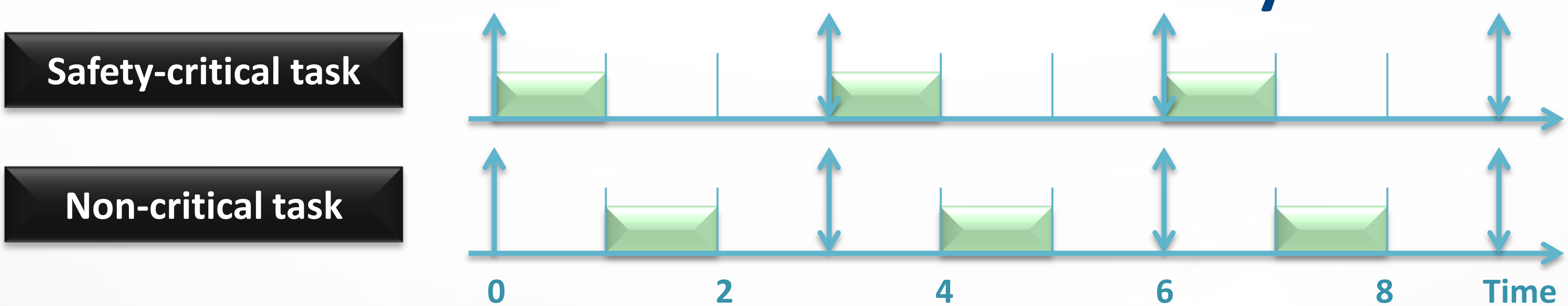


Motivation: Mixed-Criticality Systems

- Provide correctness guarantees in two levels
  - Large estimations and high-criticality constraints



  - Small estimations and low-criticality constraints



- What scheduling algorithms shall we use?
- Can we reduce resource waste?

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Thesis Statement

- New methods can be discovered to schedule real-time systems with multiple criticalities
- The methods can supply multiple temporal predictability assertions with respect to multiple WCET specifications
- The assertions can be defined and measured through a formalized description
- The methods can be efficiently implemented with acceptable computational complexities

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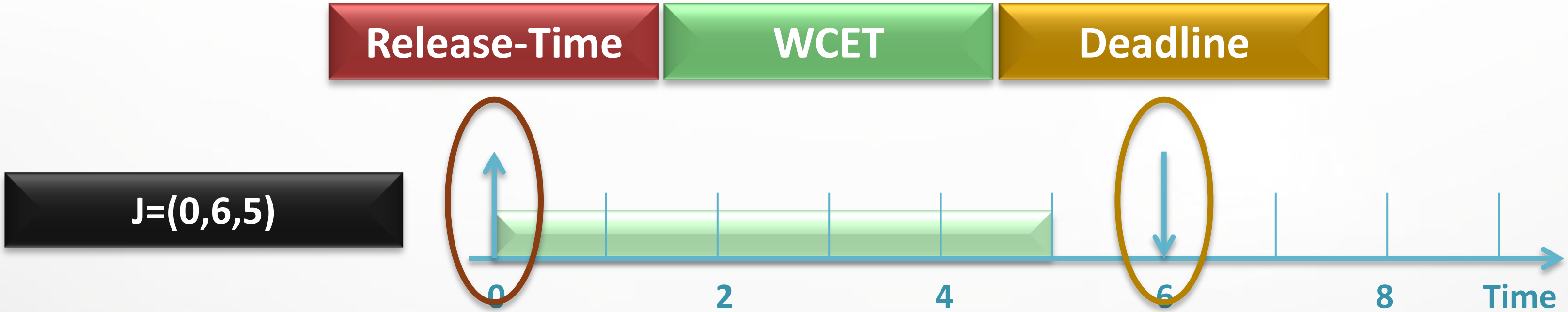
Real-Time Scheduling Theory

- The abstract model for real-time systems
  - A one-shot Job is released at its release time, takes at most its worst-case execution time to finish, and is required to be finished by its deadline



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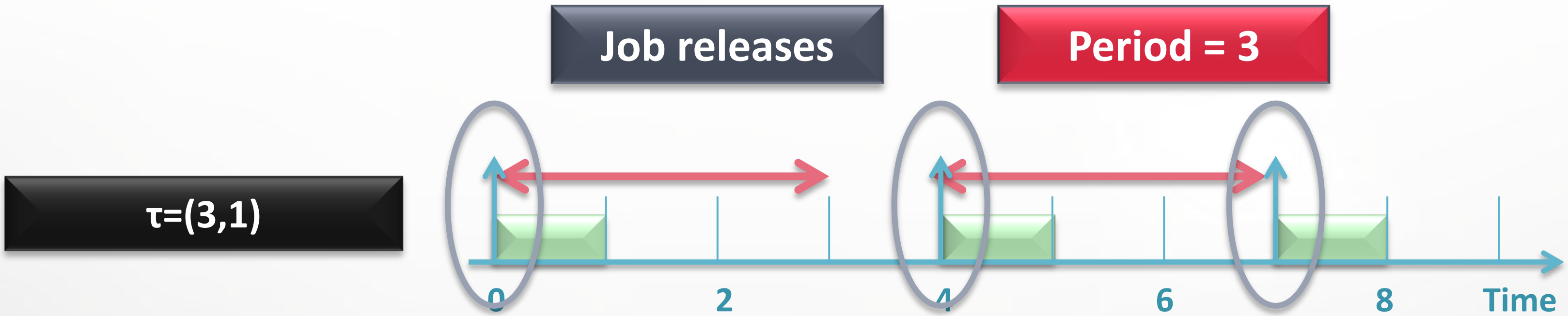
Real-Time Scheduling Theory

- **The abstract model for real-time systems**
  - **Sporadic tasks recurrently release jobs**
    - **Period**: the **minimal** gap between job releases

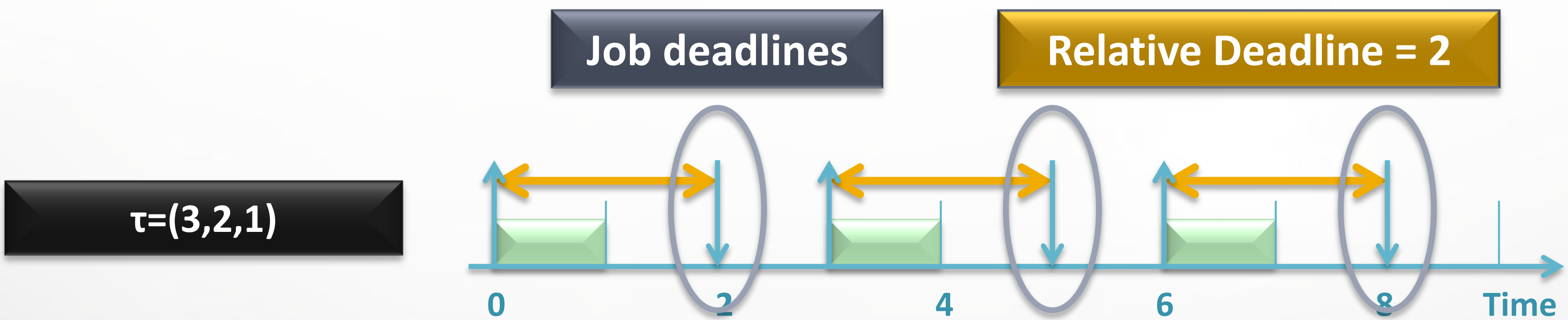


Real-Time Scheduling Theory

- **The abstract model for real-time systems**
  - **Sporadic tasks recurrently release jobs**
    - **Relative deadline: the gap between a job's release time and its deadline**
      - Implicit deadline: relative deadline is equal to period
        - Known as *Liu & Layland tasks*

Real-Time Scheduling Theory

- **The abstract model for real-time systems**
  - **Sporadic tasks recurrently release jobs**
    - Relative deadline: the gap between a job's release time and its deadline
      - Implicit deadline: relative deadline is equal to period
      - Arbitrary deadline: relative deadline isn't equal to period

