# On Spin Locks in AUTOSAR: Blocking Analysis of FIFO, Unordered, and Priority-Ordered Spin Locks


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MAX-PLANCK-GESELLSCHAFT

# Motivation: AUTOSAR

AUTOSAR: OS-specification widely used for embedded applications

Resources accessed from multiple cores:

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Resources accessed from multiple cores:

AUTOSAR mandates spin locks.

But AUTOSAR **does not specify spin lock type**!

**Which type should be used?**

# Spin Lock Types

Variety of reasonable choices:

- Non-Preemptable Spinning
- Preemptable Spinning

×

- FIFO-ordered (MSRP)
- Priority-Ordered
- Unordered
- Priority-Ordered with FIFO tie-breaking

# Spin Lock Types

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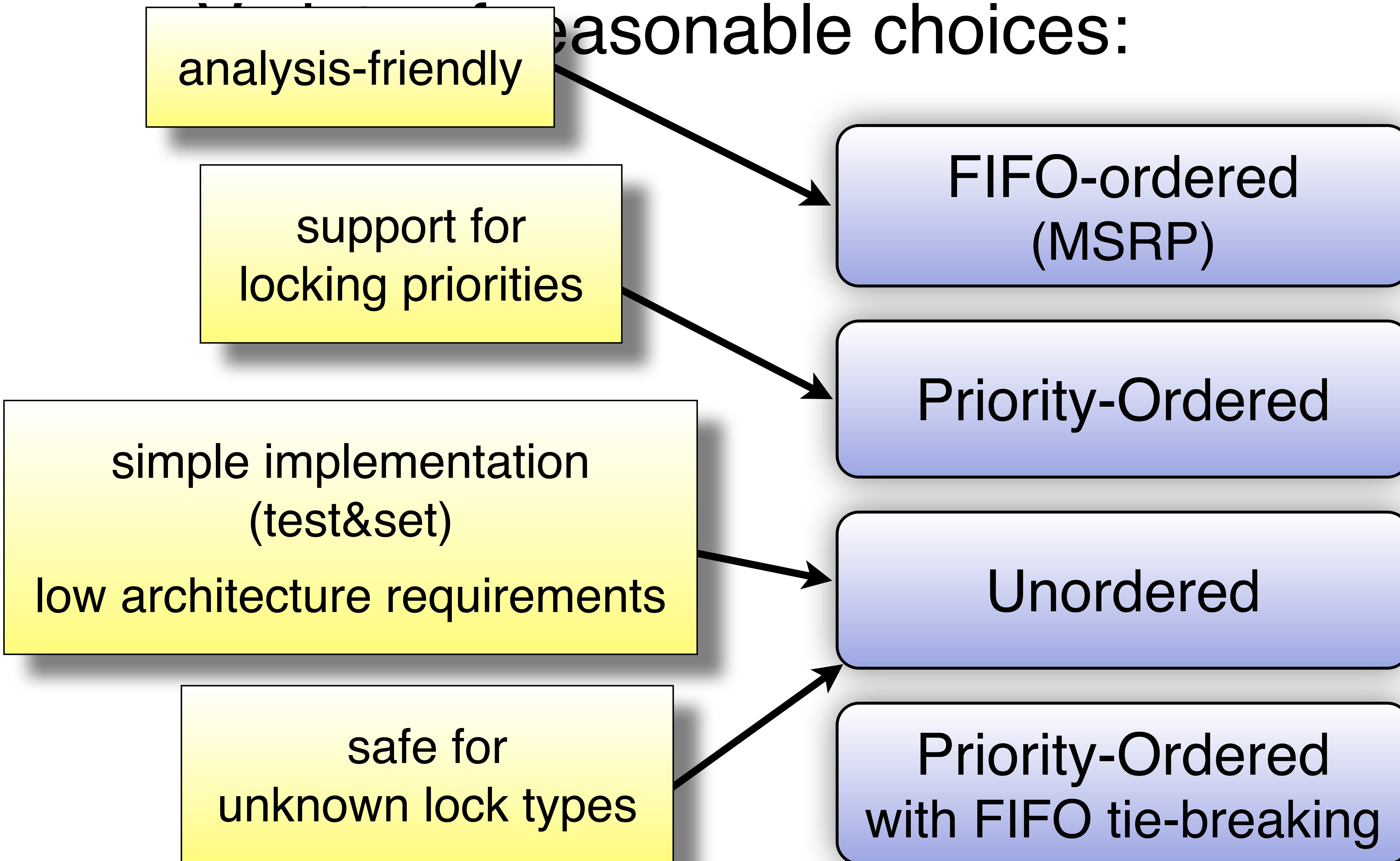

# Spin Lock Types

Variety of reasonable choices:

FIFO-ordered
SRP)

Non-Preemp
Spinning

**No blocking analysis**
available
for most types!

Ordered

dered

Preemptable
Spinning

Priority-Ordered
with FIFO tie-breaking

# Contributions

Blocking analysis
for **8 types** of
spin locks

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7/8 spin lock types:
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Asymptotically **less pessimistic** than prior approaches

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7/8 spin lock types:
**first blocking analysis**

Asymptotically
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**Suggest AUTOSAR API changes**
based on evaluation results

# Novel Spin Lock Analysis

Key Technique:

Blocking Analysis
modeled as
**Integer Linear Program** (ILP)

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Blocking Analysis
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Worst-case blocking bounds
determined by ILP solver

# Challenges

Prior analysis is **pessimistic due to inflation**.

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# Task Model

- sporadic tasks: $T_i : \ (e_i, d_i, p_i)$
- constrained deadlines: $d_i \leq p_i$
- partitioned fixed-priority scheduling

# Basic Spin Lock Analysis

Spin locks **busy-wait** while waiting for contended resource.

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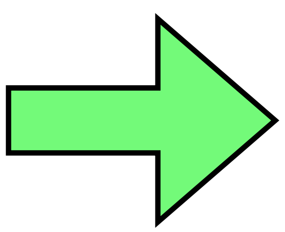

Straight-forward analysis approach:

- treat spin-time as execution time
- apply response-time analysis

# FIFO-Ordered Spin Locks

## Multiprocessor Stack Resource Policy (MSRP) [1]

[1] P. Gai, G. Lipari, and M. Di Natale, “Minimizing memory utilization of real-time task sets in single and multi-processor systems-on-a-chip,” in RTSS’01. IEEE, 2001.

# FIFO-Ordered Spin Locks

## Multiprocessor Stack Resource Policy (MSRP) [1]

The MSRP uses
**non-preemptable**
**FIFO-ordered spin locks**
for resources shared across processors.

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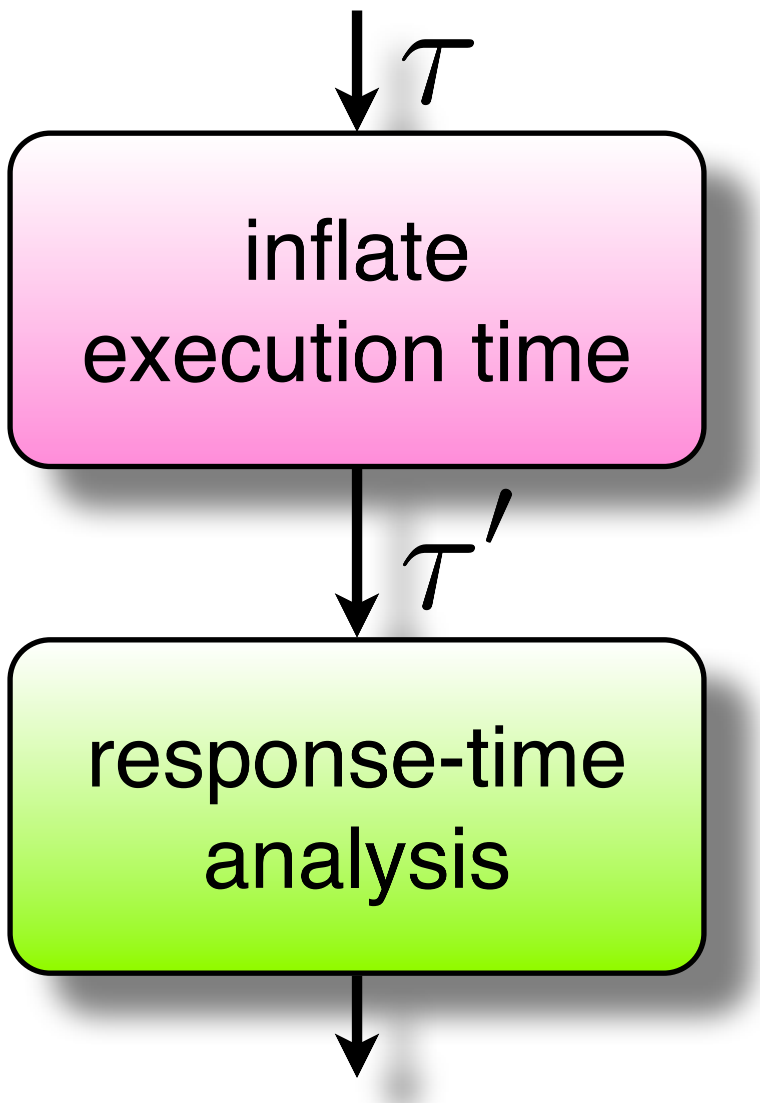
# FIFO-Ordered Spin Locks

classic MSRP analysis



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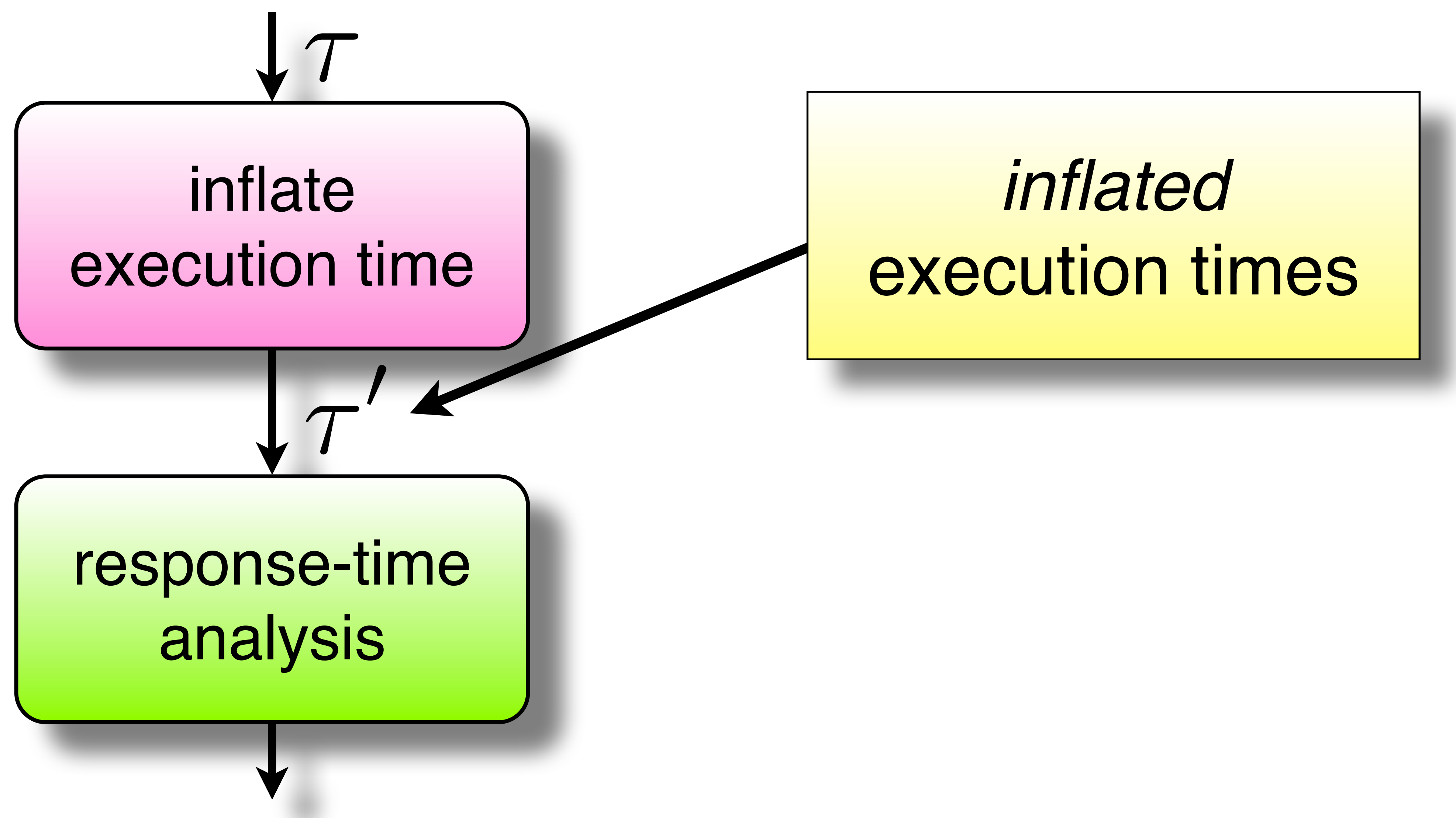

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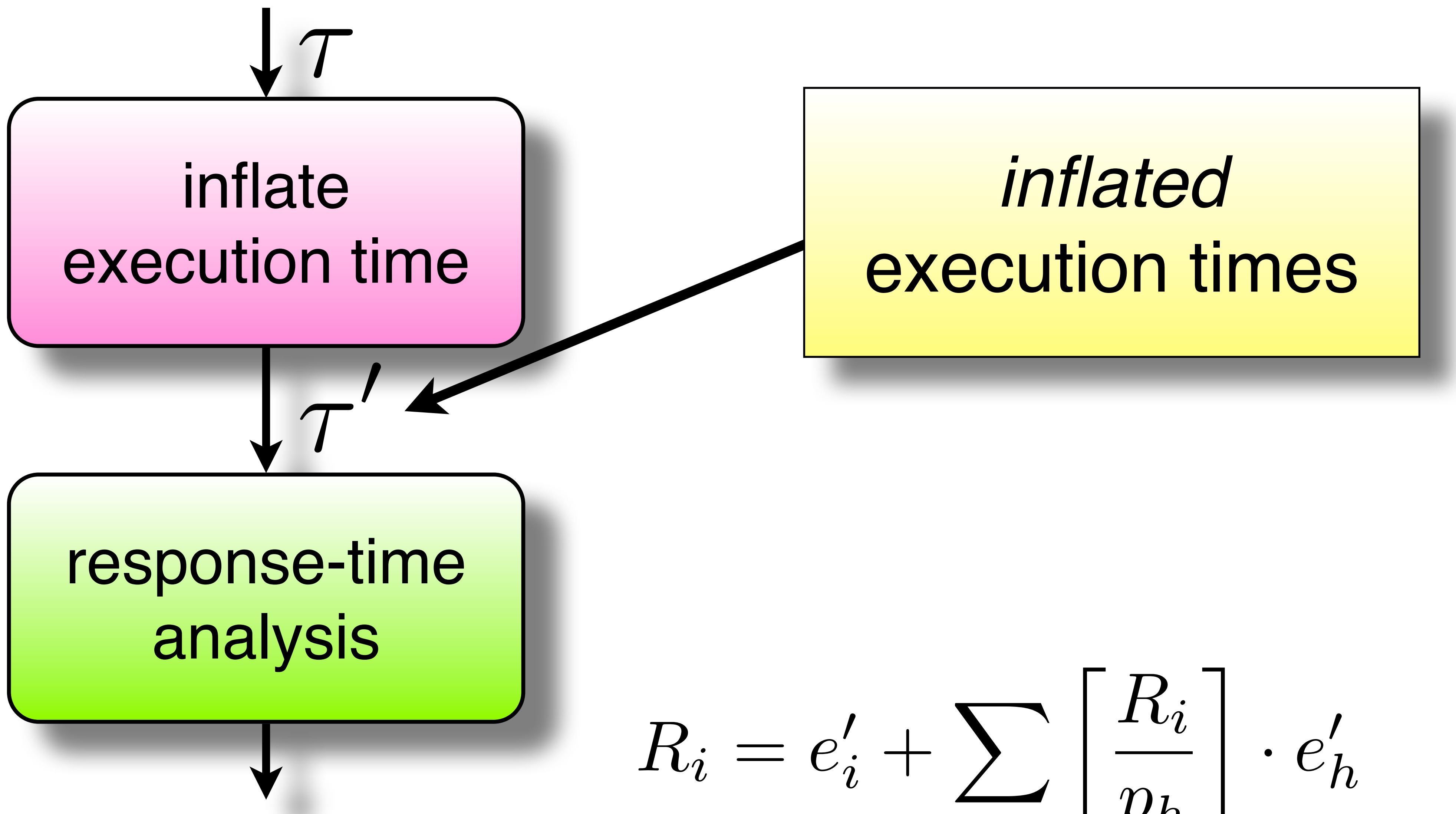