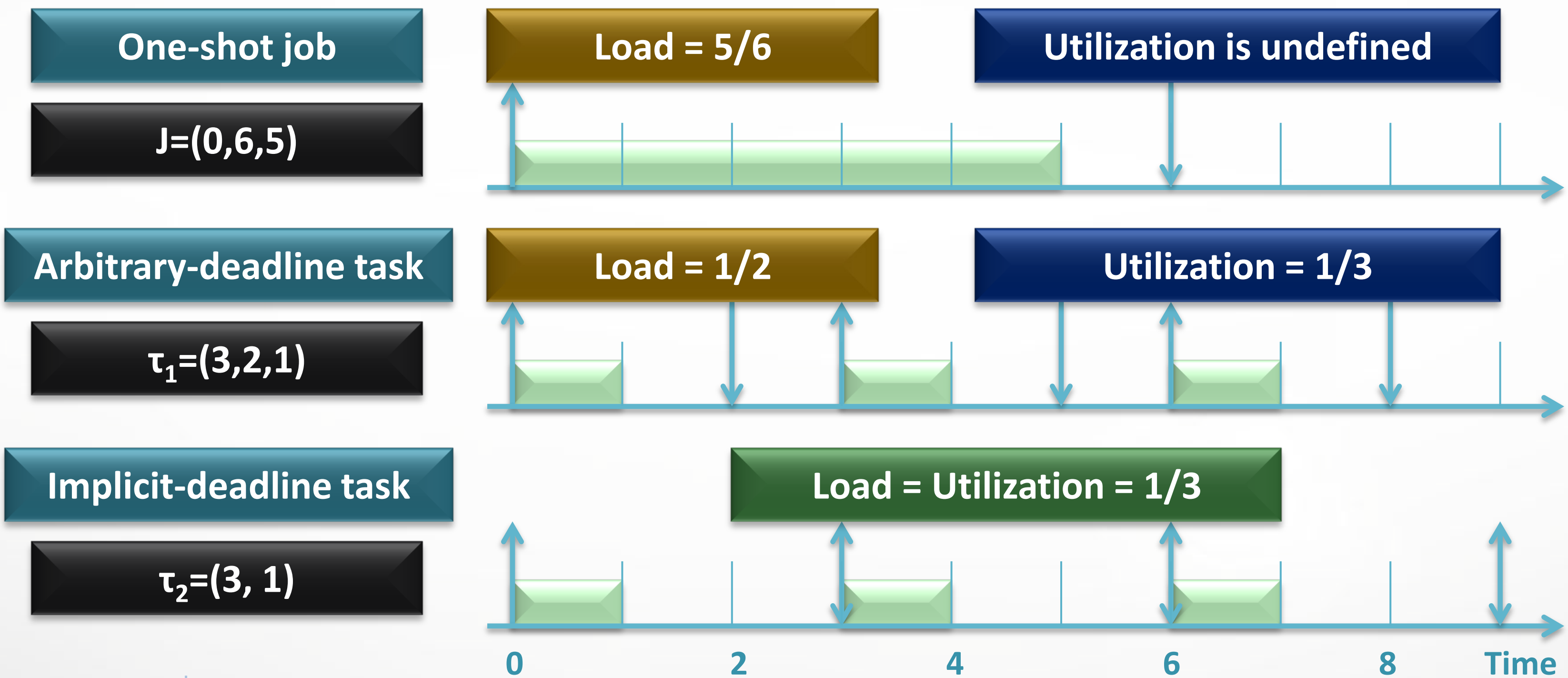


Real-Time Scheduling Theory

- **The abstract model for real-time systems**
  - **One-shot jobs**
    - Release-time, deadline, worst-case execution time
  - **Sporadic tasks**
    - Period, relative deadline, worst-case execution time
  - **Utilization and load to measure CPU capacity**
    - Utilization: the **overall fraction** of processor time demand of a system
    - Load: the **maximum fraction** of processor time demand of a system over any time interval

Real-Time Scheduling Theory

- **The abstract model for real-time systems**
  - **CPU capacity measurement: load and utilization**



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Dissertation Research

- New model for real-time systems
  - Mixed-criticality systems
    - Additional parameters and constraints
- Scheduling algorithms in the new model
  - OCBP algorithm
  - EDF-VD algorithm
- Capacity loss and optimality analysis

Contributions

- **First solutions to many fundamental questions**
  - **One-shot jobs**
  - **Sporadic arbitrary-deadline tasks**
  - **Multiprocessor scheduling**
- **Effectively reduce resource waste**
  - **Both algorithms are proved to utilize resources more efficiently than traditional methods**
  - **Both algorithms have the best *speedup factor* for two criticality levels**

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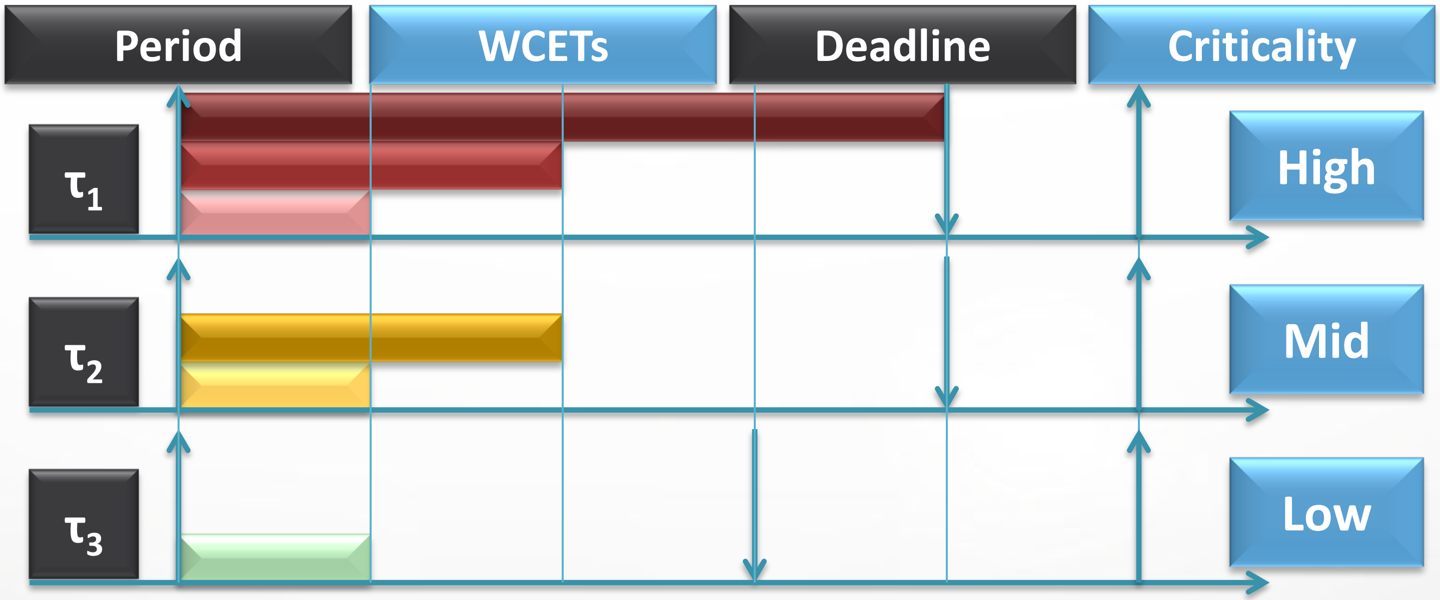
Model of Mixed-Criticality Systems

- **Parameters for mixed-criticality tasks**
  - Inherited from traditional real-time systems
  - Exclusive for mixed-criticality systems



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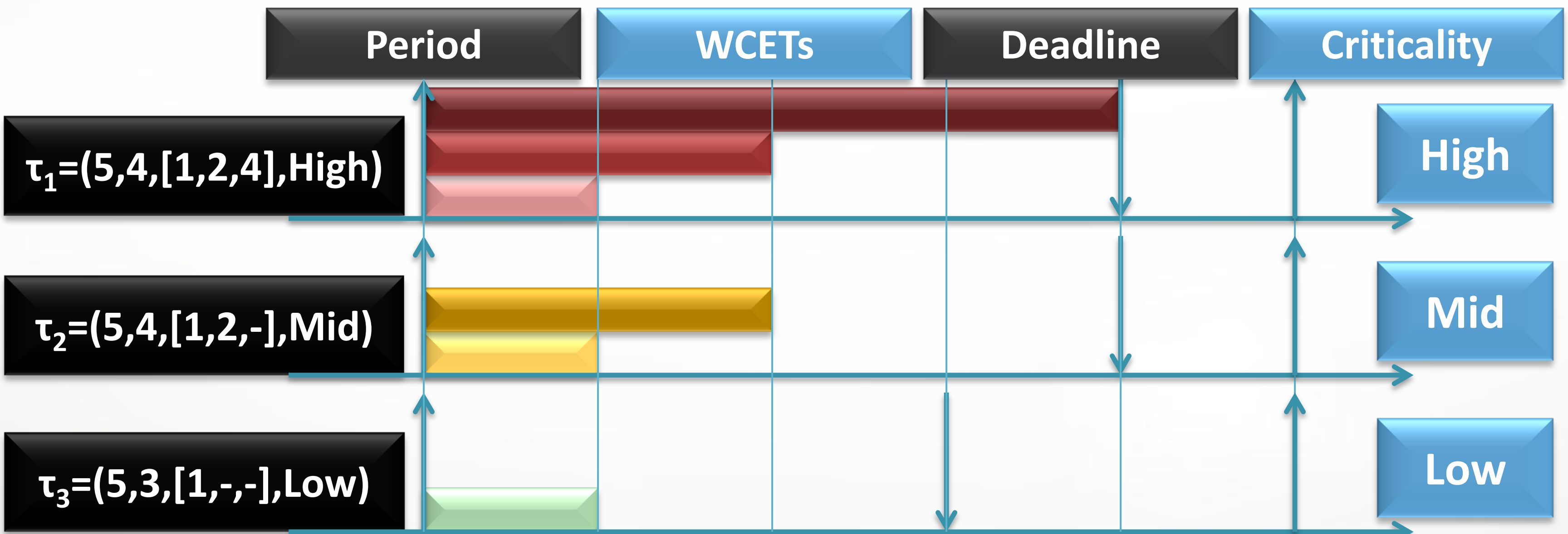
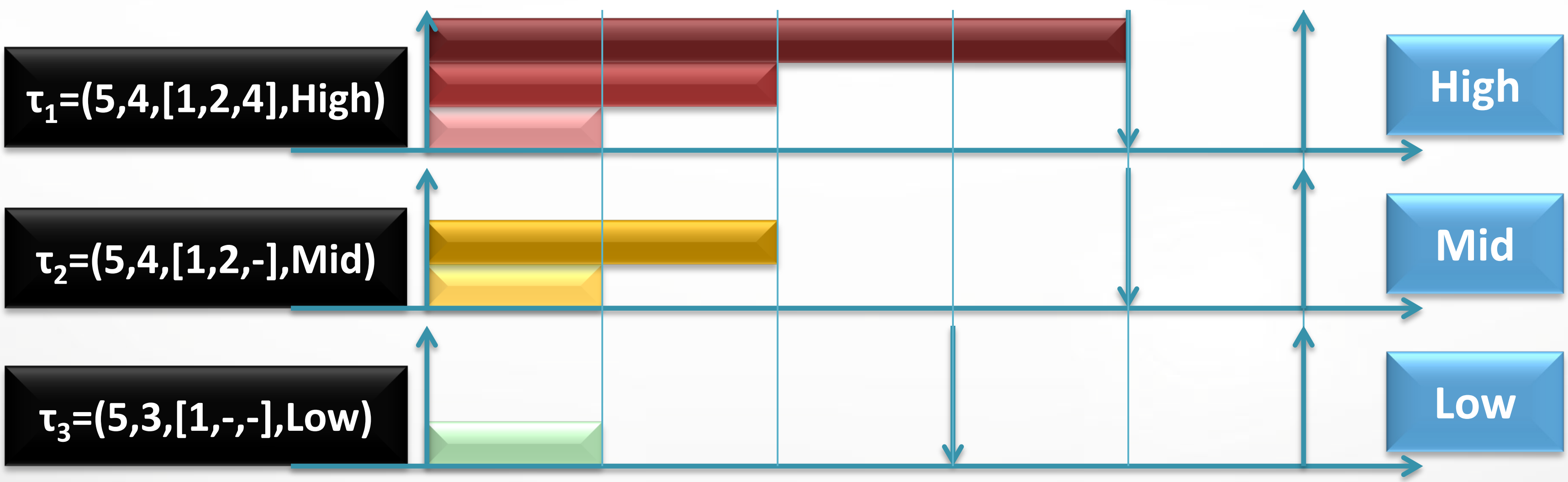


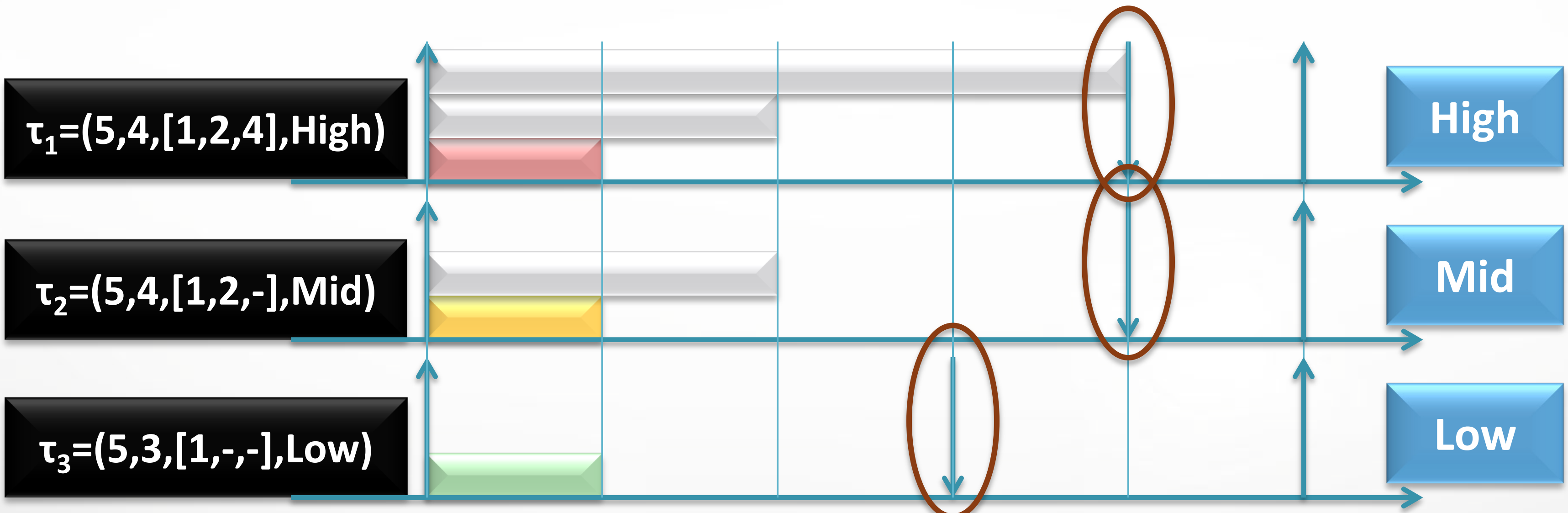
Model of Mixed-Criticality Systems

- **Valid scheduling algorithms**
  - Basic idea: if high-criticality tasks overruns, low-criticality tasks can be ignored



Model of Mixed-Criticality Systems

- Valid scheduling algorithms
  - If no task exceeds level-X WCET, all tasks with level-X and above should meet their deadlines



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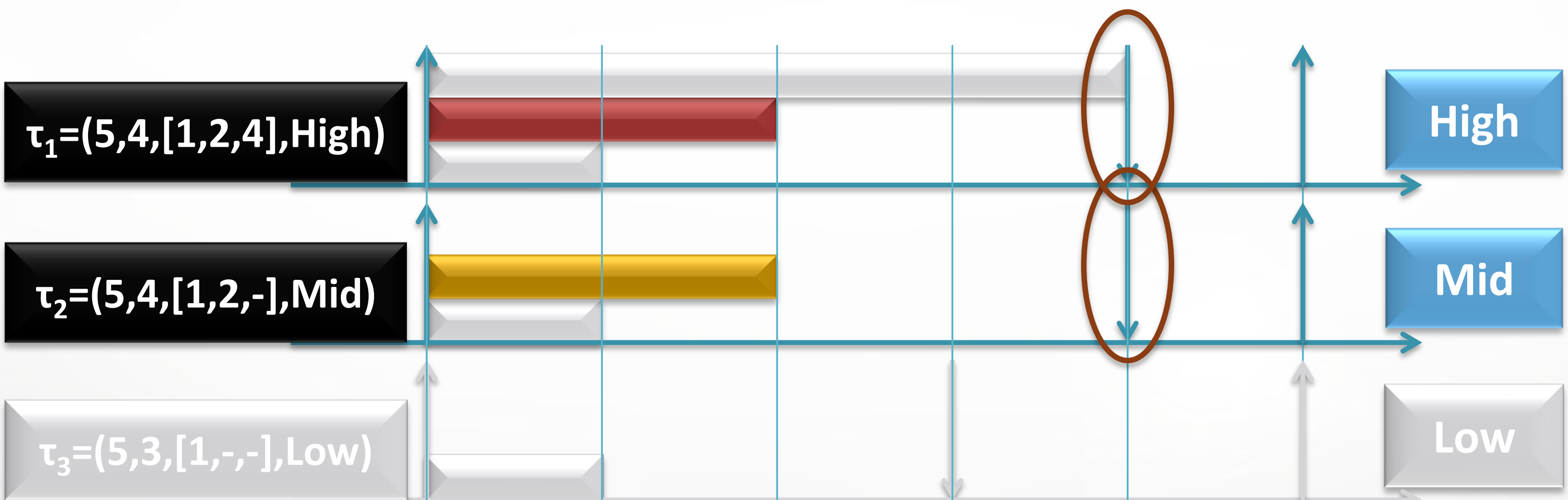

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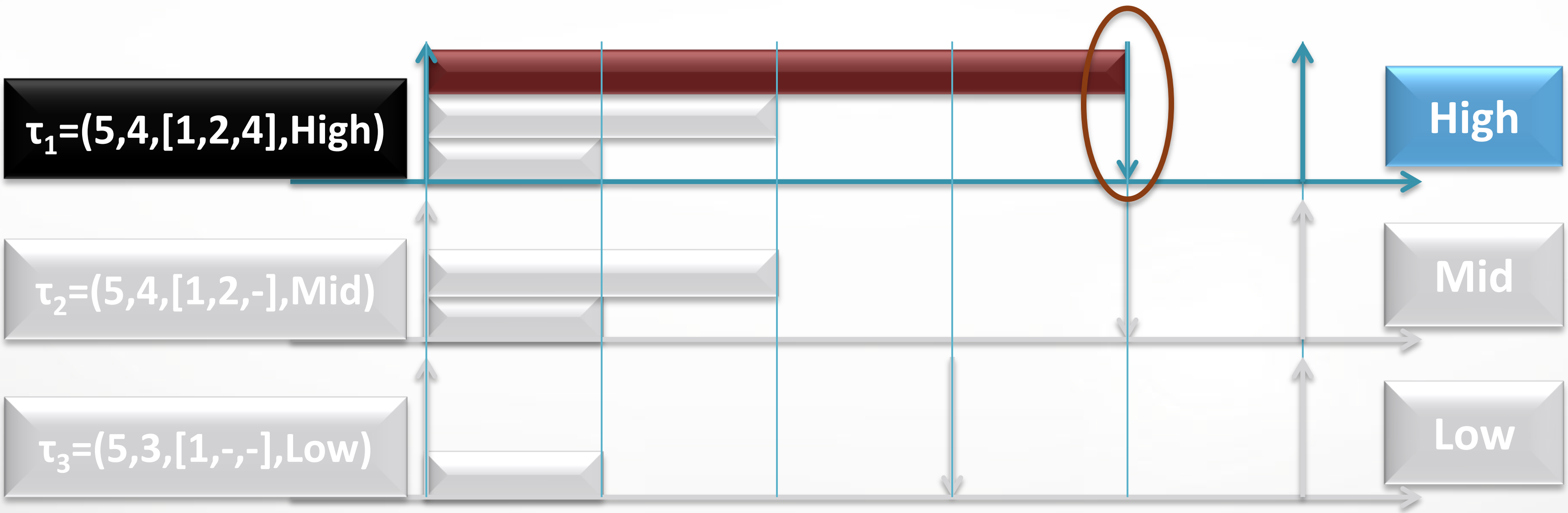