$$R_i = e'_i + \sum_{h<i} \left\lceil \frac{R_i}{p_h} \right\rceil \cdot e'_h$$

# FIFO-Ordered Spin Locks

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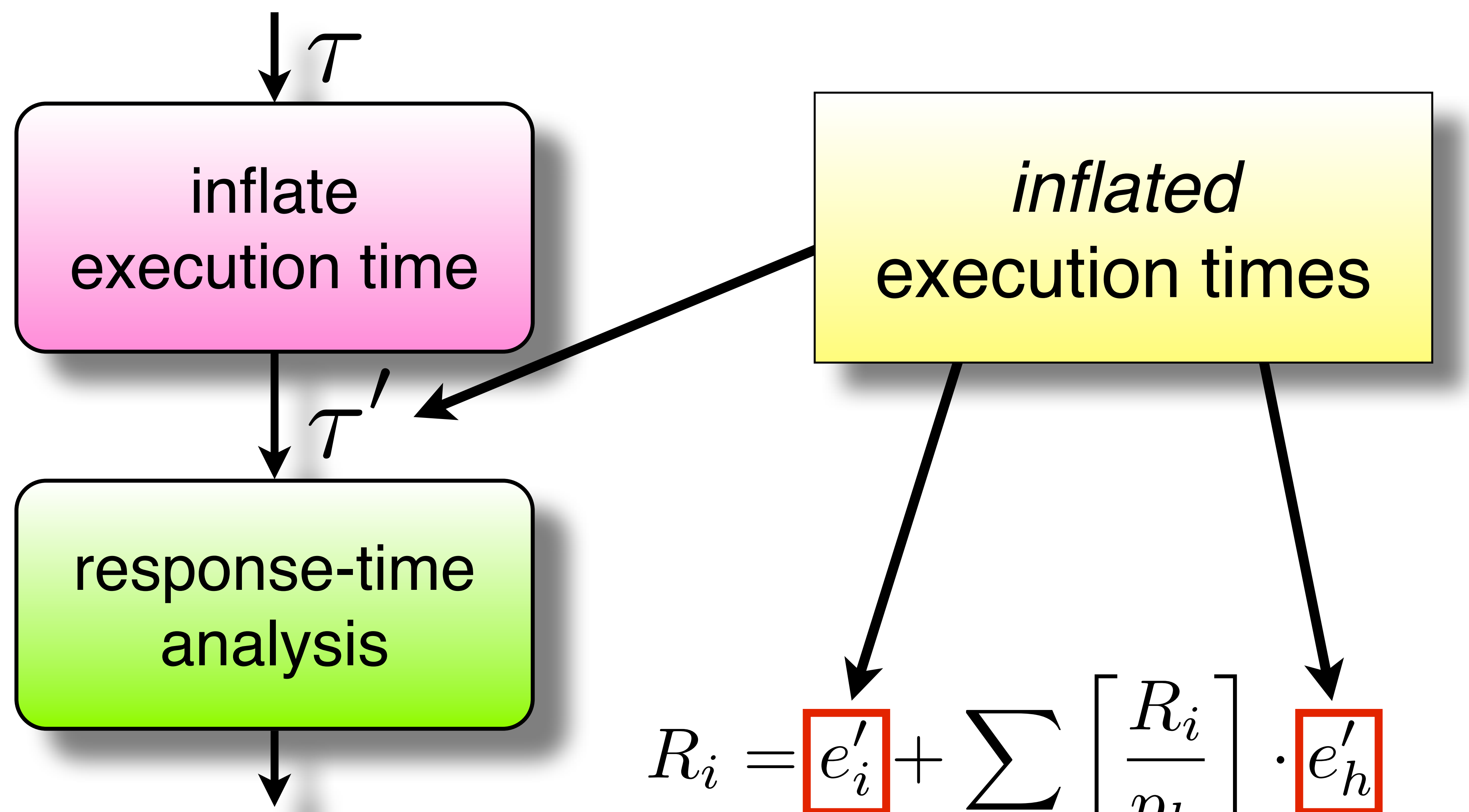
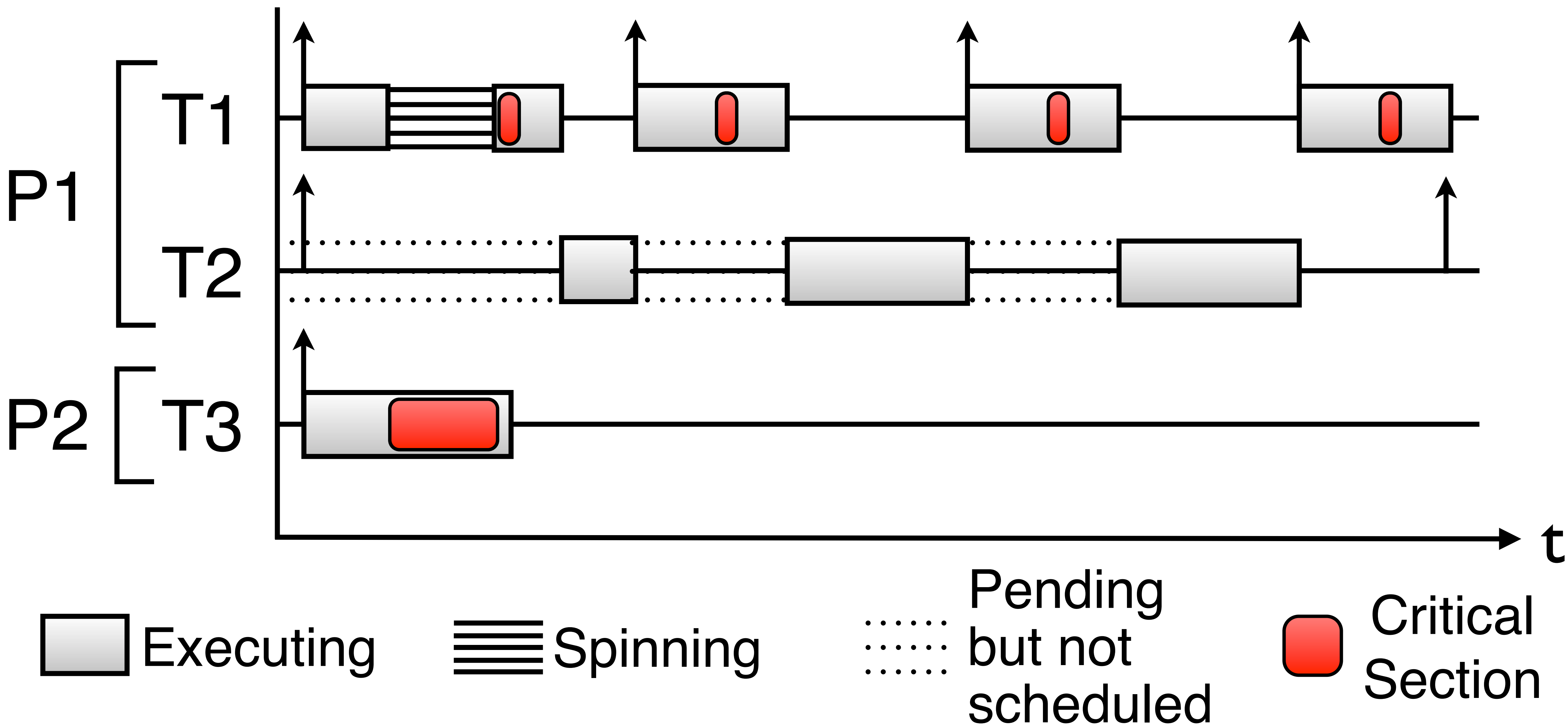



$$R_i = \boxed{e_i'} + \sum_{h<i} \left\lceil \frac{R_i}{p_h} \right\rceil \cdot \boxed{e_h'}$$

# Execution-Time Inflation in Classic MSRP Analysis



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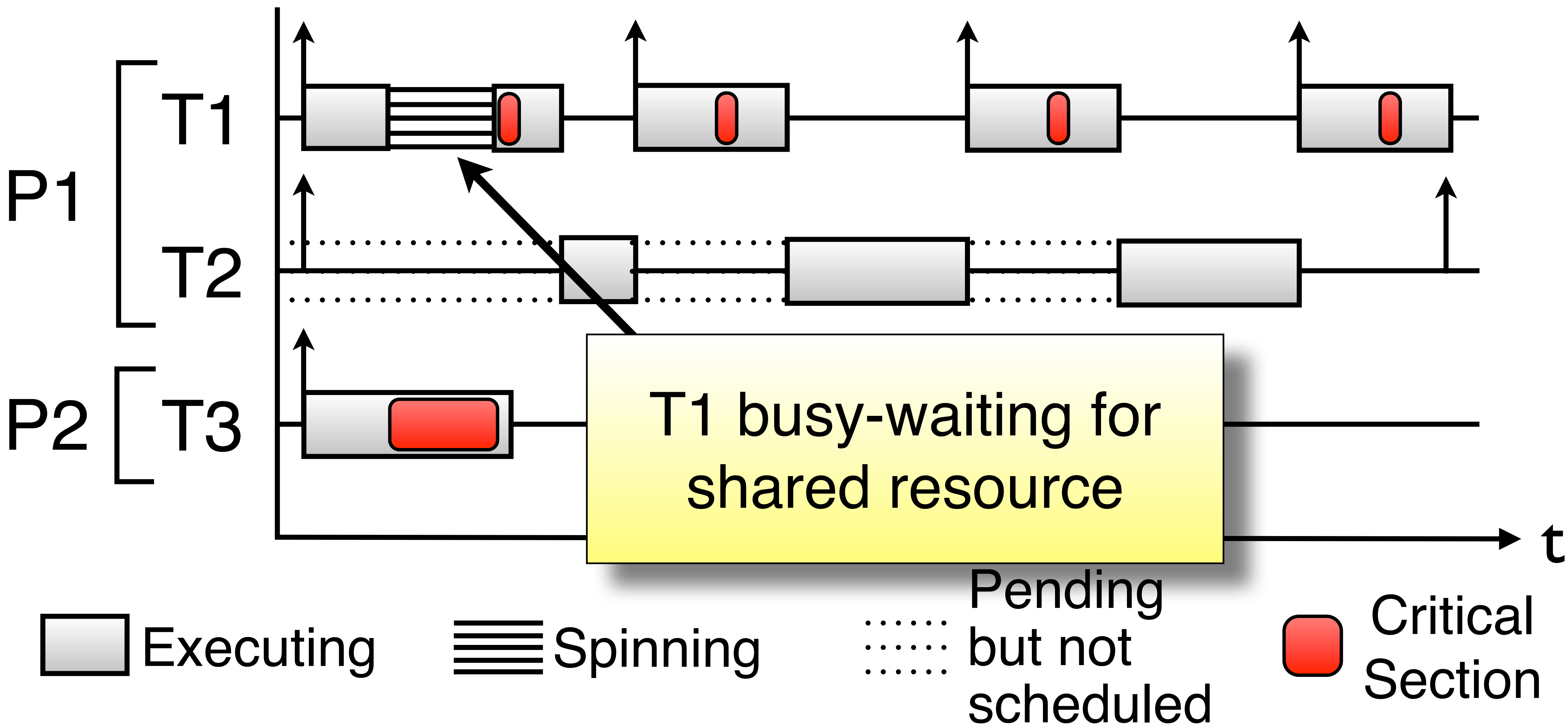

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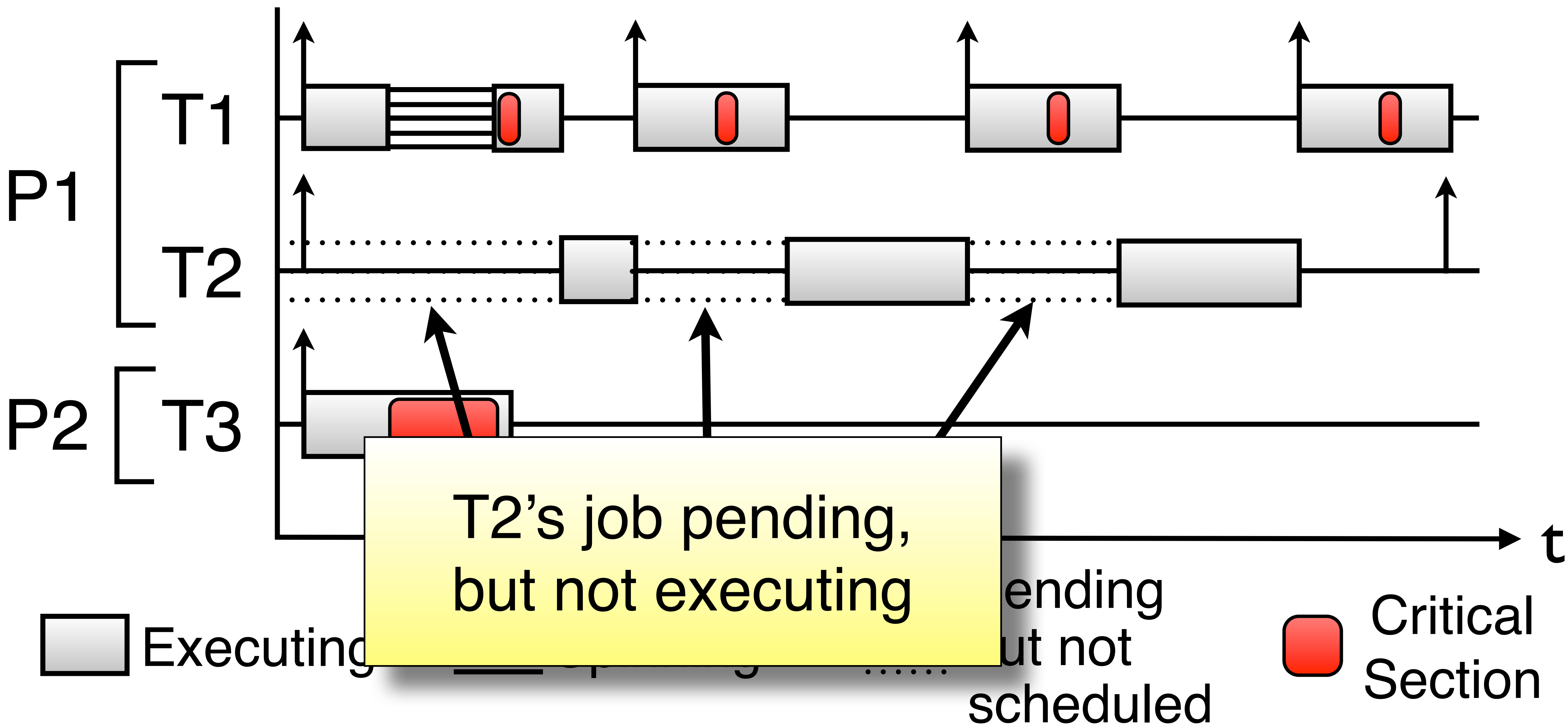

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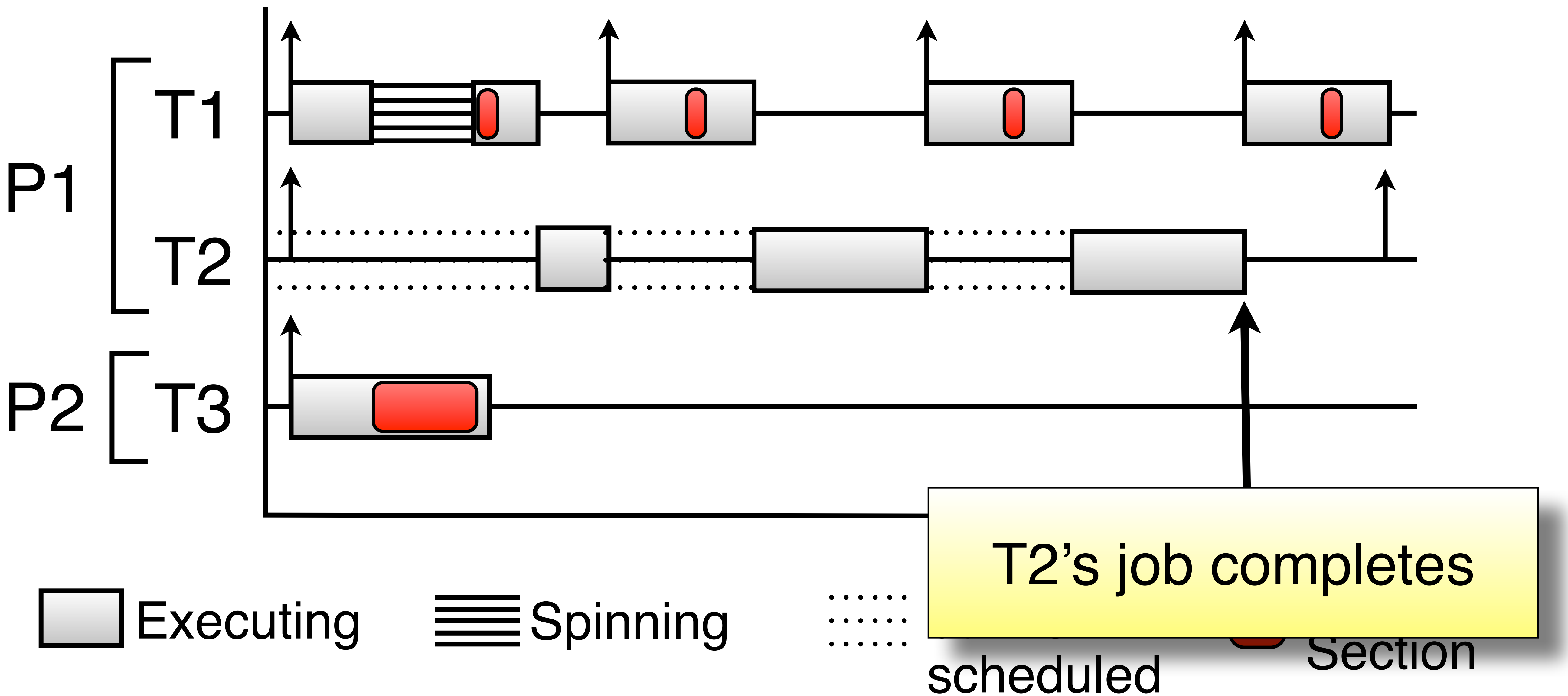