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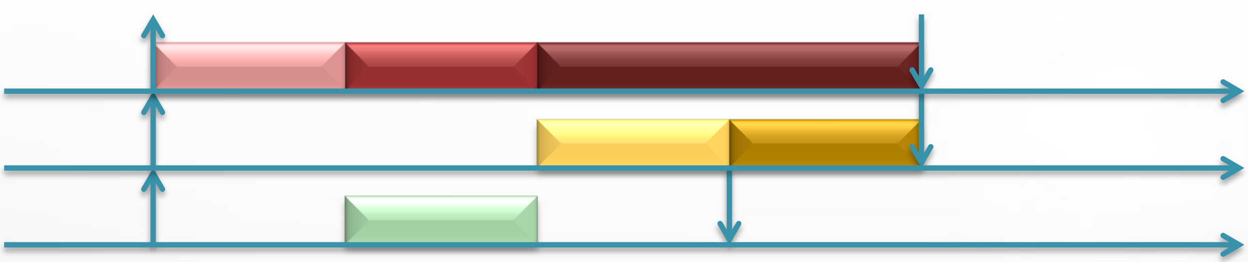
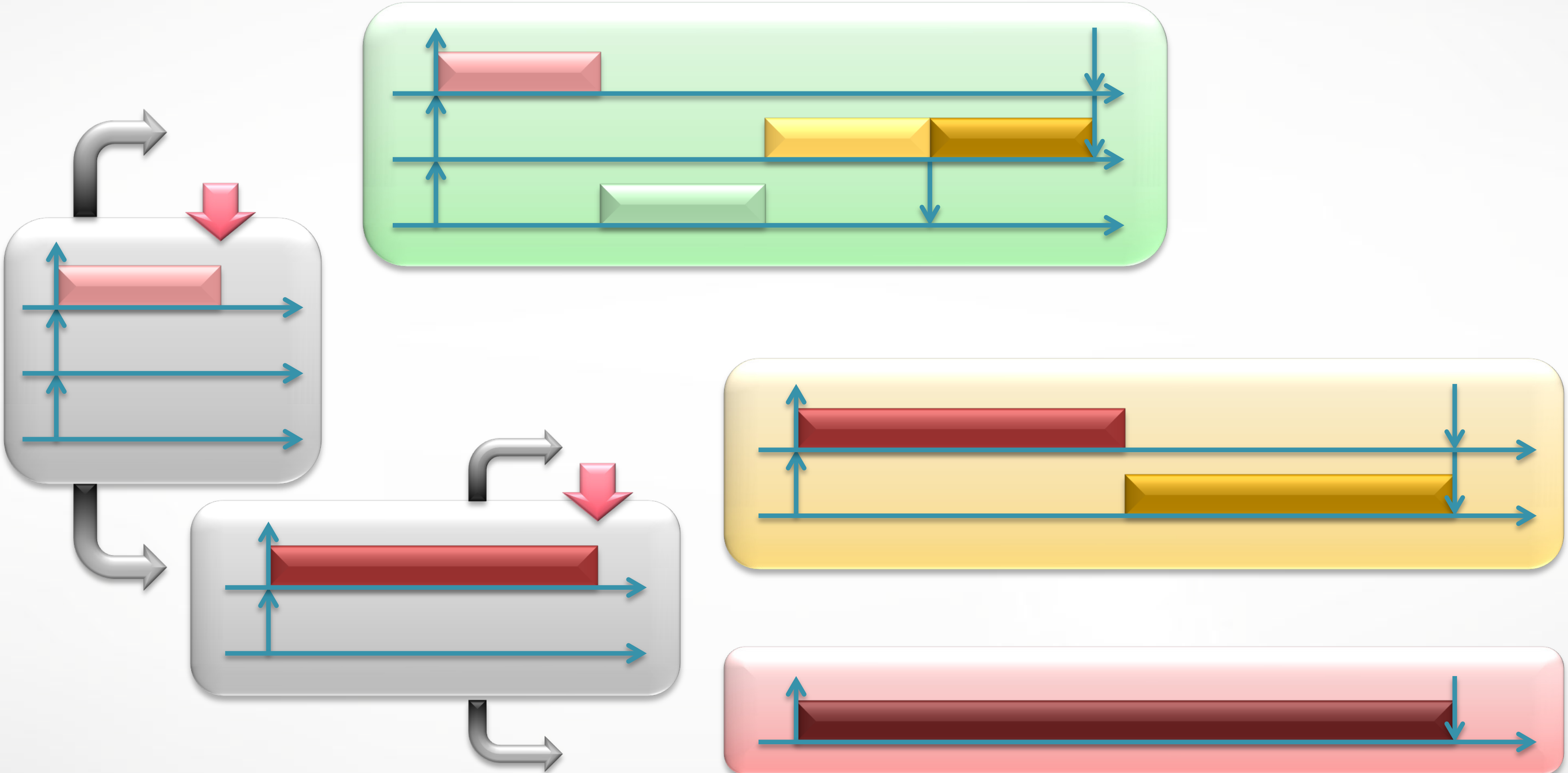
Scheduling Mixed-Criticality Systems

- The challenge is that we do not know if a high-level task will use the high-level WCET
  - We denote this as ***non-clairvoyant***
  - The scheduling policy must detect the behavior of the system, and drop tasks when necessary



Scheduling Mixed-Criticality Systems



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Scheduling Mixed-Criticality Systems

- The challenge is that we do not know if a high-level task will use the high-level WCET
  - The scheduling policy must detect the behavior of the system, and drop tasks when necessary
  - When a low-criticality and urgent job and a high-criticality and non-urgent job are both pending, we have to make a proper decision

Example: Mixed-Criticality Jobs

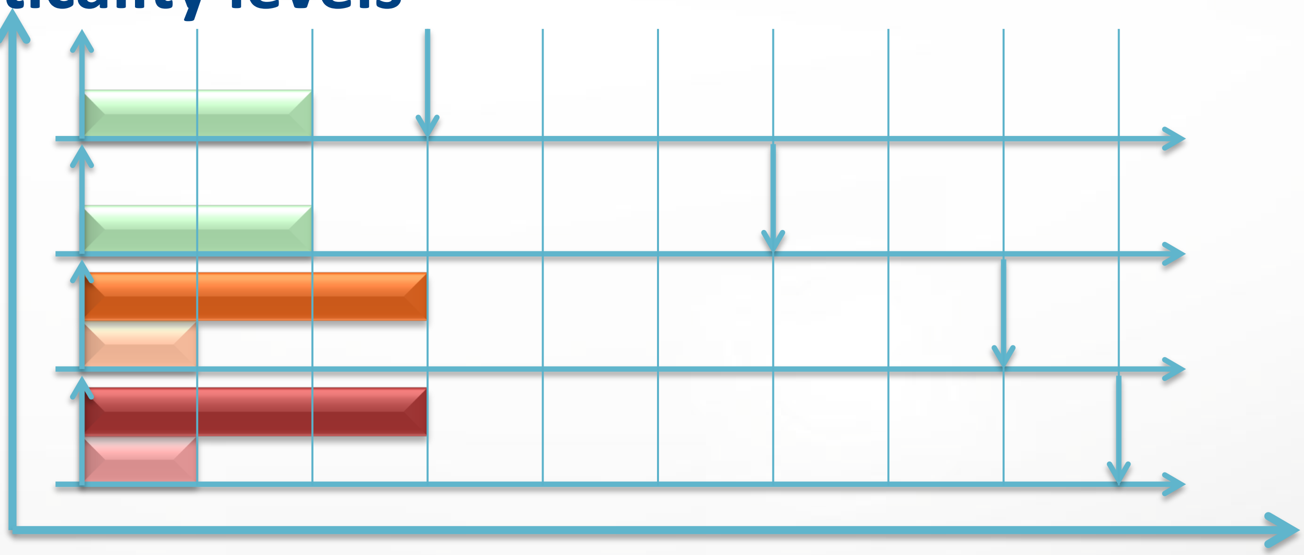
- **Here is a detailed example to explain our solutions to the questions within our model**
  - One-shot jobs
  - Two criticality levels

J_1=(0,3,[2,-],Low)

J_2=(0,6,[2,-],Low)

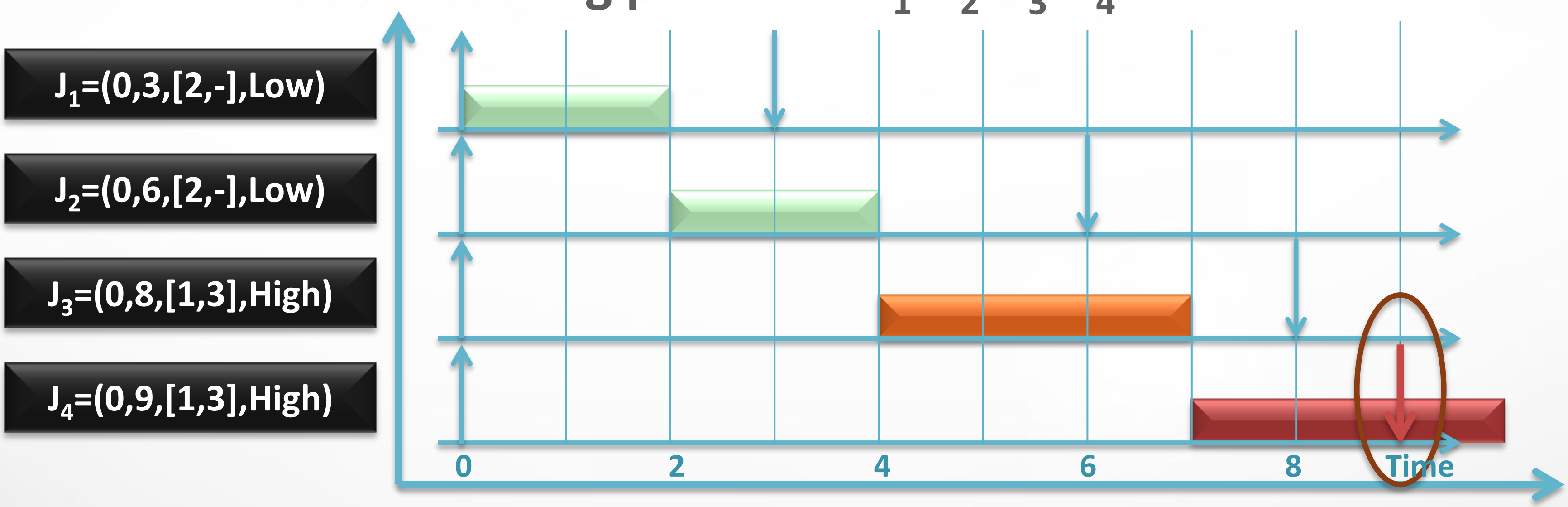
J_3=(0,8,[1,3],High)

J_4=(0,9,[1,3],High)



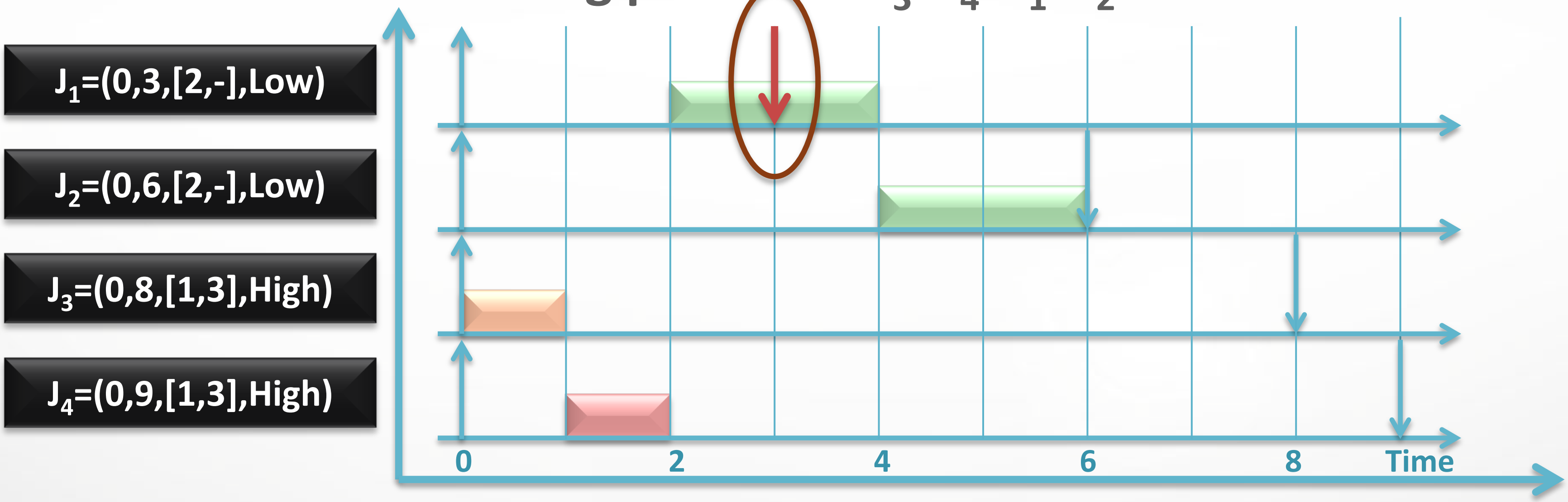
Example: Mixed-Criticality Jobs

- **Traditional scheduling policies don't work efficiently on mixed-criticality systems**
  - **Traditional method: Earliest-deadline-first (EDF)**
    - Job scheduling priorities: $J_1 < J_2 < J_3 < J_4$



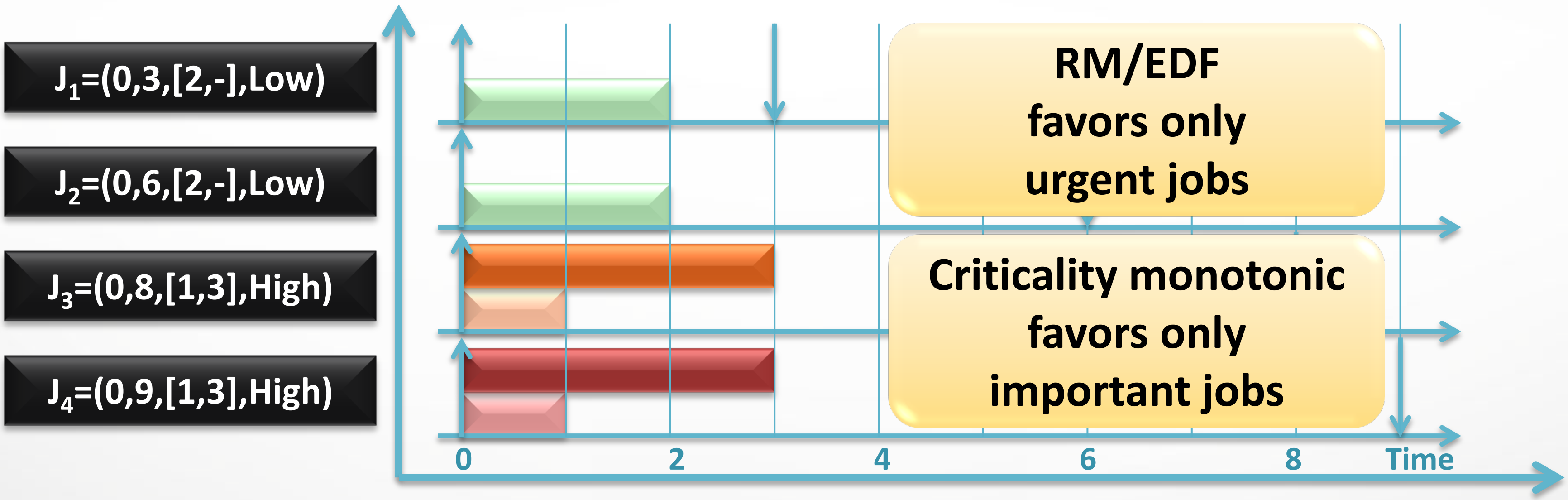
Example: Mixed-Criticality Jobs

- **Traditional scheduling policies don't work efficiently on mixed-criticality systems**
  - **Traditional method: Criticality-monotonic**
    - Job scheduling priorities: $J_3 < J_4 < J_1 < J_2$



Scheduling Mixed-Criticality Systems

- **Traditional scheduling policies don't work efficiently on mixed-criticality systems**
  - **Urgency and importance may differ**



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Evaluation of Scheduling Algorithms

- **Mixed-criticality scheduling problem is NP-hard in the strong sense**
  - **The performance of scheduling algorithms is quantified in the form of speedup factors**
    - **An algorithm has a speedup factor *s* if it can schedule a task set that is schedulable by a clairvoyant scheduling algorithm on a speed-*s* processor**
      - **Exact algorithm has a speedup factor of 1, but no polynomial or pseudo-polynomial algorithm can reach it**
      - **Smaller factor represents better performance**

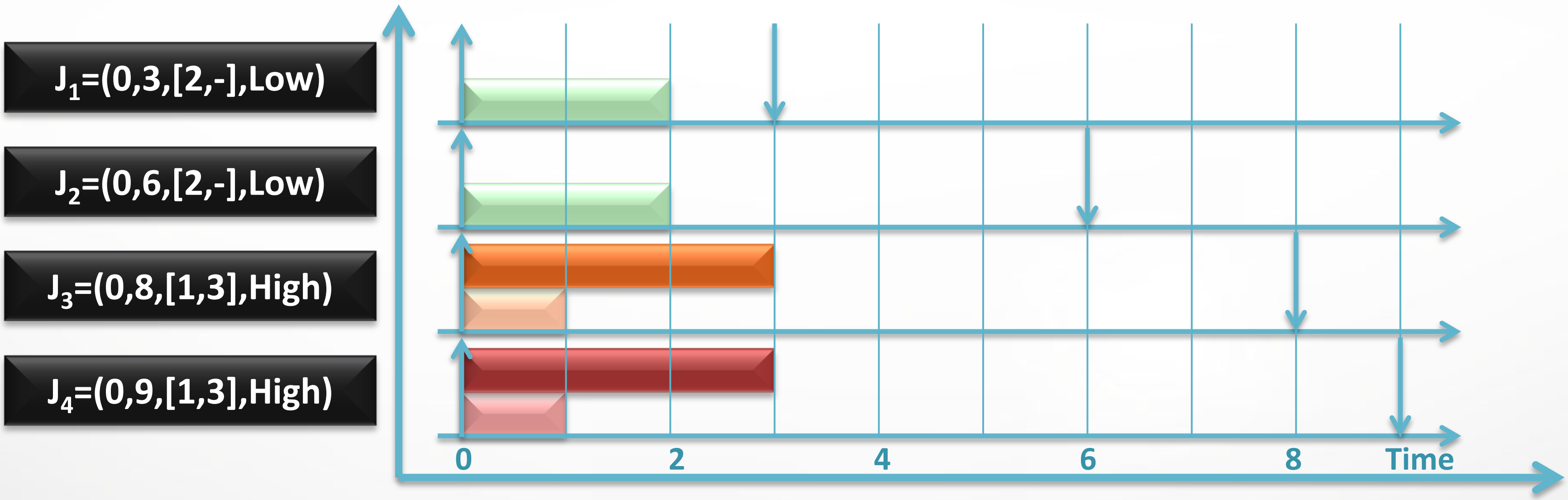
OCBP Algorithm

- **The first solution: OCBP algorithm [RTAS 10]**
  - **Own-criticality-based-priority algorithm**
    - **An approximation algorithm for one-shot jobs in preemptive uniprocessor systems**
    - **Priorities are assigned to jobs before run-time**
    - **OCBP seeks a balance between urgency and importance**

[RTAS 10] Baruah, Li, and Stougie. Towards the design of certifiable mixed-criticality systems. In *Proceedings of the IEEE Real-Time Technology and Applications Symposium (RTAS)*. 2010. IEEE.

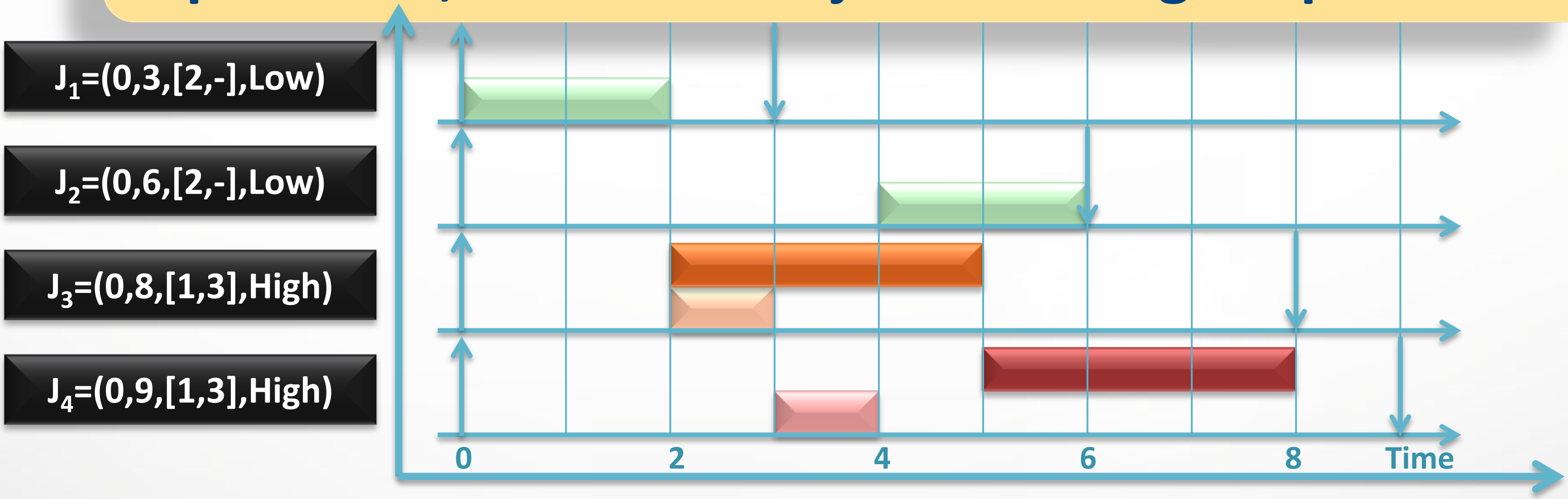
OCBP Algorithm

- **The first solution: OCBP algorithm [RTAS 10]**
  - **Own-criticality-based-priority algorithm**
    - An **approximation** algorithm for **one-shot jobs** in **preemptive uniprocessor** systems