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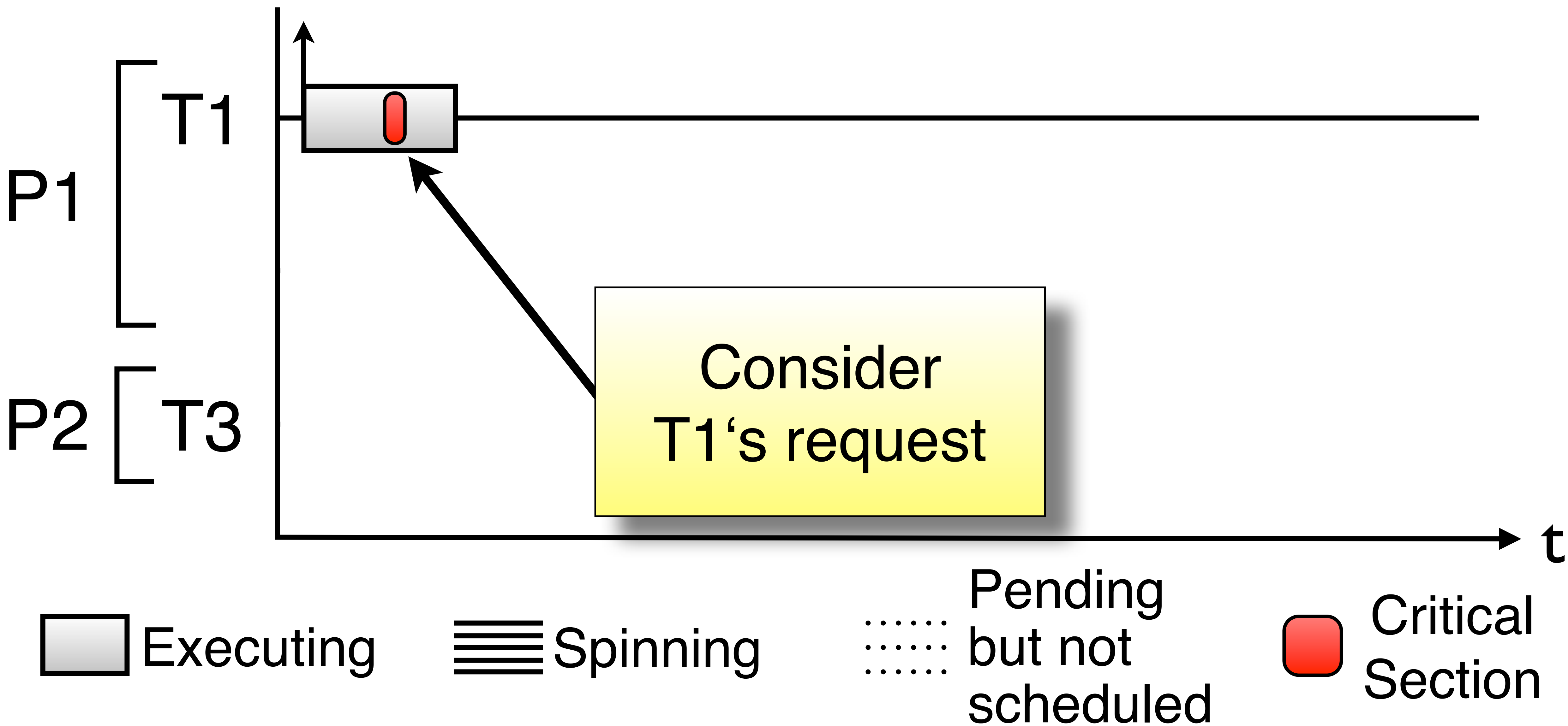

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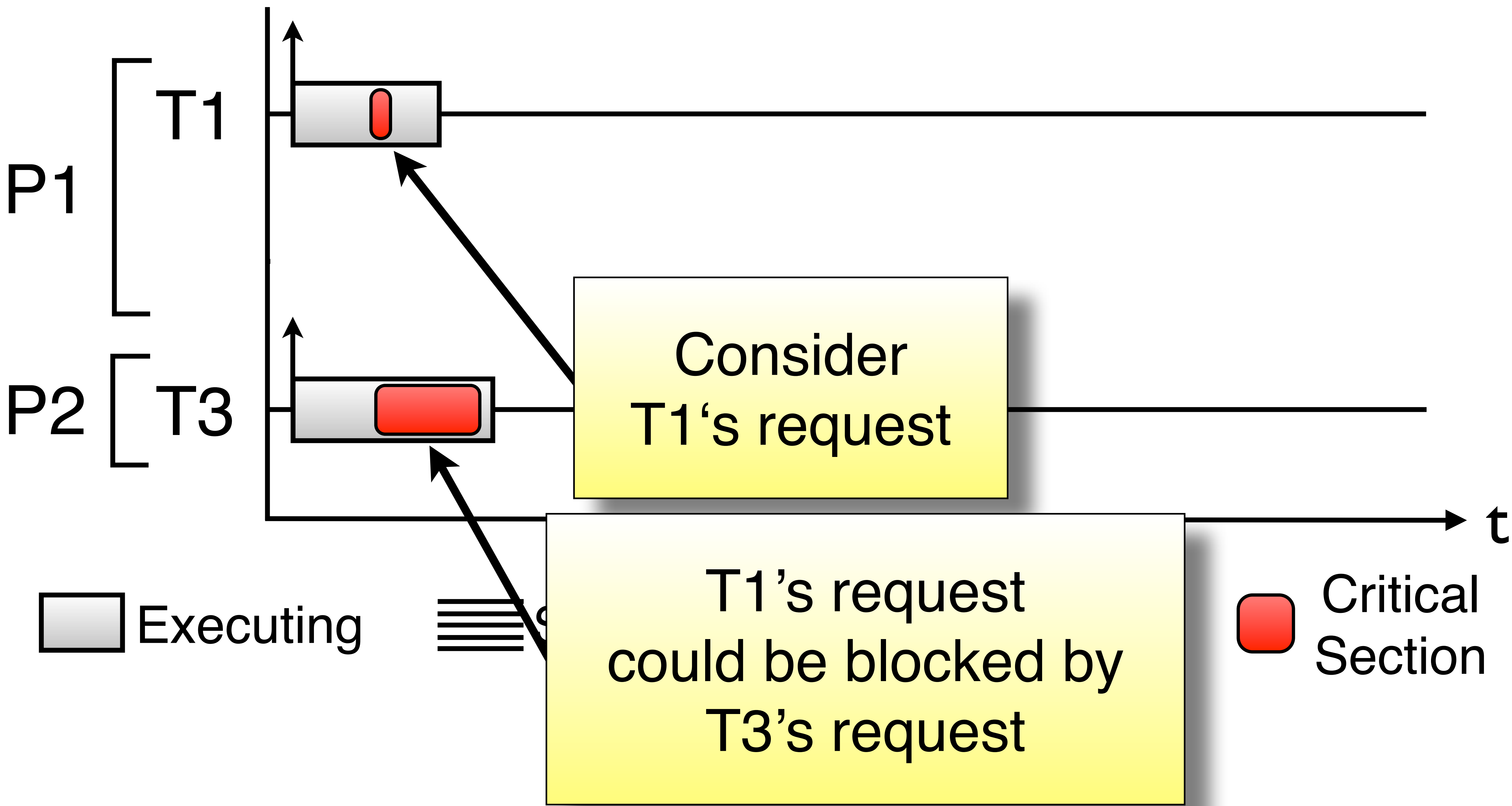

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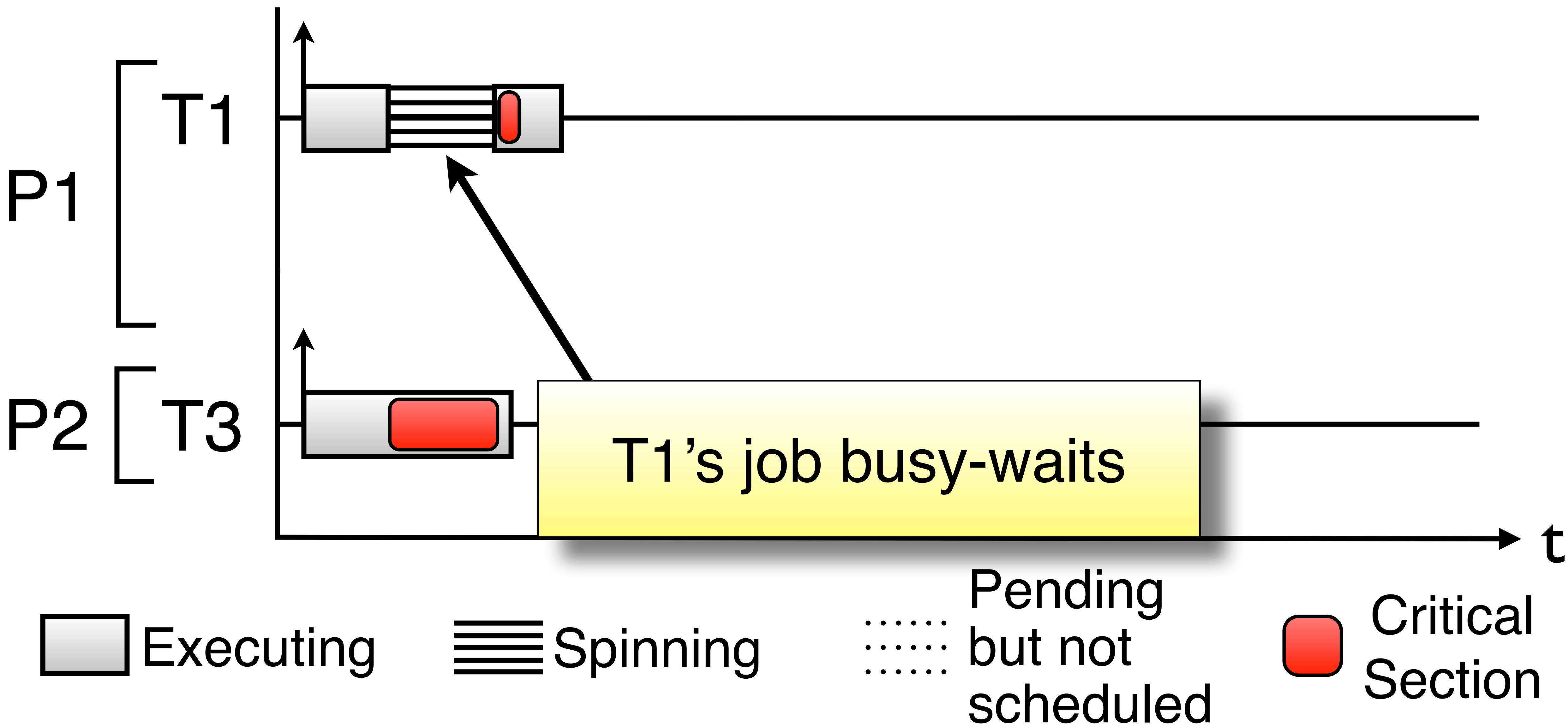

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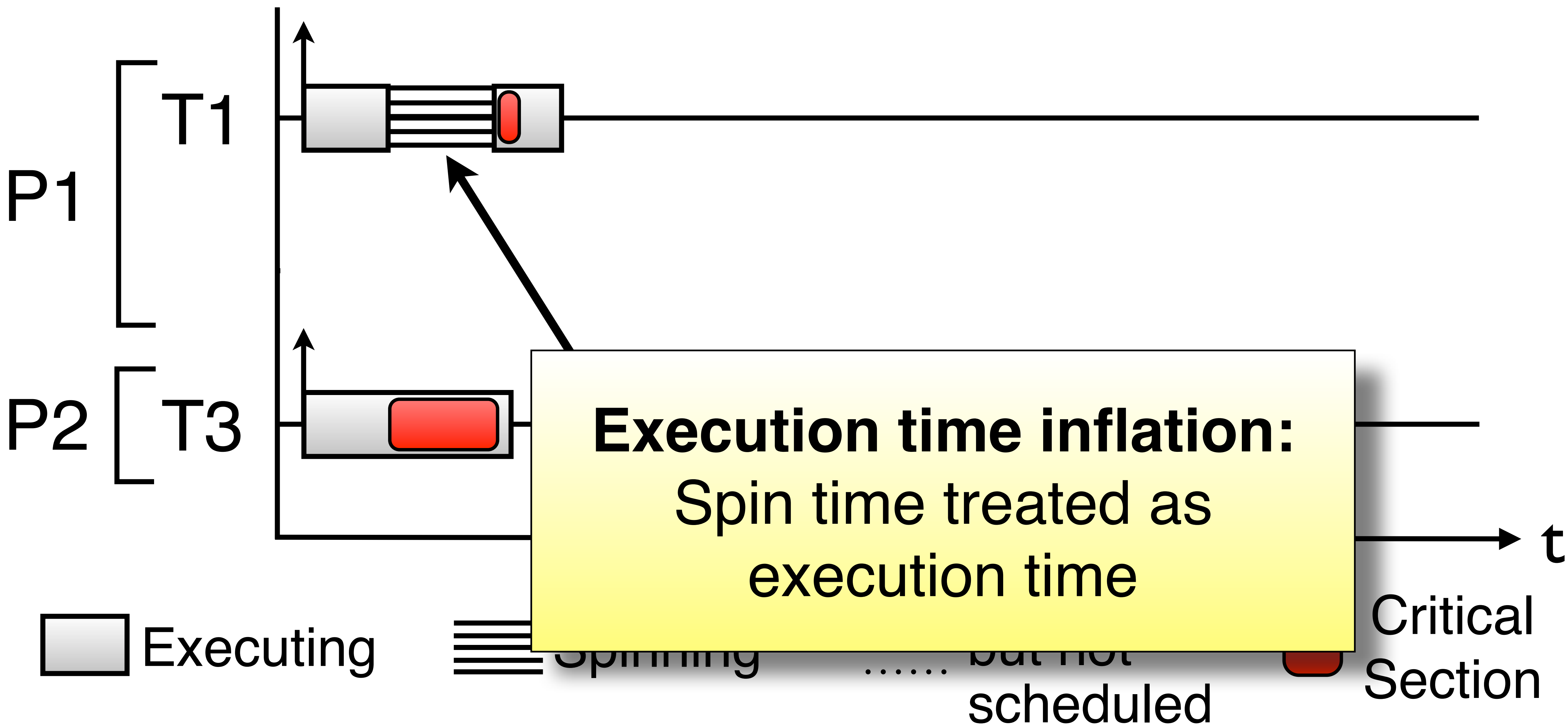

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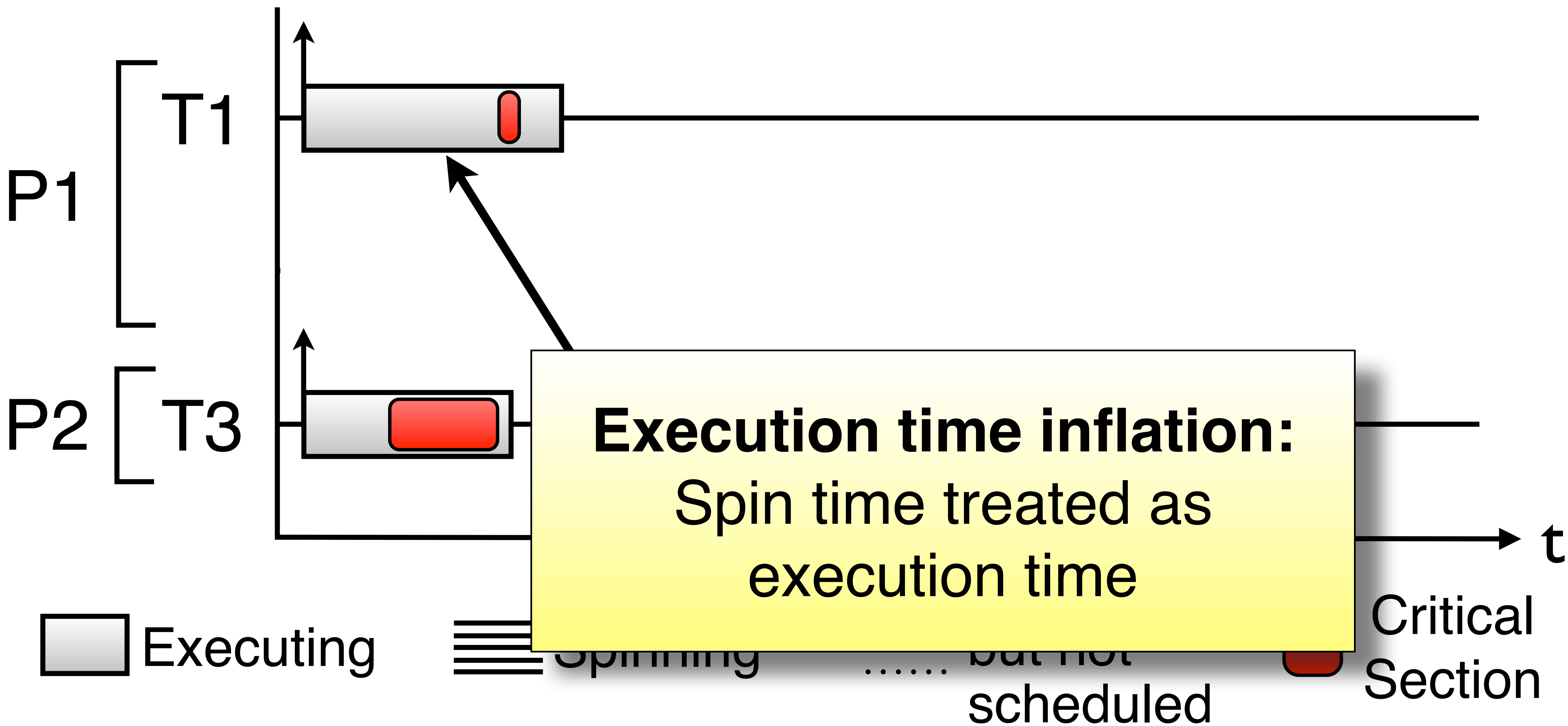