OCBP Algorithm

- OCBP algorithm constructs a priority list
  - In this example, priority list is $J_1 < J_3 < J_4 < J_2$
  - Basic idea: a job should ignore jobs with lower priorities, and tolerate jobs with higher priorities



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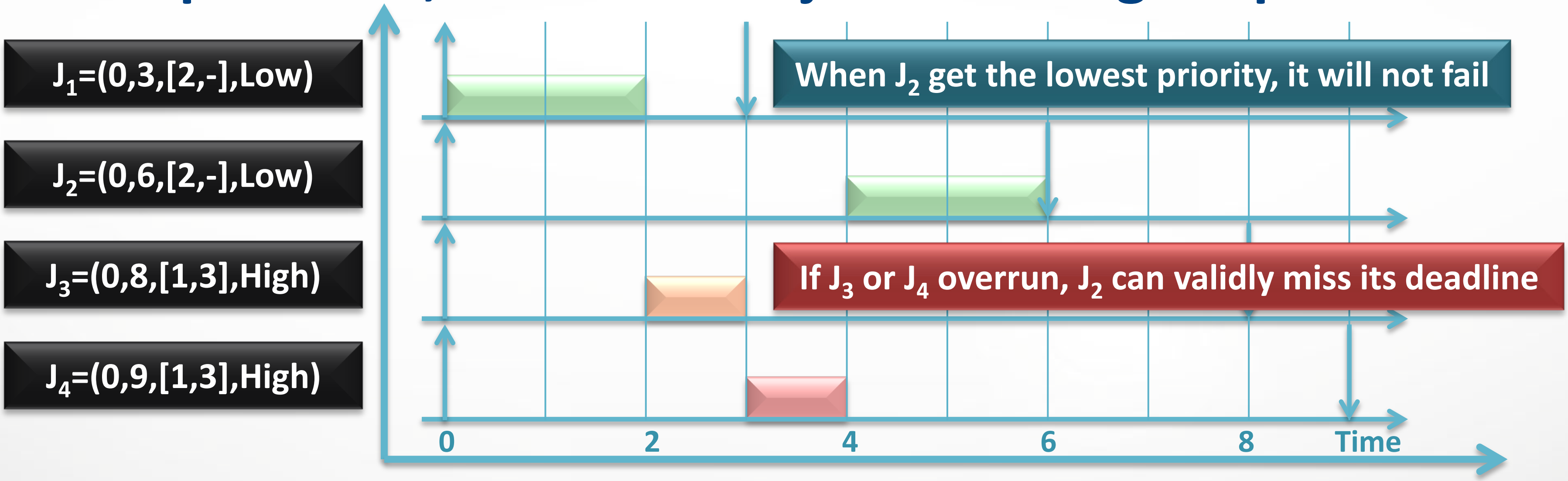

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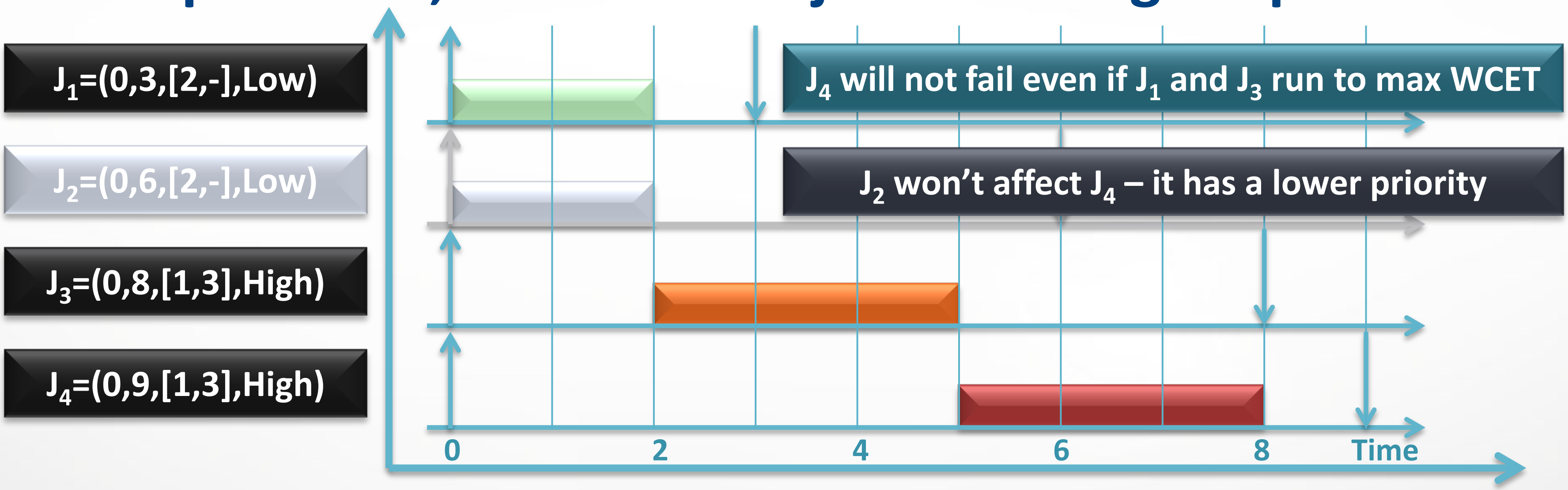

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OCBP Algorithm

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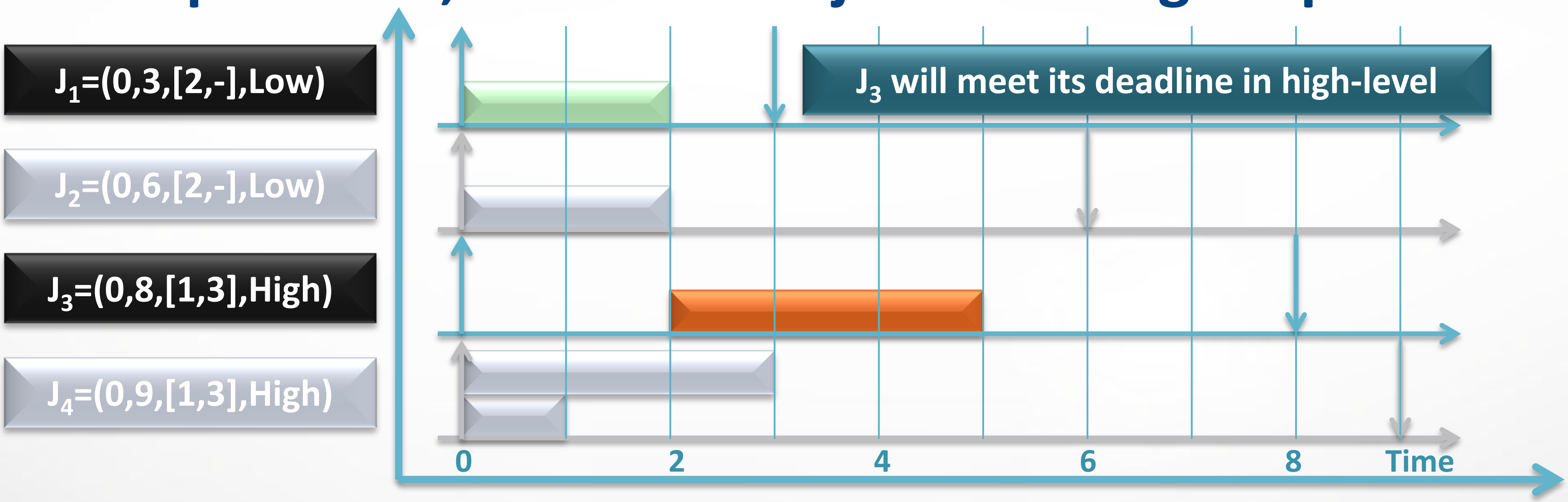
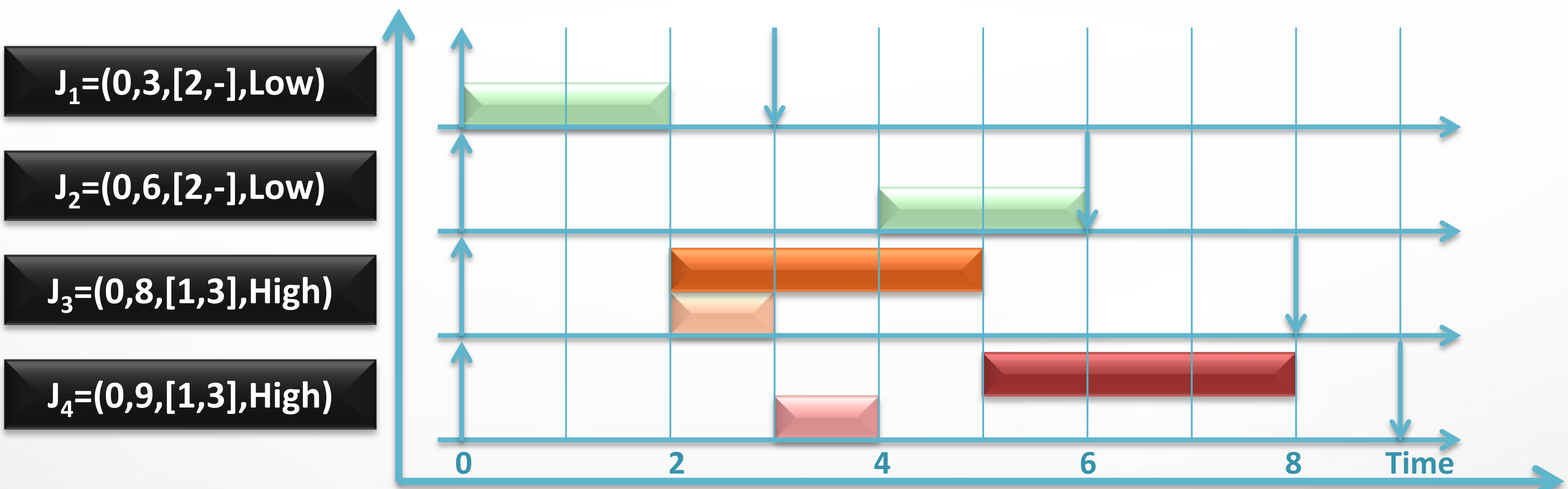


OCBP Algorithm

- **OCBP algorithm constructs a priority list**
  - **The algorithm will recursively seek the lowest-priority job, and build the list from backward**



Evaluation of OCBP Algorithm

- **Speedup factor [RTAS 10]**
  - Speedup factor of EDF for two criticality levels is 2
    - Intuitively, EDF requires a full processor for each criticality level, which sums up to 2
  - Speedup factor of OCBP algorithm for two criticality levels is 1.618
    - The factor 1.618 is the golden ratio

Evaluation of OCBP Algorithm

- **Speedup factor [TC 12]**
  - **OCBP can handle more that two criticality levels**
  - **Speedup factor of EDF for N criticality levels is N**
    - **Still, EDF requires a full processor for each criticality level, which sums up to N**
  - **Speedup factor of OCBP for N criticality levels is the root of the equation $(x+1)^{N-1} = x^N$**
    - **The asymptotic form is $\Theta(N/\log N)$**

[TC 12] Baruah, Bonifaci, D'Angelo, Li, Marchetti-Spaccamela, Megow and Stougie. Scheduling real-time mixed-criticality jobs. In *IEEE Transactions on Computers*. 2012. IEEE.

Evaluation of OCBP Algorithm

- **Speedup factor [TC 12]**
  - **No scheduling algorithms can have a speedup factor better than 1.618 for two criticality levels**
    - OCBP algorithm is **optimal with respect to speedup factors** for two criticality levels
  - **No fixed-job-priority scheduling algorithms can have a speedup factor better than the root of the equation $(x+1)^{N-1} = x^N$**

EDF-VD Algorithm

- **OCBP algorithm works on one-shot jobs**
  - **Extending to sporadic tasks is complicated**
    - **Priorities must be assigned to each job**
- **EDF-VD algorithm on sporadic tasks [ECRTS 12]**
  - **Run-time complexity is significantly improved**

[ECRTS 12] Baruah, Bonifaci, D'Angelo, Li, Marchetti-Spaccamela, van der Ster and Stougie. The preemptive uniprocessor scheduling of mixed-criticality implicit-deadline sporadic task systems. In *Proceedings of the EuroMicro Conference on Real-Time Systems (ECRTS)*. 2012. IEEE.

EDF-VD Algorithm

- OCBP algorithm works on one-shot jobs
  - Extending to sporadic tasks is complicated
    - Priorities must be assigned to each job
- EDF-VD algorithm on sporadic tasks [ECRTS 12]
  - Earliest-Deadline-First with Virtual Deadlines
  - Based on EDF – the optimal scheduling algorithm on traditional real-time systems
  - The priority of each job is simply determined according to its virtual deadline

EDF-VD Algorithm

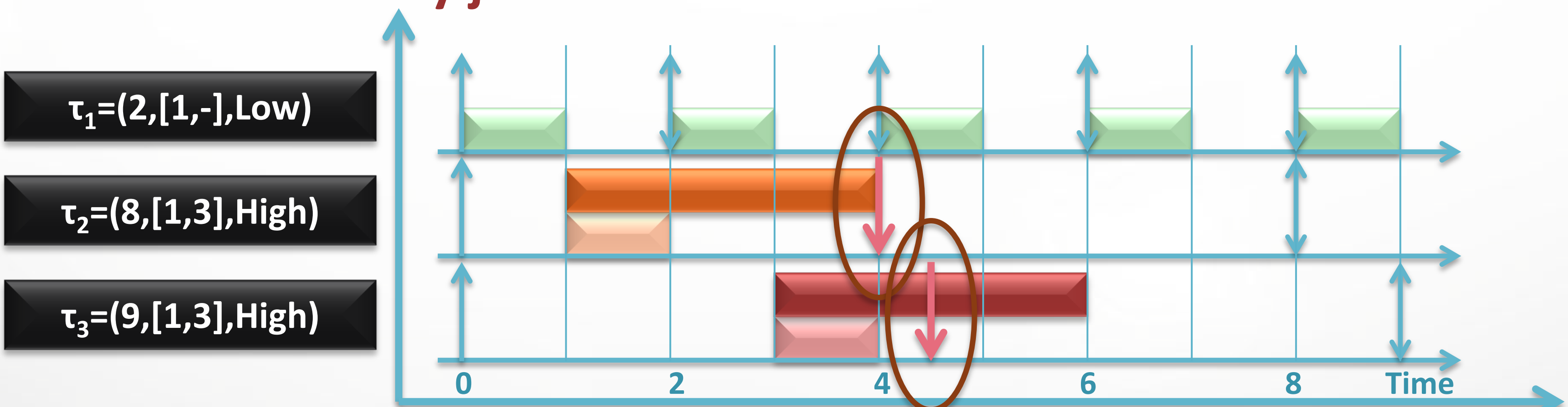
- **Basic idea**
  - Give high-criticality tasks earlier (and virtual) deadlines
    - Not only urgent jobs are favored
    - High-criticality tasks will also get higher priorities
- **Base case**
  - Two criticality levels
  - Firstly on implicit-deadline tasks, then on arbitrary-deadline tasks

EDF-VD Algorithm

- Virtual deadlines are assigned proportionally to original deadlines with factor x (0<x<1)
  - Use virtual deadlines in low-criticality behavior
  - Change to original deadlines when high-criticality behavior is detected
  - My research proposes a mechanism to choose x
  - My research proposes a schedulability test
- The analysis of EDF-VD is different from OCBP
  - Priorities are relative; deadlines are absolute

EDF-VD Algorithm

- **In the example, we try to set a scaling factor x=½ for high-criticality tasks**
  - **τ_2 and τ_3 use virtual deadlines if no criticality change is detected**
    - **Will any job miss its deadline?**



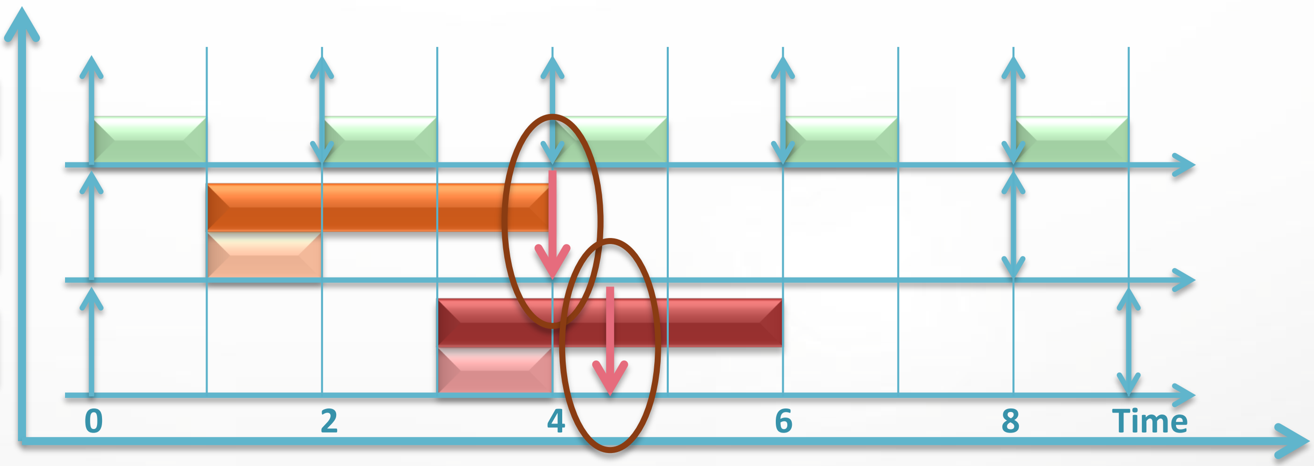
EDF-VD Schedulability Test

- **Basic idea**
  - **Check the worst case response time for any job**
    - Try to find as many jobs as possible that **have earlier deadlines** and can preempt the candidate job

τ_1=(2,[1,-],Low)

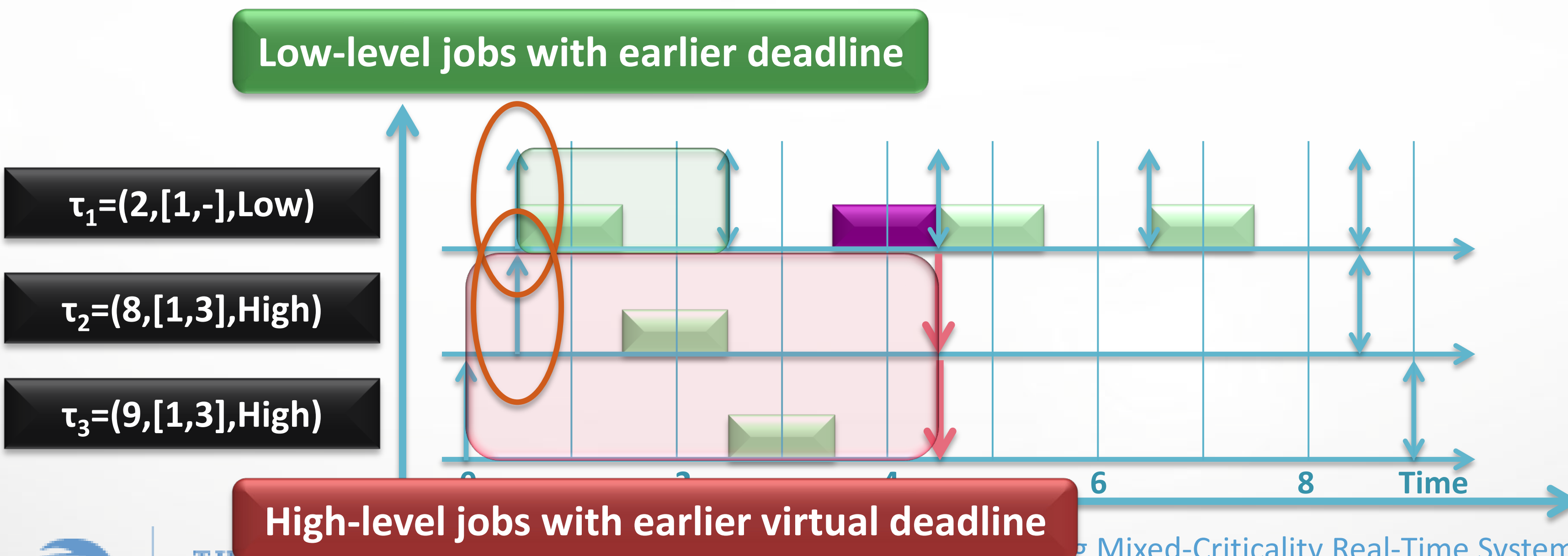
τ_2=(8,[1,3],High)