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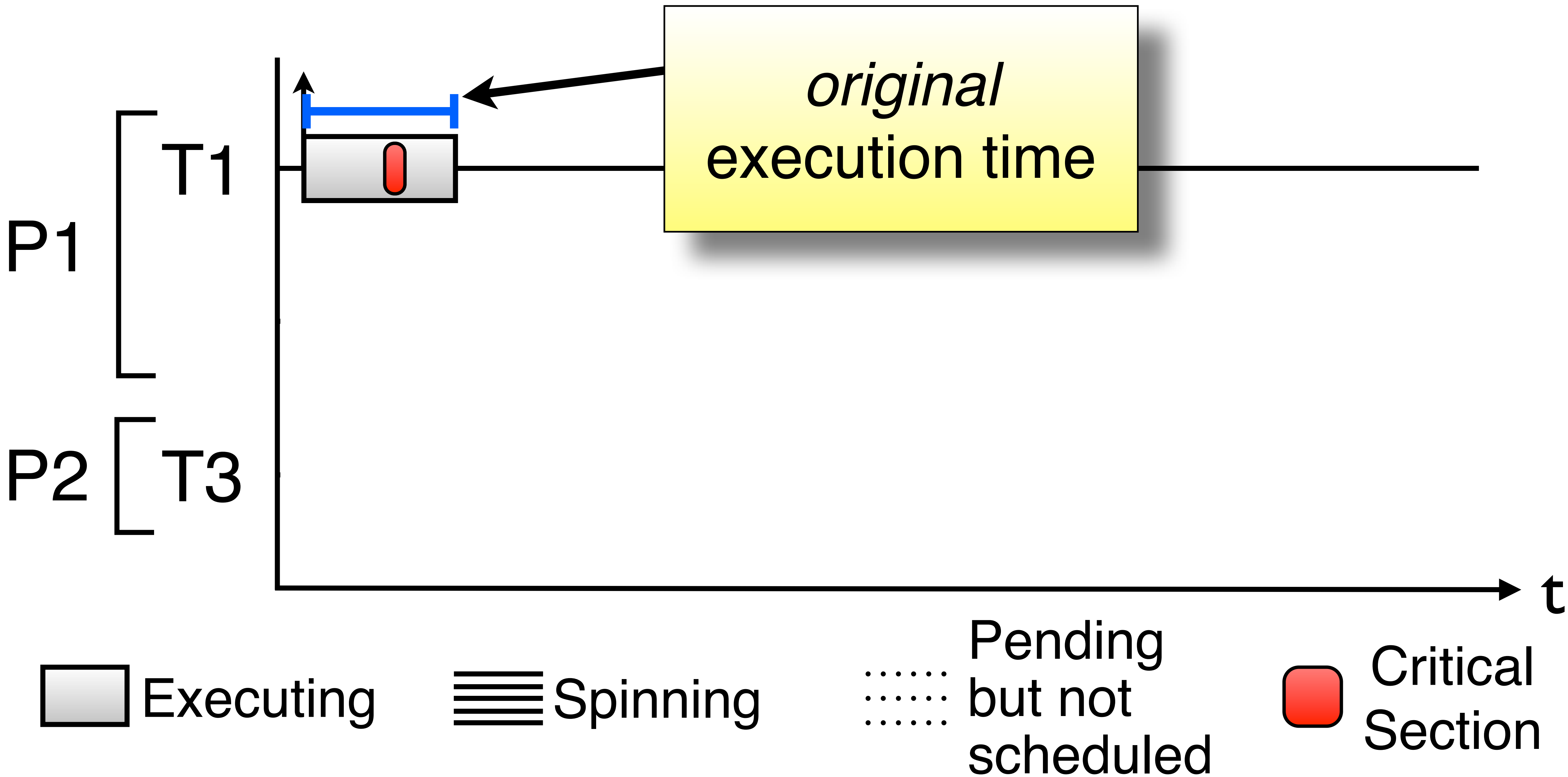

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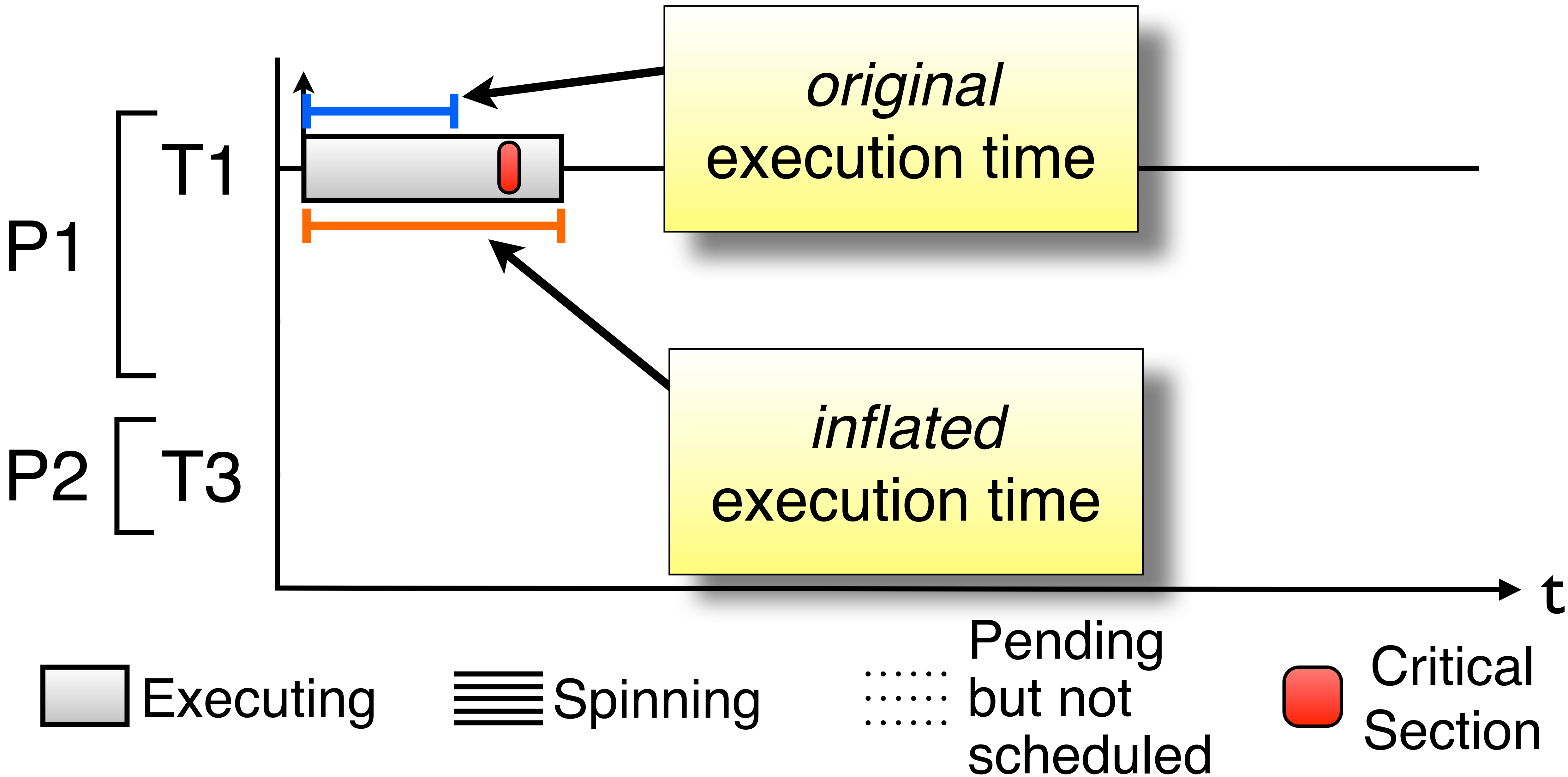

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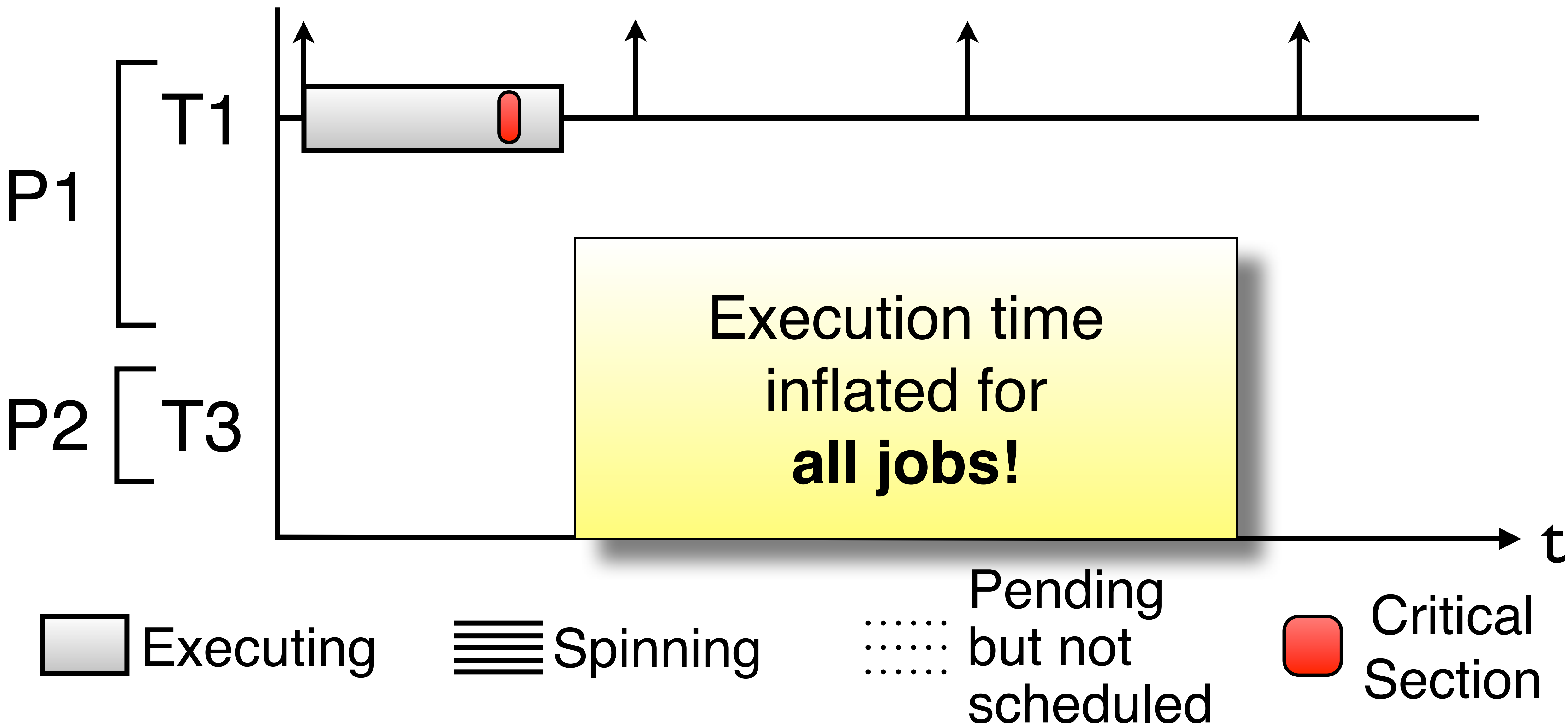

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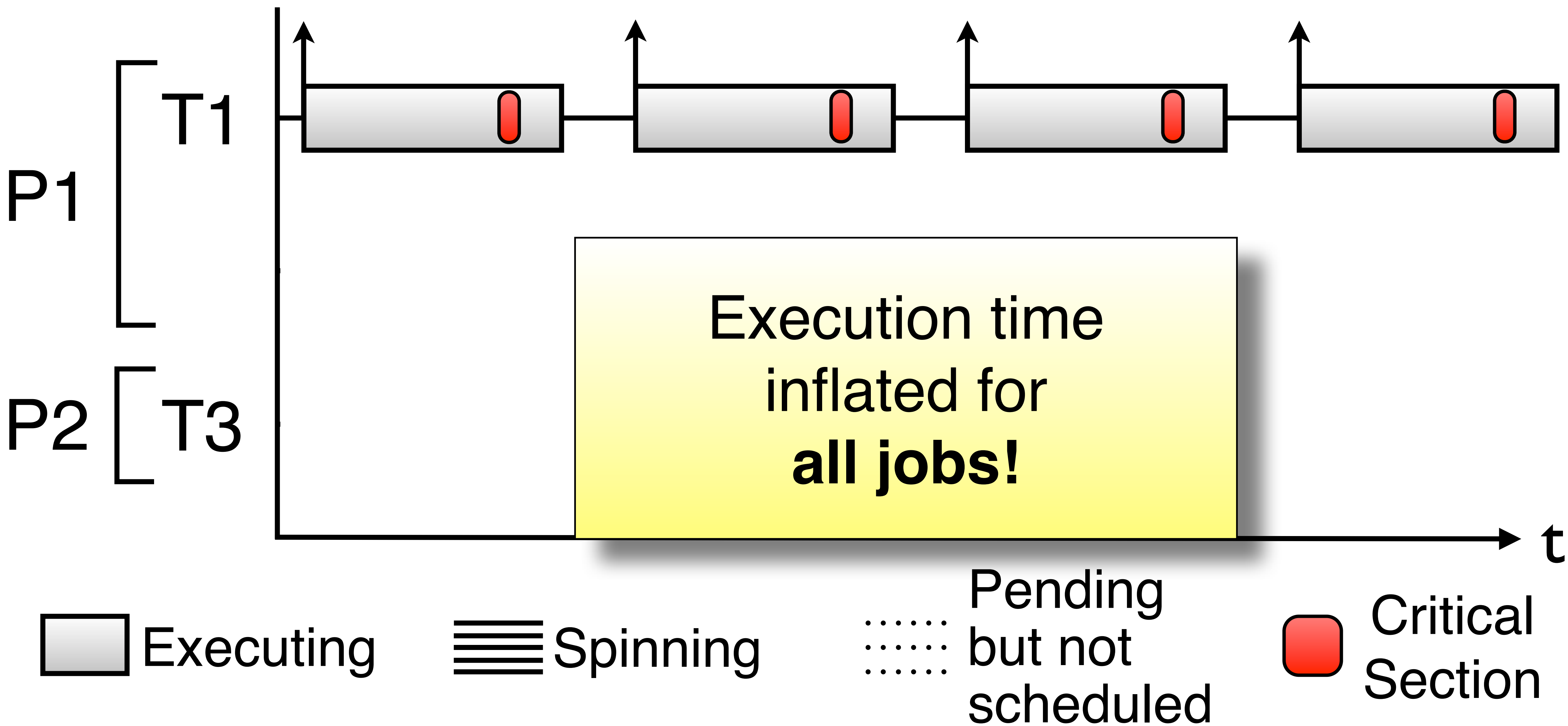
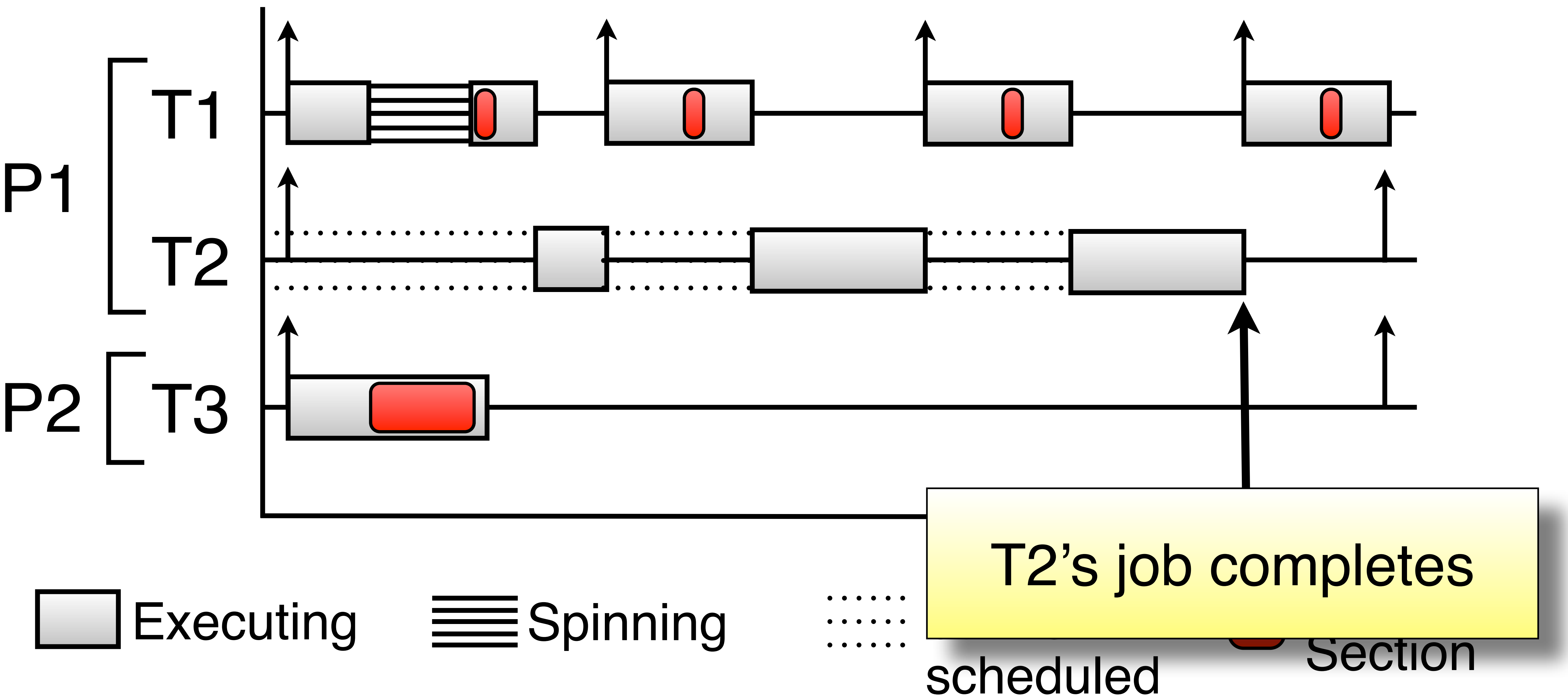
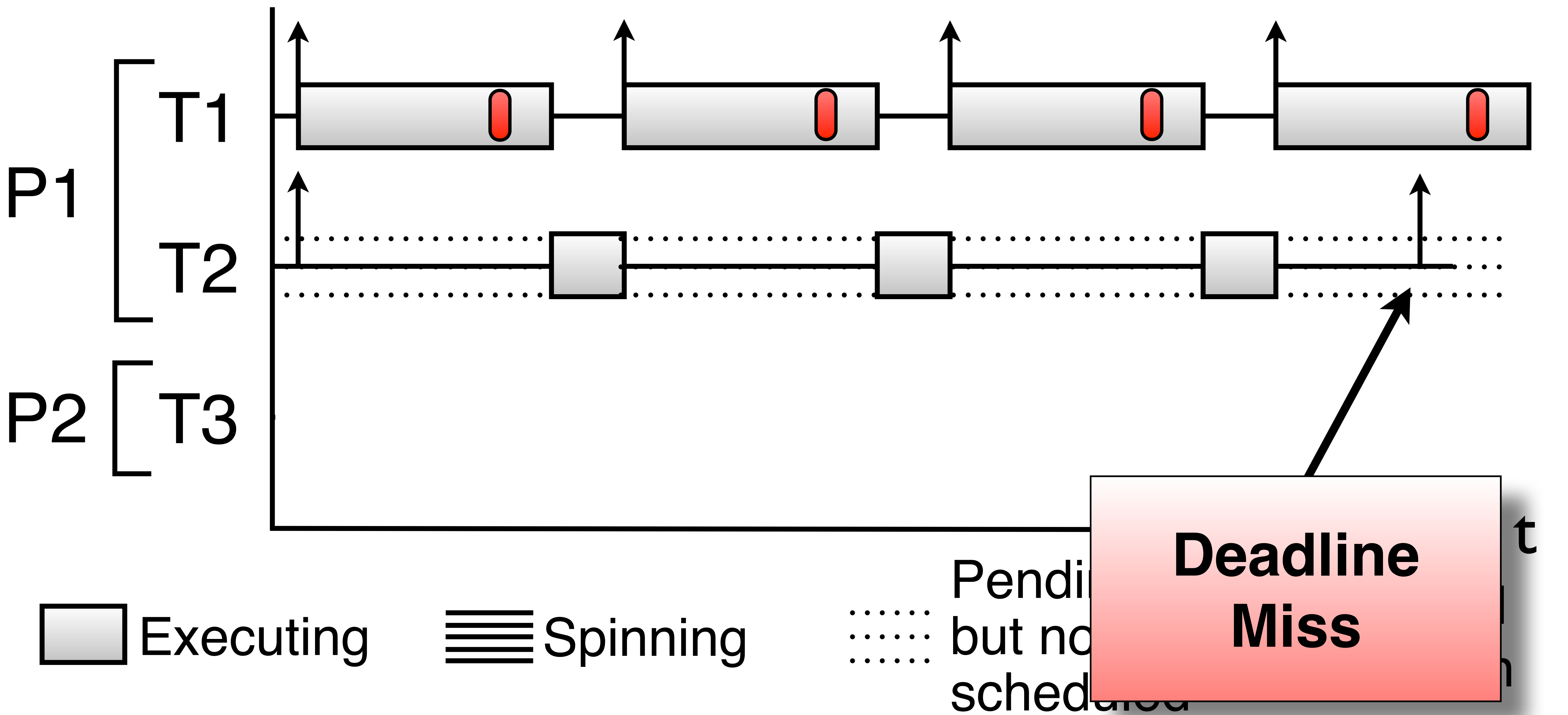