τ_3=(9,[1,3],High)



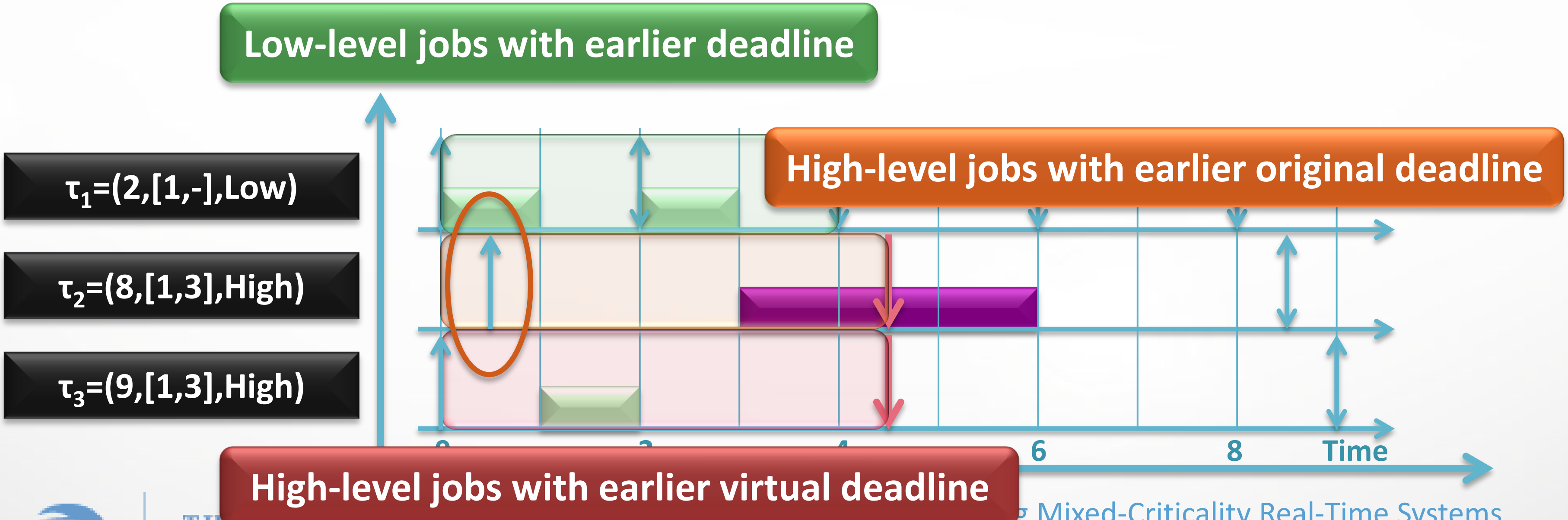
EDF-VD Schedulability Test

- In the low-criticality behavior, which jobs can have earlier deadlines and preempt the job?
  - In the example, we check the 2nd job of τ_1



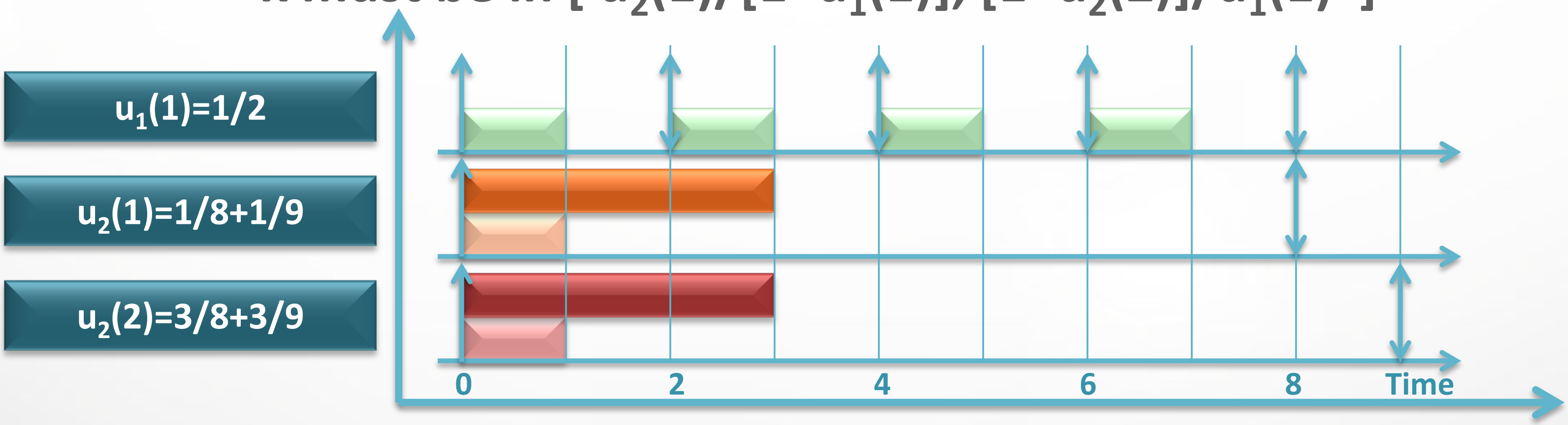
EDF-VD Schedulability Test

- In the **high-criticality** behavior, which jobs can have earlier deadlines and preempt the job?
  - In the example, we check the 1st job of τ_2



EDF-VD Schedulability Test

- **We use the following inequality to check if a task set is schedulable**
    - $u_1(1)+u_2(2)-u_1(1)[u_2(2)-u_2(1)] <= 1$
  - **x is chosen in the following range**
    - x must be in $[\ u_2(1)/[1-u_1(1)],\ [1-u_2(2)]/u_1(1)\ ]$



EDF-VD for Arbitrary-Deadline Tasks

- **Extend to arbitrary-deadline sporadic tasks**
  - **The task system is schedulable if**
    - $L_1+L_2/2 \le 1$
    - $[L_1L_2-2L_1]^2 - 4L_1[L_1-L_2+L_2^2] \ge 0$
    - x must be $1-L_2/2$
  - **It's not implicit-deadline any more. Thus load is used to check the schedulability**

EDF-VD Algorithm Speedup Factors

- The speedup factor of EDF-VD on implicit-deadline tasks with two levels is 1.33
  - This is also shown to be optimal with respect to speedup factors
- The speedup factor of EDF-VD on arbitrary-deadline tasks with two levels is 1.866
  - It's proved that no better bound can be found
    - Optimal speedup factor is 1.618
    - EDF-VD is not optimal for arbitrary-deadline tasks

Summary of Dissertation Research

- **OCBP algorithm for one-shot jobs**
  - **Applicable to arbitrary number of criticality levels**
  - **Optimal with respect to speedup factors for two criticality levels**
- **EDF-VD algorithm for sporadic tasks in two criticality levels**
  - **Applicable to implicit and arbitrary deadlines**
  - **Optimal with respect to speedup factors for implicit-deadline tasks**

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  - Models
  - Algorithms
- Other contributions and future work

Other Contributions

- **OCBP algorithm on sporadic tasks [RTSS 10]**
  - **OCBP algorithm is extended to sporadic tasks**
    - **The speedup factor results are maintained**
    - **My solution has a pseudo-polynomial run-time complexity. It is then improved to $O(n^2)$ [Guan et al., RTSS 11]**

[RTSS 10] Li and Baruah. An algorithm for scheduling certifiable mixed-criticality sporadic task systems. In *Proceedings of the IEEE Real-Time Systems Symposium (RTSS)*. 2010. IEEE.

[Guan et al., RTSS 11] Guan, Ekberg, Stigge, and Yi. Effective and efficient scheduling for certifiable mixed criticality sporadic task systems. In *Proceedings of the IEEE Real-Time Systems Symposium (RTSS)*. 2011. IEEE.

Other Contributions

- **EDF-VD algorithm on multiprocessors**
  - **EDF-VD algorithm is extended to multiprocessor platforms**
    - **Partitioned multiprocessor scheduling [RTS 12]**
    - **Global multiprocessor scheduling [ECRTS 12]**

[RTS 12] Baruah, Chattopadhyay, Li and Shin. Mixed-criticality scheduling on multiprocessors. In *Real-Time Systems*. 2012. Springer.

[ECRTS 12] Li and Baruah. Global mixed-criticality scheduling on multiprocessors. In *Proceedings of the EuroMicro Conference on Real-Time Systems (ECRTS)*. 2012. IEEE.

Other Contributions

- EDF-VD algorithm on multiprocessors
  - Partitioned multiprocessor scheduling [RTS 12]
    - Each task is allocated to a processor
    - Jobs (and tasks) can not migrate from a processor to another
  - Global multiprocessor scheduling [ECRTS 12]
    - Jobs can migrate to and execute on different processors
  - Both algorithms are for implicit-deadline tasks

Other Contributions

- EDF-VD algorithm on multiprocessors
  - Partitioned multiprocessor scheduling [RTS 12]
    - The speedup factor is shown to be no greater than 2.67
  - Global multiprocessor scheduling [ECRTS 12]
    - The speedup factor is shown to be no greater than 3.24
  - The traditional partitioned and global EDF method has a speedup factor of 4

Future Work

- **More efficient uniprocessor algorithms**
  - **Pragmatic improvement to OCBP algorithm**
  - **More criticality levels for EDF-VD algorithm**
- **Exploration of multiprocessor algorithms**
  - **Arbitrary-deadline tasks**
  - **More criticality levels**
  - **Better analysis and better algorithms**

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Friday, April 26th, 2013

Haohan Li

Thank you!