# Original Schedule



# Schedule with Inflated Execution Times



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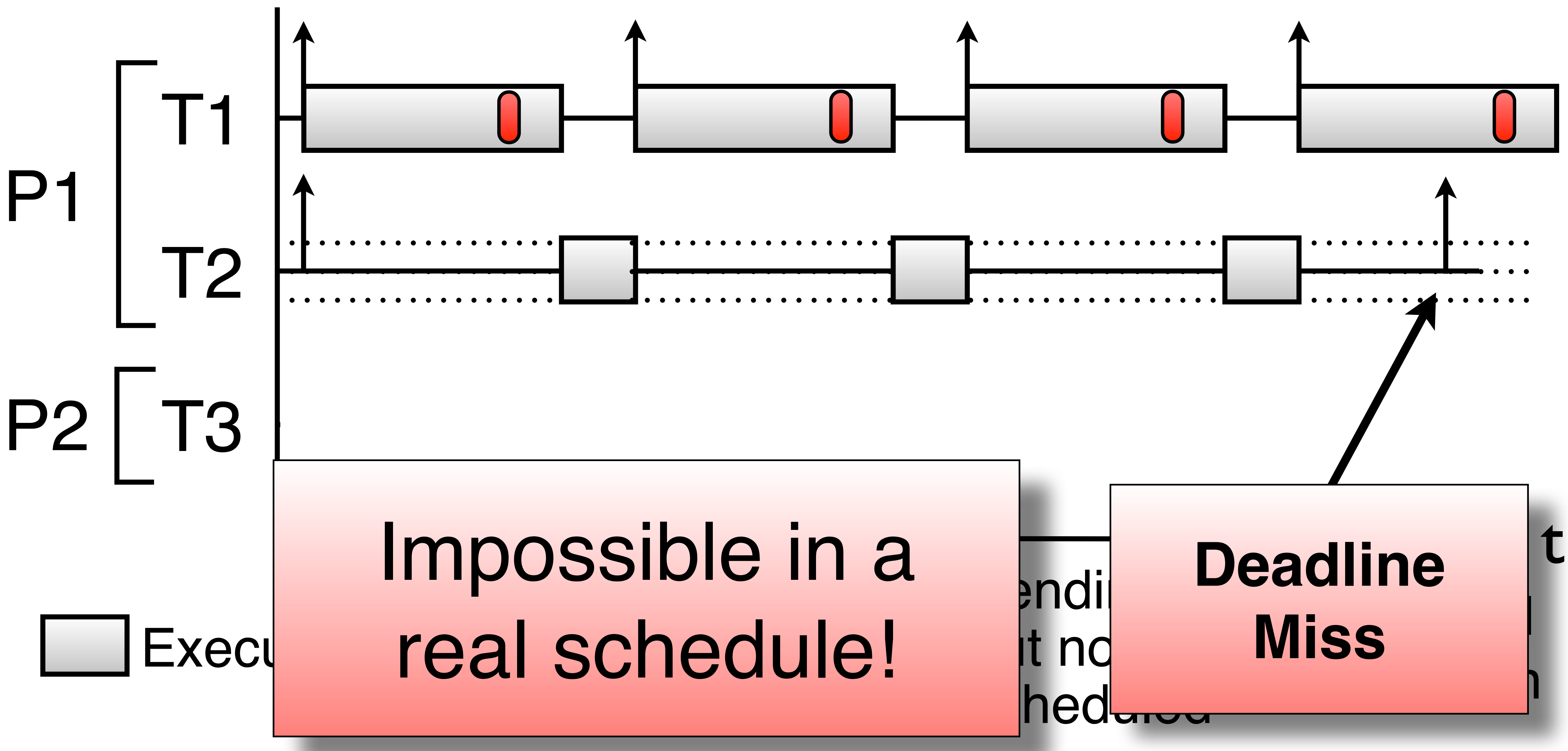

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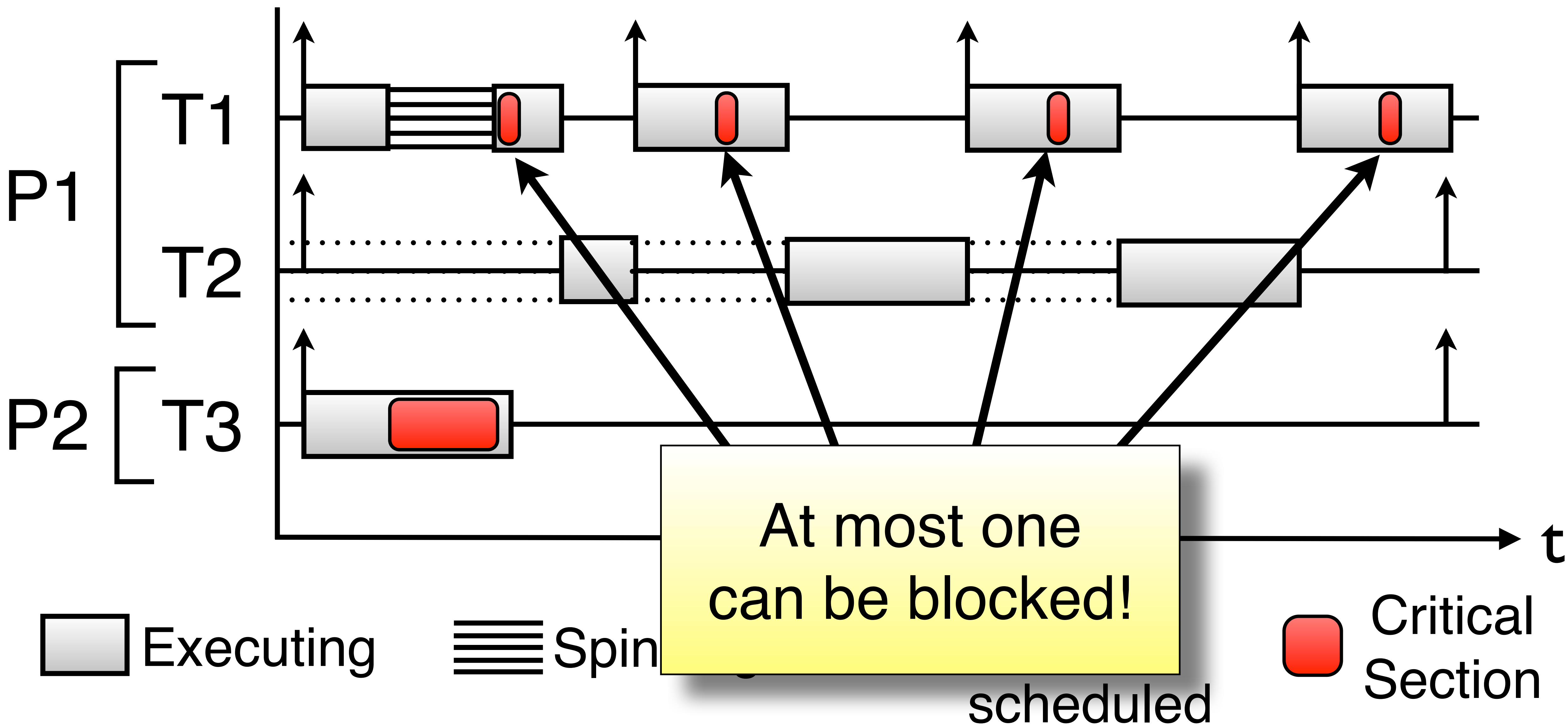

# Inflation is Inherently Pessimistic

All prior analyses rely on execution time inflation!

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We show that
**execution time inflation**
is an
**inherent source of pessimism**
in blocking analysis.

# Inflation is Inherently Pessimistic

**Theorem**

Any blocking analysis relying on the inflation of job execution costs can be pessimistic by a factor of $\Omega(\phi \cdot n)$.

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maximal ratio of shortest and longest task period

number of tasks

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**Theorem**

Any blocking analysis relying on the inflation of job execution costs can be pessimistic by a factor of $\Omega(\phi \cdot n)$.

Details and proof in paper

# Challenges

Prior analysis is
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**due to inflation**.

Prior analysis is **specific**
**to non-preemptable**
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ILP formulation
Explicit blocking terms

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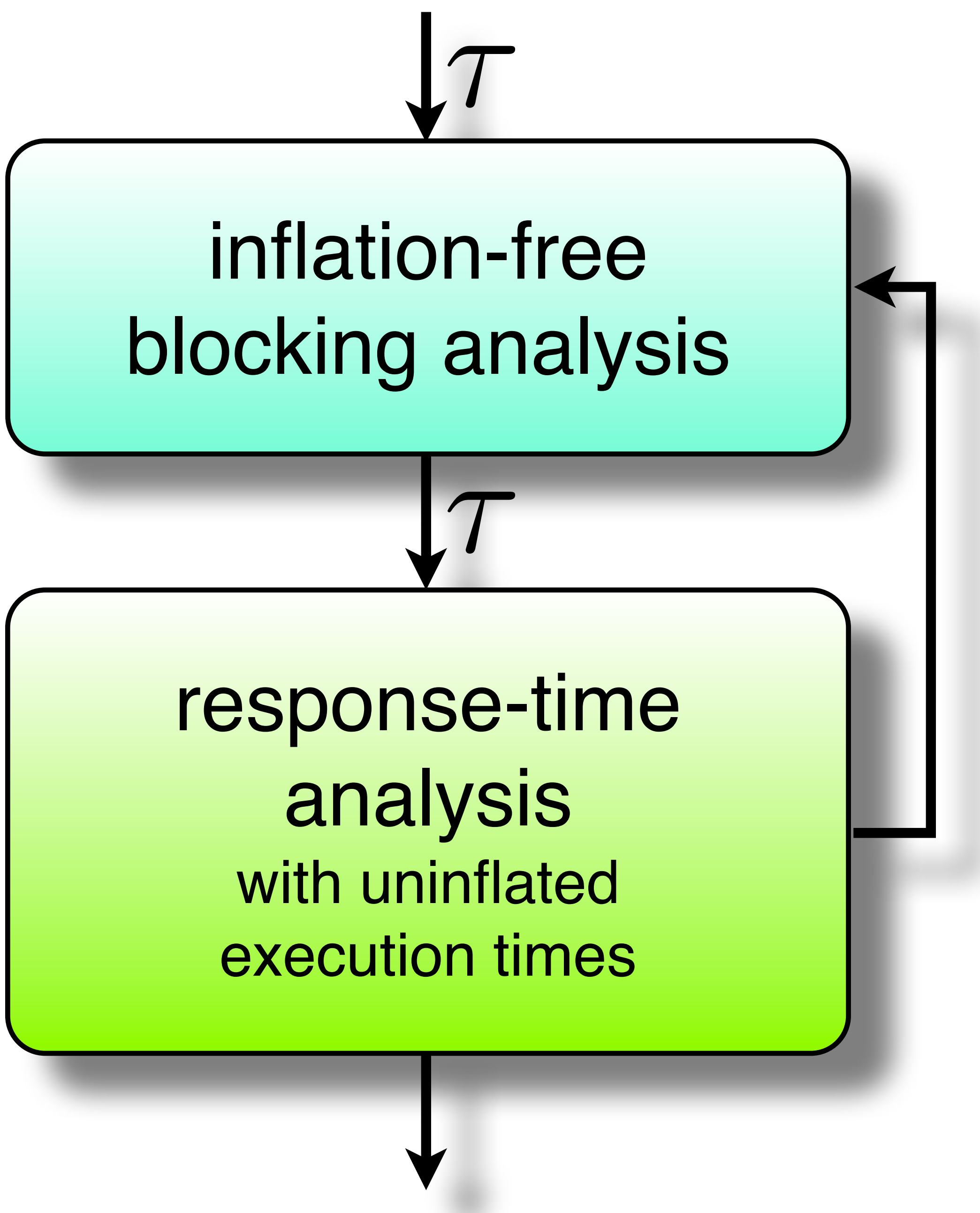

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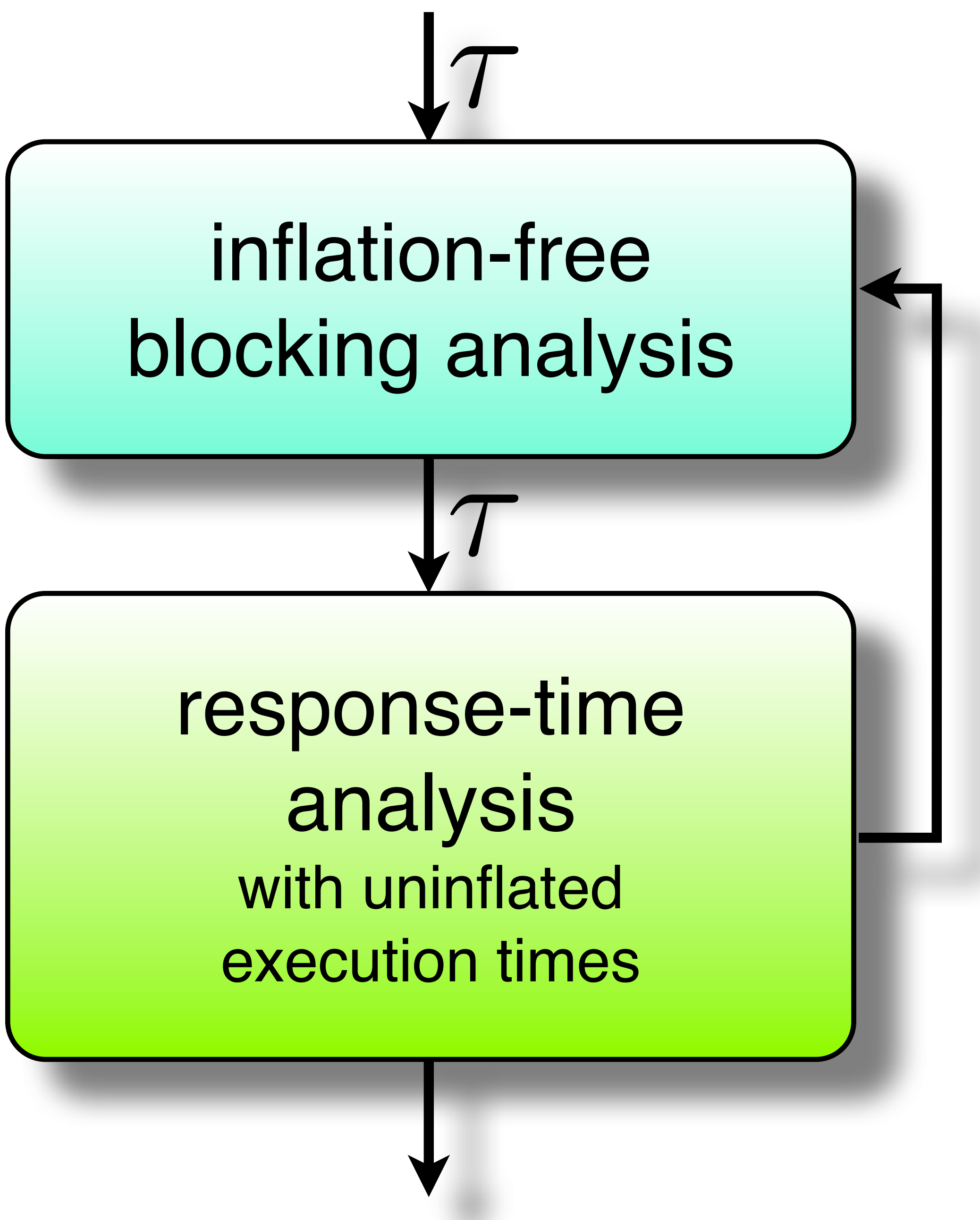
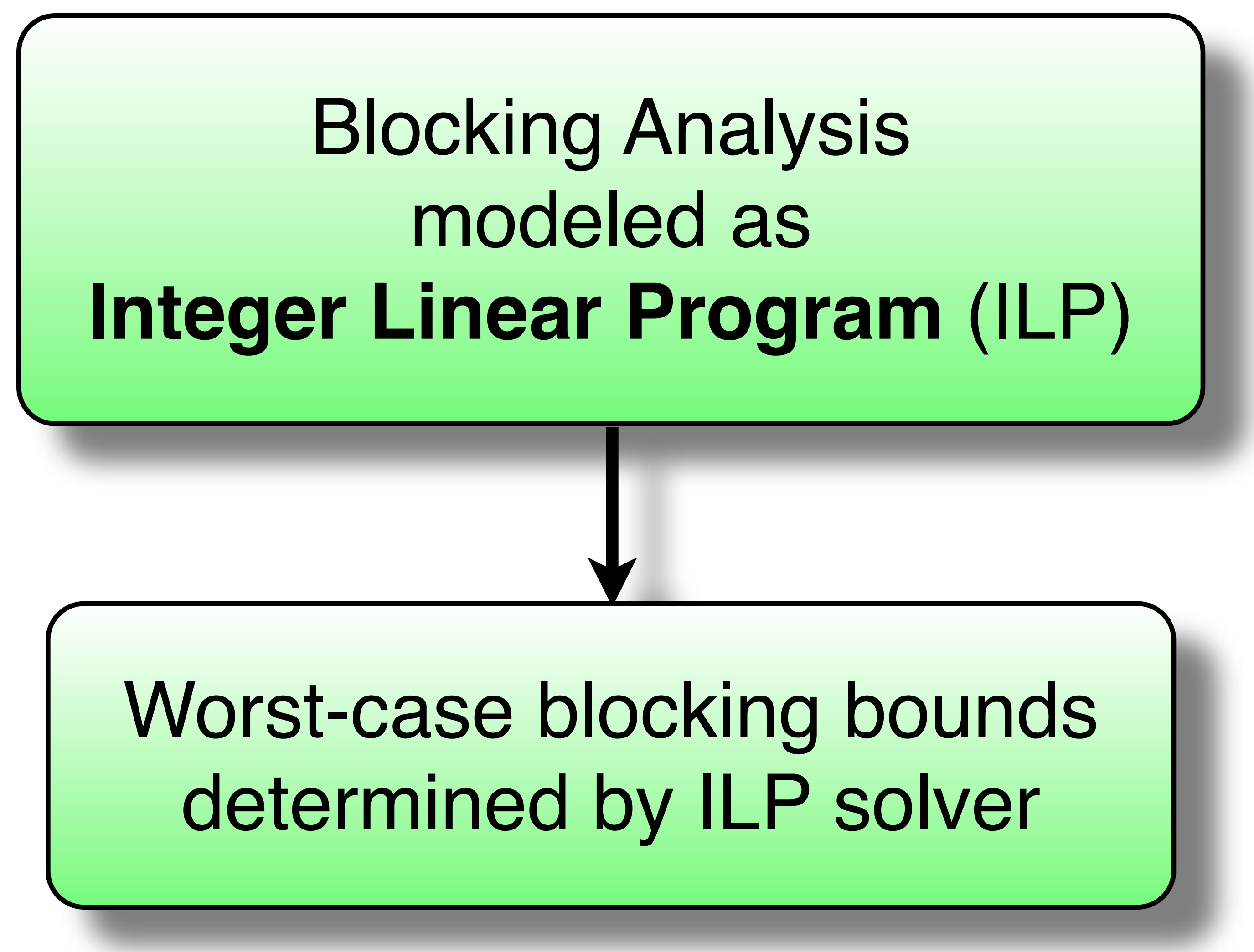
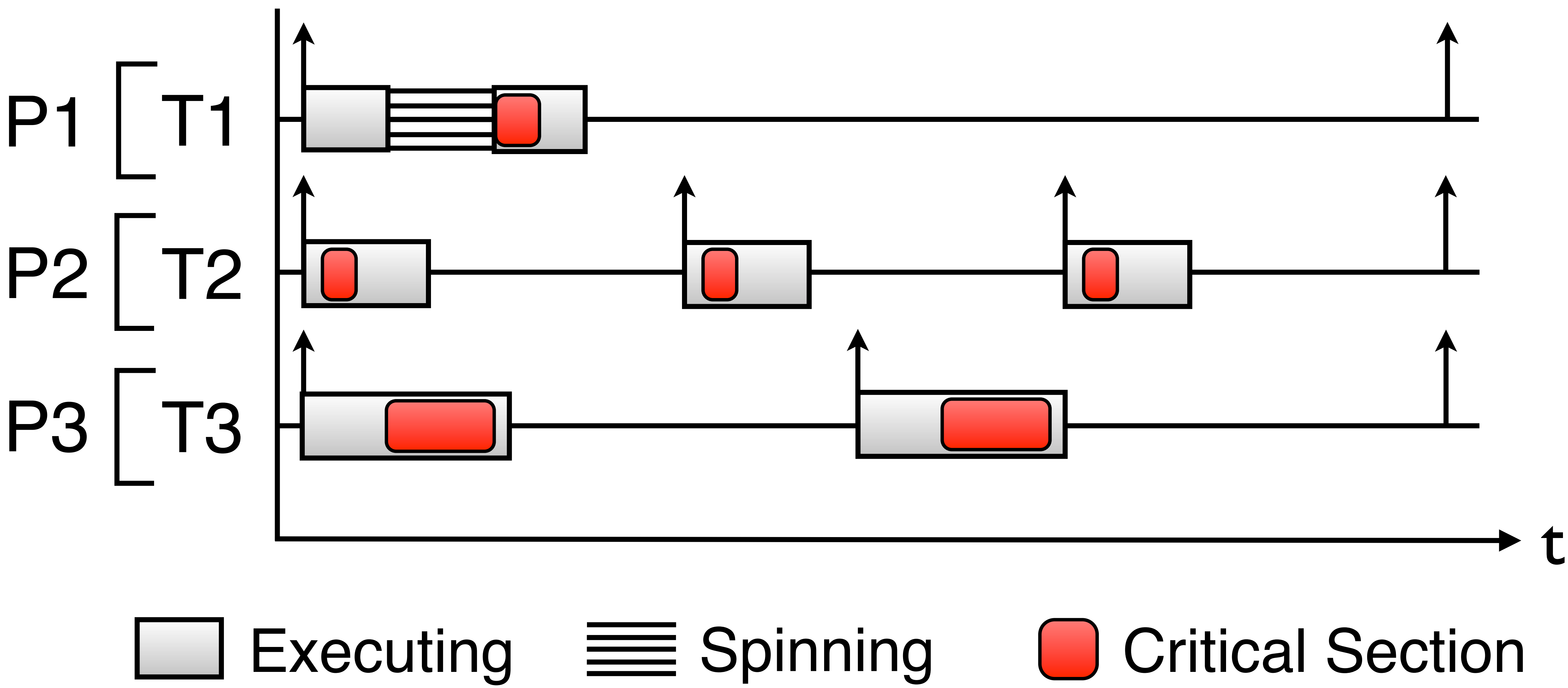



Key technique for inflation-free blocking analysis:



# ILP Generation for FIFO-Ordered Spin Locks



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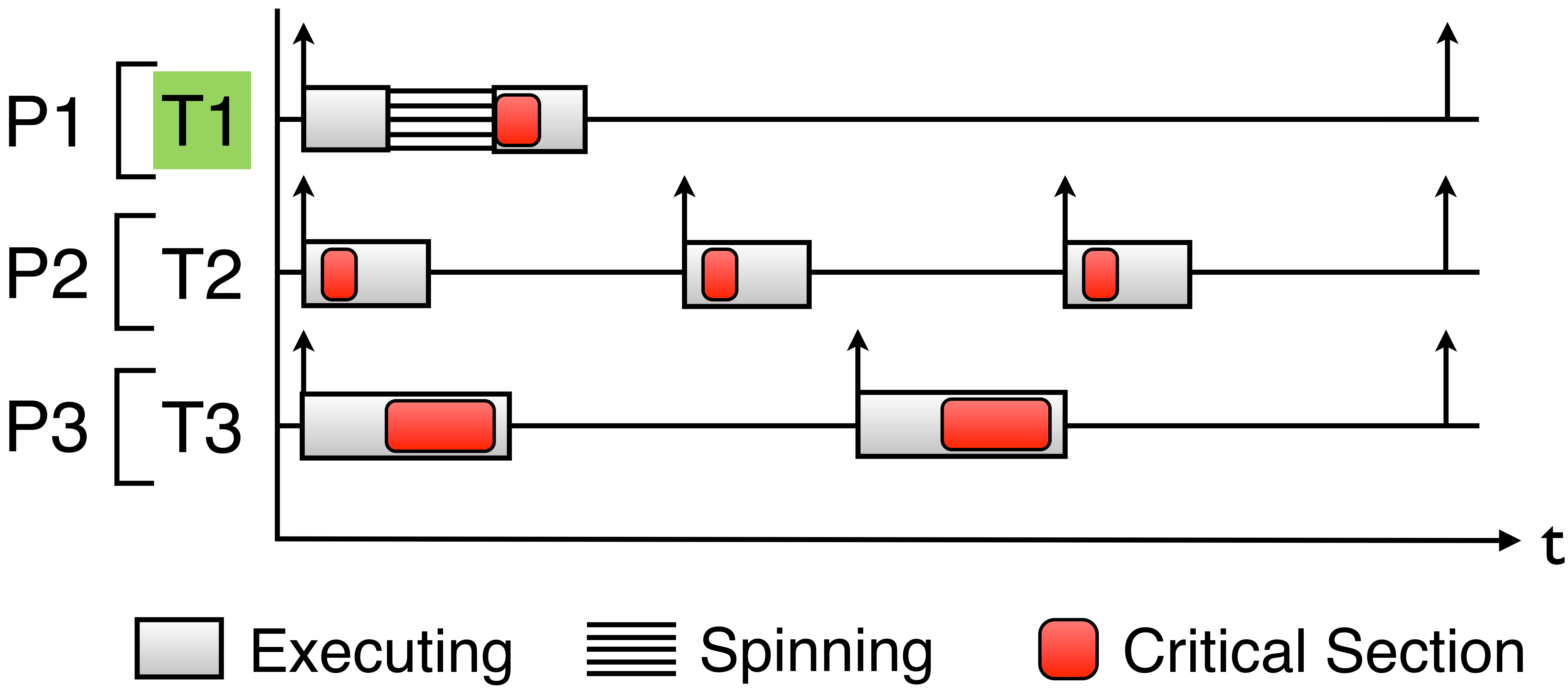
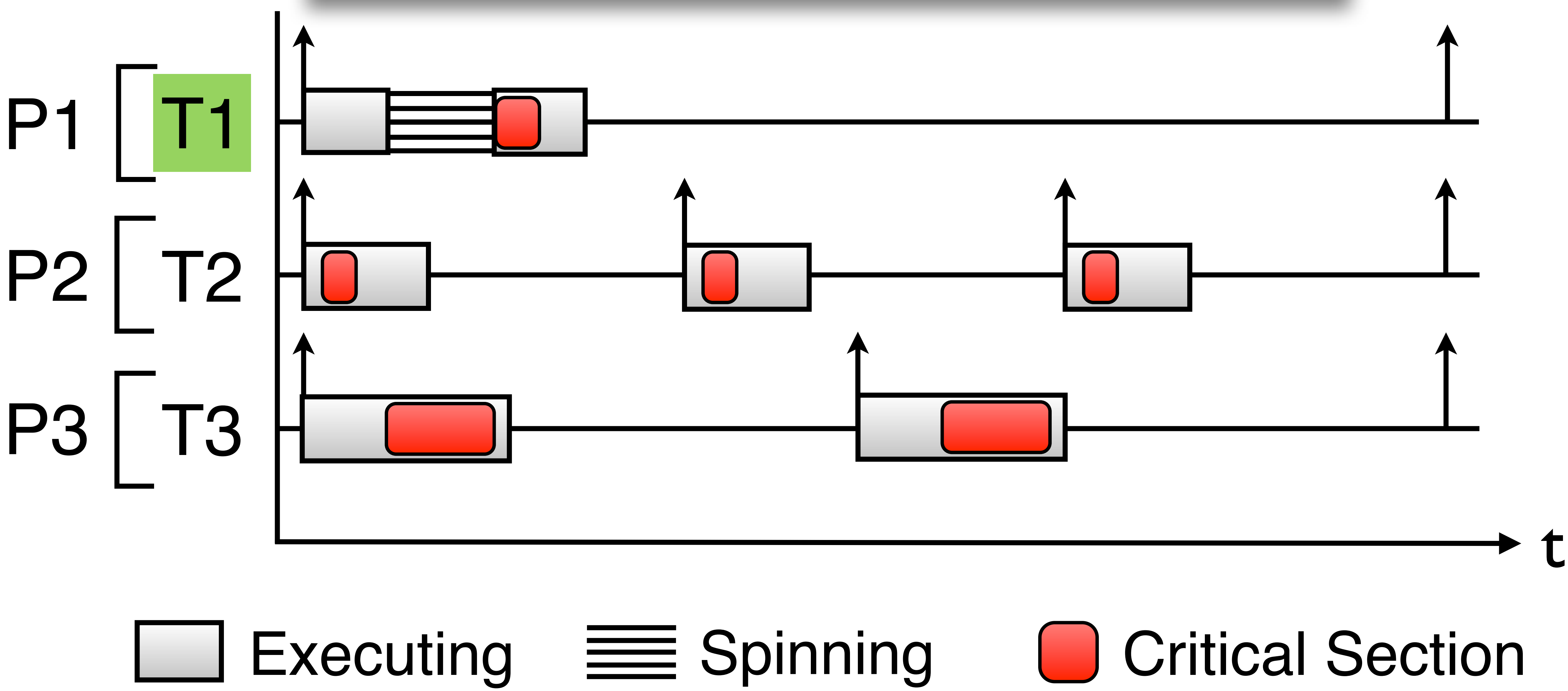


# ILP Generation for FIFO-Ordered Spin Locks

Assign *blocking variables*:



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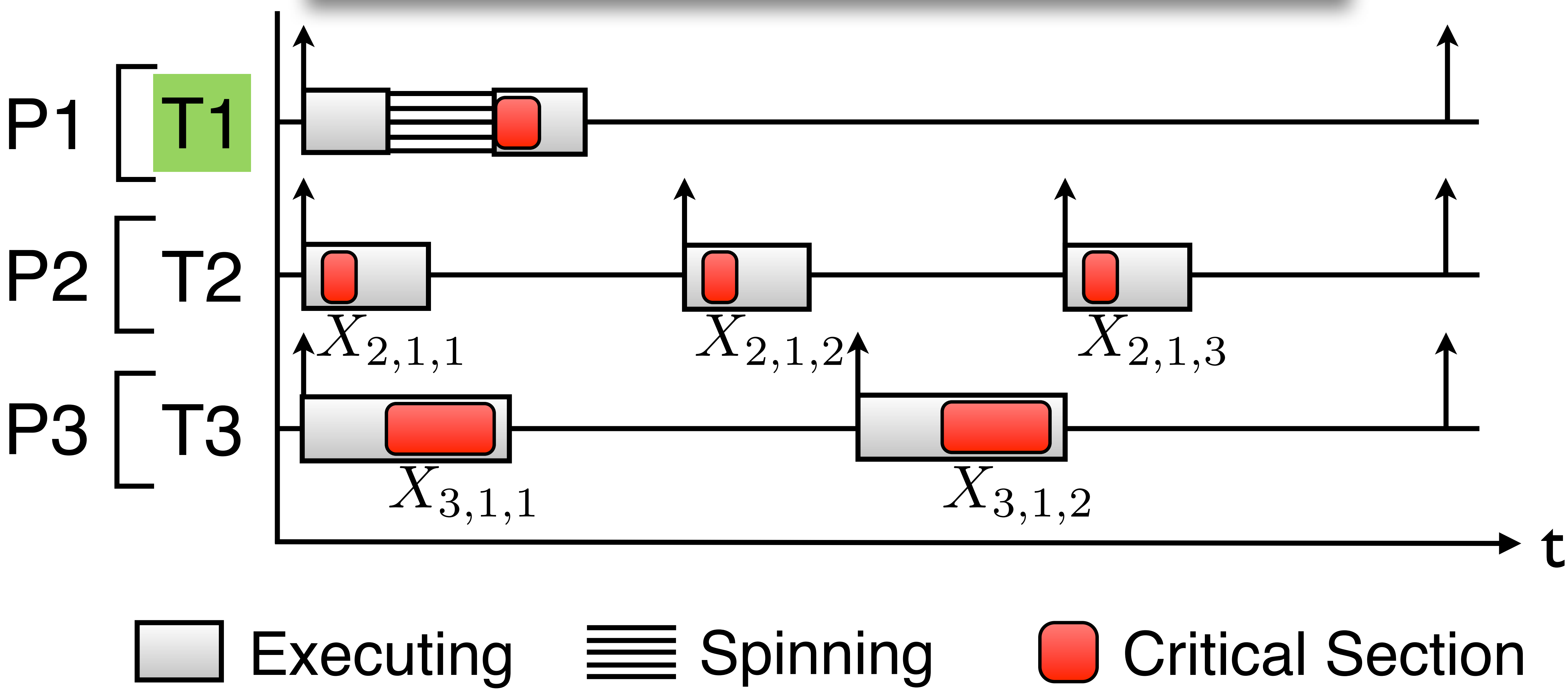

# Blocking Variables

$$0 \leq X \leq 1$$

$X:$ Fraction of critical section length contributing to T1's blocking

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$X = 0$ Request **does not contribute** to T1's blocking.

$X = 1$ Request **contributes** to T1's blocking.

# Blocking Variables

$$0 \leq X \leq 1$$

Analysis accounts
**at most once**
for each request

$X$ … length
… cking

$X = 0$ … to T1's blocking.

$X = 1$

Request
**contributes**
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# Blocking Variables

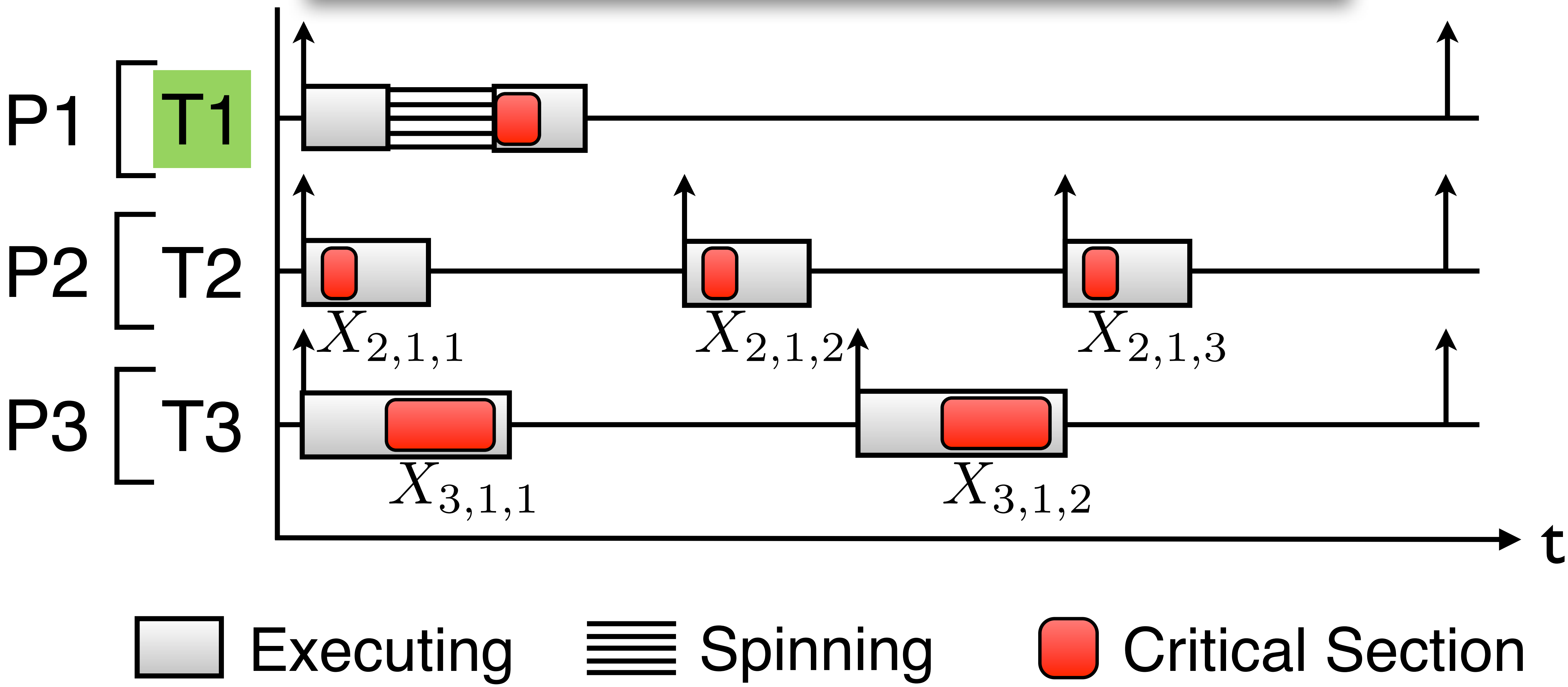
$$0 \leq X \leq 1$$

Analysis accounts
**at most once**
for each request

No double counting!

# ILP Generation for FIFO-Ordered Spin Locks

Impose constraints:



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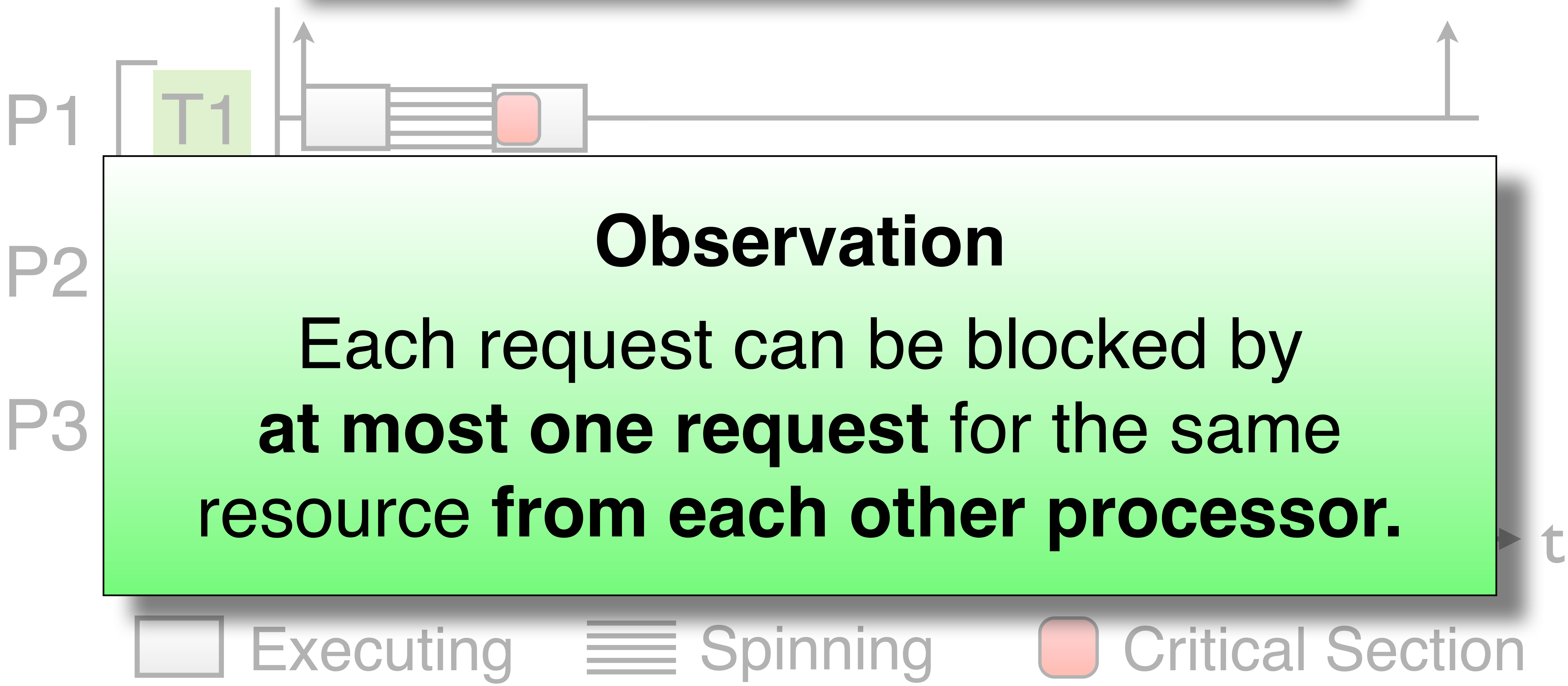
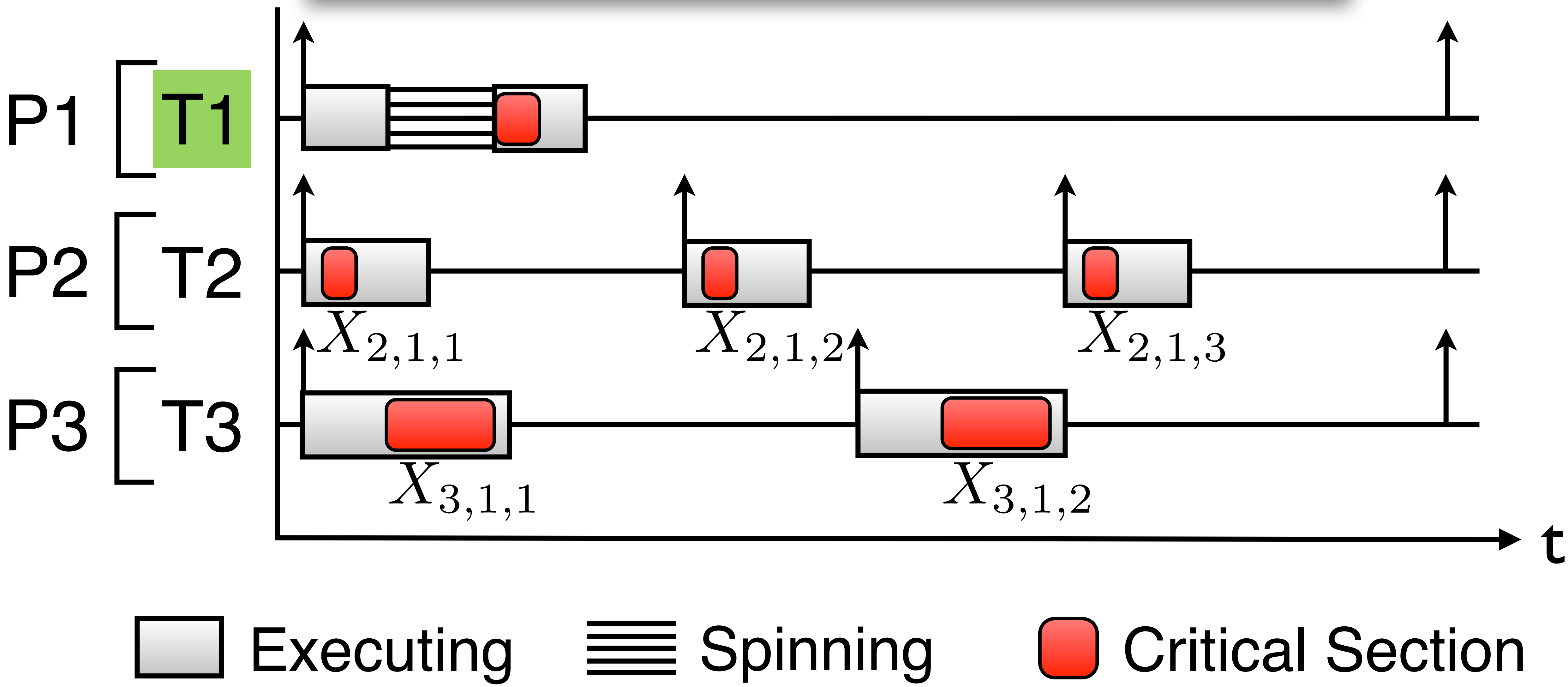



**Observation**

Each request can be blocked by **at most one request** for the same resource **from each other processor.**

# ILP Generation for FIFO-Ordered Spin Locks

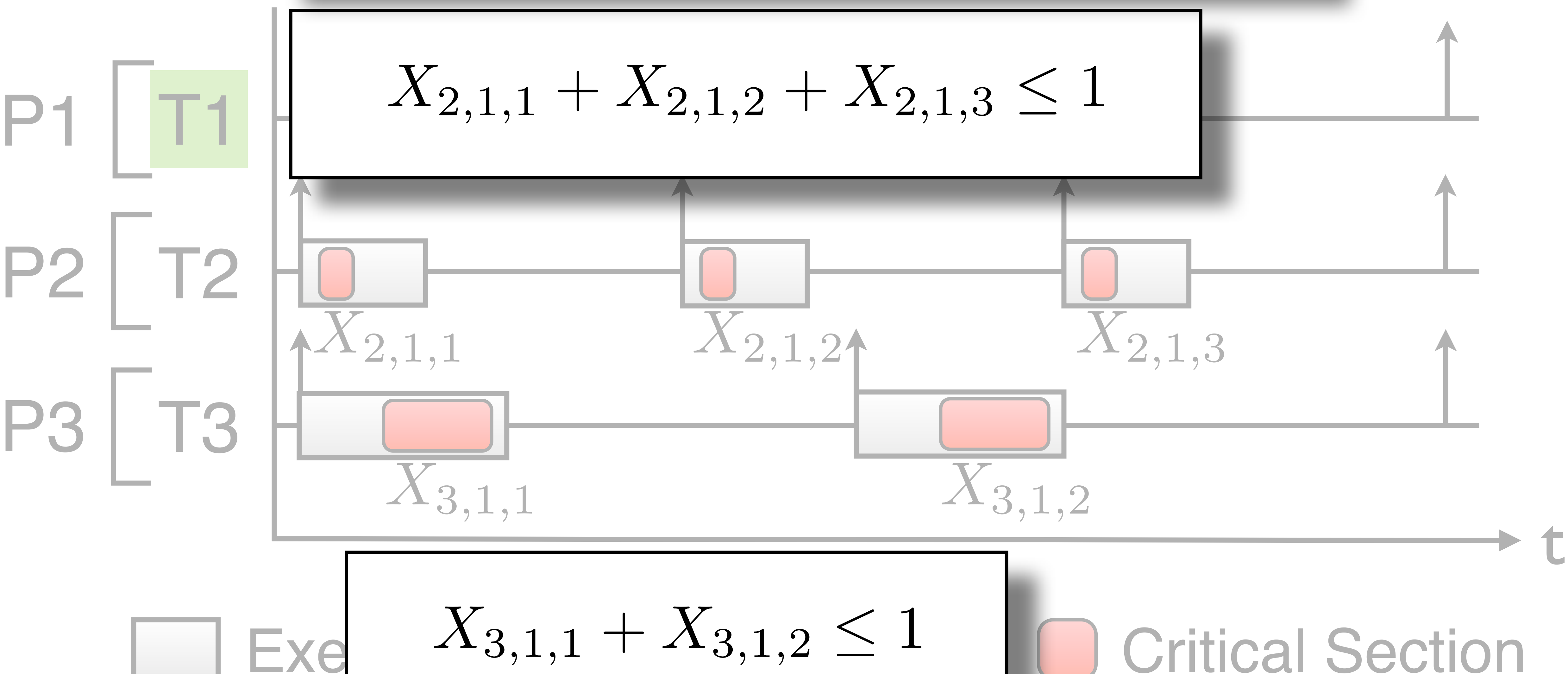
Impose constraints:



# ILP Generation for FIFO-Ordered Spin Locks

**Impose constraints:**

$$X_{2,1,1} + X_{2,1,2} + X_{2,1,3} \leq 1$$

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Impose constraints:

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constraints to
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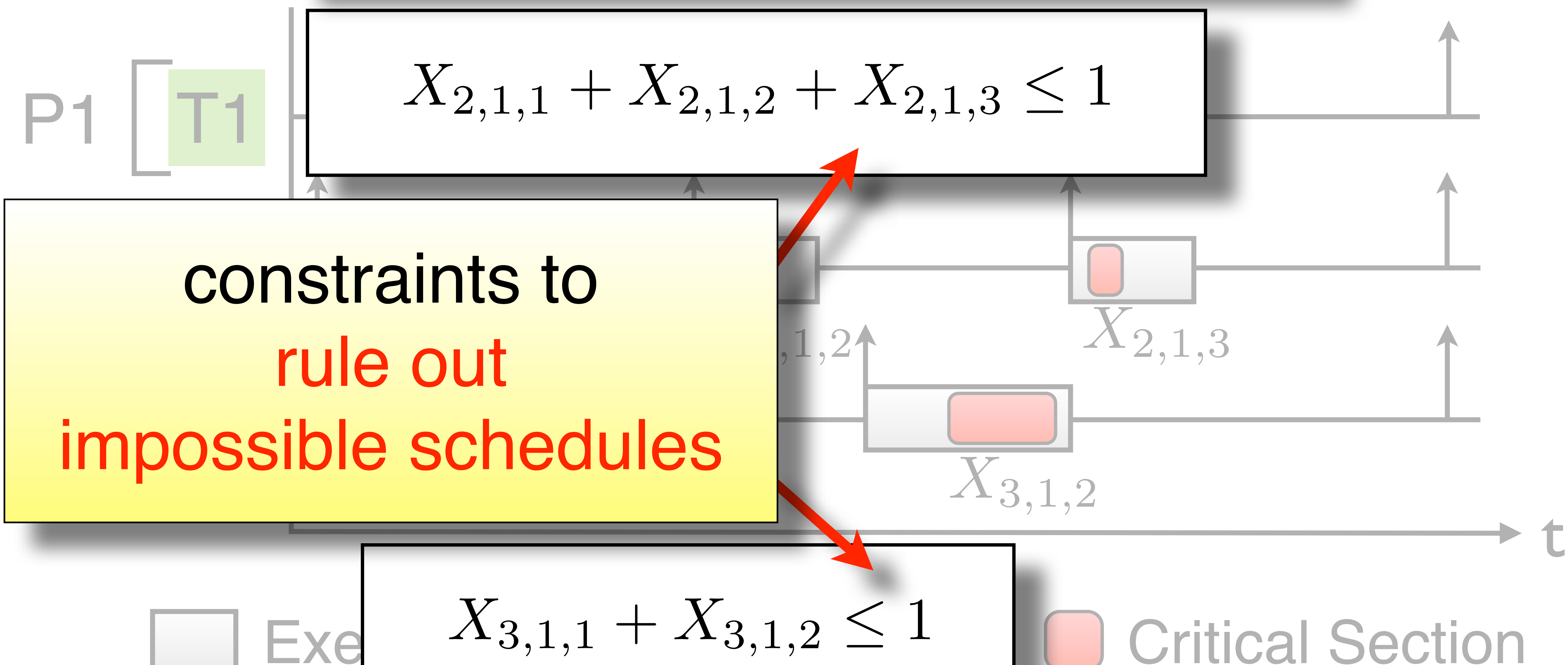

# ILP Generation for FIFO-Ordered Spin Locks

Impose constraints:

P1 T1

$$X_{2,1,1} + X_{2,1,2} + X_{2,1,3} \leq 1$$

constraints to
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**ILP Constraints**

- simple
- composable

$$X_{3,1,1} + X_{3,1,2} \leq 1$$

Exe Critical Section

# ILP for Worst-Case Blocking

Generate Integer Linear Program:

$$\boxed{X_{2,1,1} + X_{2,1,2} + X_{2,1,3} \leq 1}$$

$$\boxed{X_{3,1,1} + X_{3,1,2} \leq 1}$$

# ILP for Worst-Case Blocking

Generate Integer Linear Program:

worst-case blocking

$\simeq$

maximal blocking

$$X_{2,1,1} + X_{2,1,2} + X_{2,1,3} \leq 1$$

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# ILP for Worst-Case Blocking

Generate Integer Linear Program:

**maximize**

$$X_{2,1,1} \cdot L_{2,1,1} + X_{2,1,2} \cdot L_{2,1,2} + X_{2,1,3} \cdot L_{2,1,3} + X_{3,1,1} \cdot L_{3,1,1} + X_{3,1,2} \cdot L_{3,1,2}$$

**subject to**

$$X_{2,1,1} + X_{2,1,2} + X_{2,1,3} \leq 1$$

$$X_{3,1,1} + X_{3,1,2} \leq 1$$

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maximal critical section length

**subject to**

$$X_{2,1,1} + \ldots$$

$$X_{3,1,1} + X_{3,1,2} \leq 1$$

# ILP for Worst-Case Blocking

Generate Integer Linear Program:

**maximize**

$$X_{2,\ldots} \quad \ldots L_{2,1,3}$$

$$+ \ldots$$

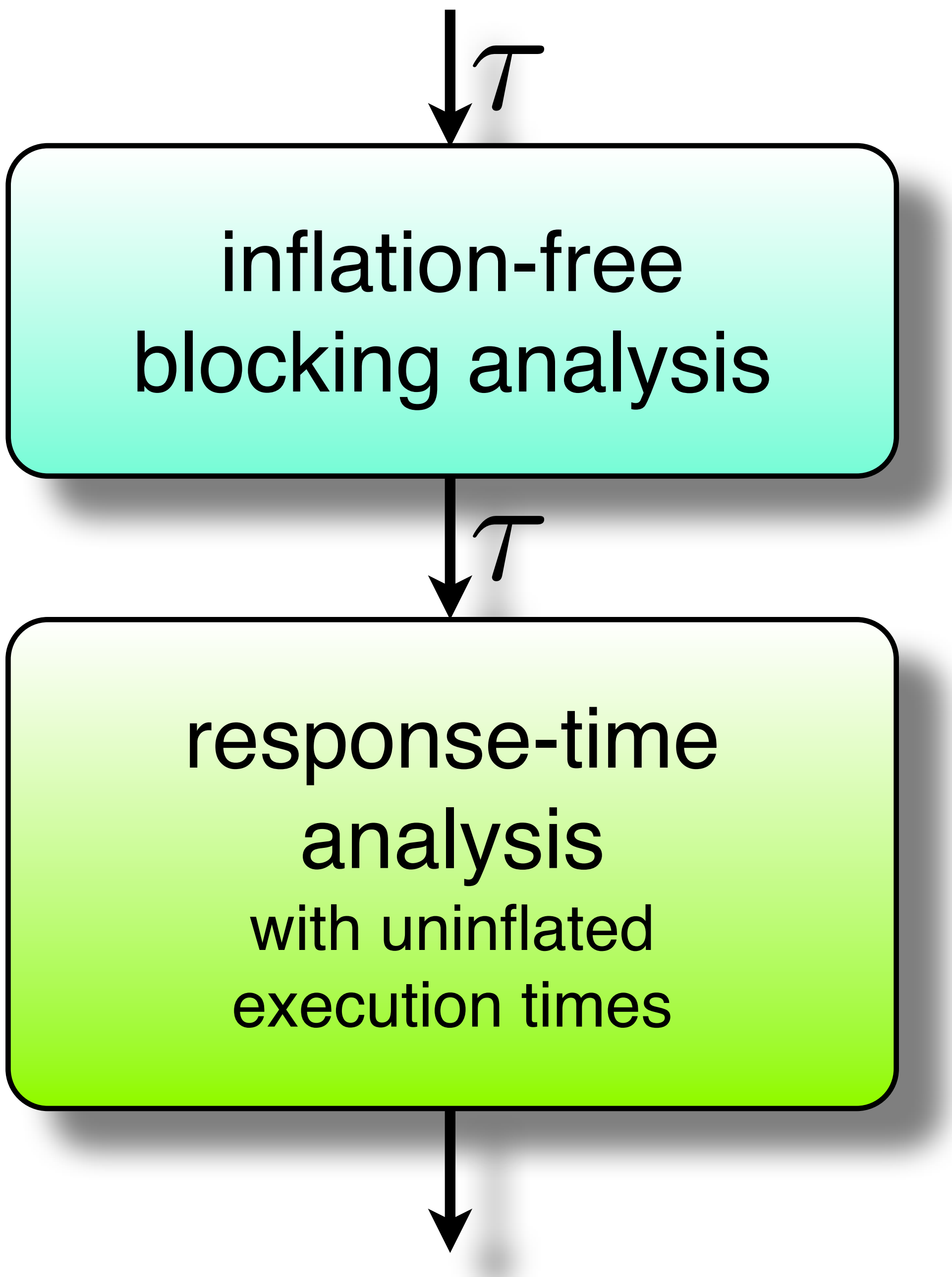
Worst-case blocking bound determined by ILP solver.

**subject to**

$$X_{2,1,1} + X_{2,1,2} + X_{2,1,3} \leq 1$$

$$X_{3,1,1} + X_{3,1,2} \leq 1$$

# Explicit Accounting for Blocking




$$R_i = e_i + b_i + \sum_{h<i} \left\lceil \frac{R_i}{p_h} \right\rceil \cdot e_h$$

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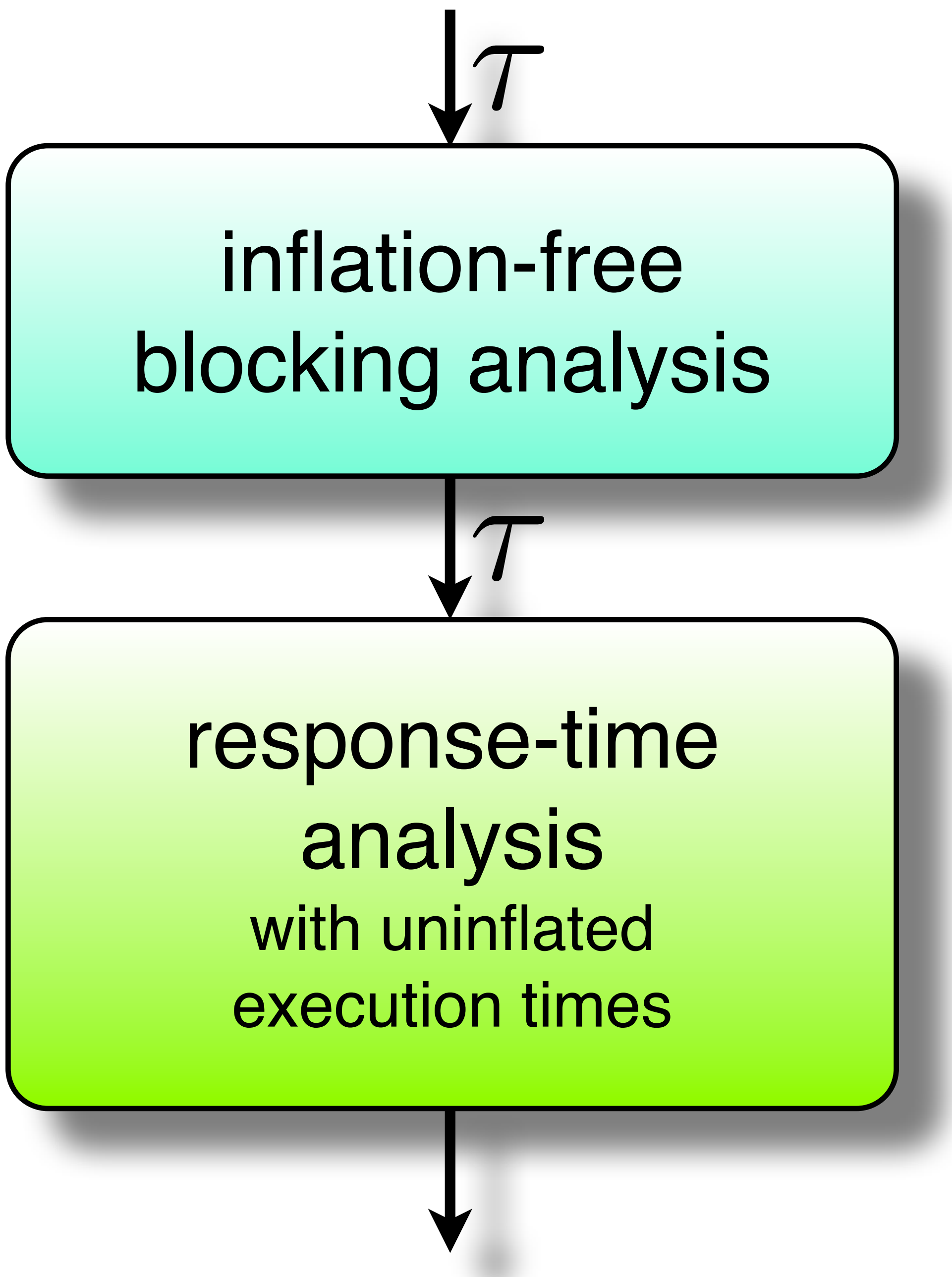


**worst-case blocking bound**
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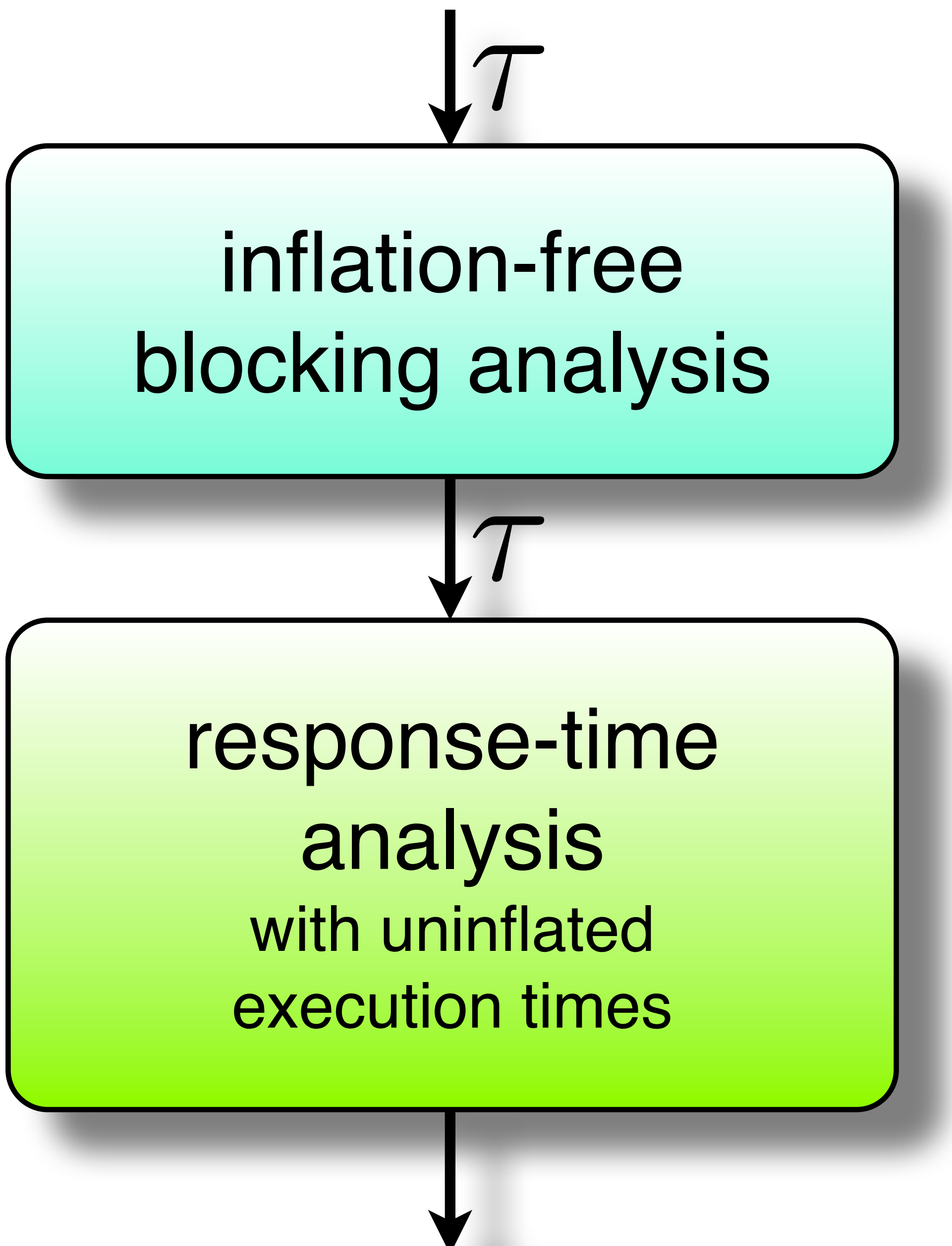


**worst-case blocking bound** determined by ILP-solver

$$R_i = \boxed{e_i} + \boxed{b_i} + \sum_{h<i} \left\lceil \frac{R_i}{p_h} \right\rceil \cdot \boxed{e_h}$$

**uninflated** execution costs

# Challenges

Prior analysis is **pessimistic due to inflation**.

Explicit blocking terms ILP formulation

Prior analysis is **specific to non-preemptable FIFO-ordered** spin locks.

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So far we only talked about the MSRP...

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...but there's more.

# Spin Lock Types

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Preemptable Spinning

×

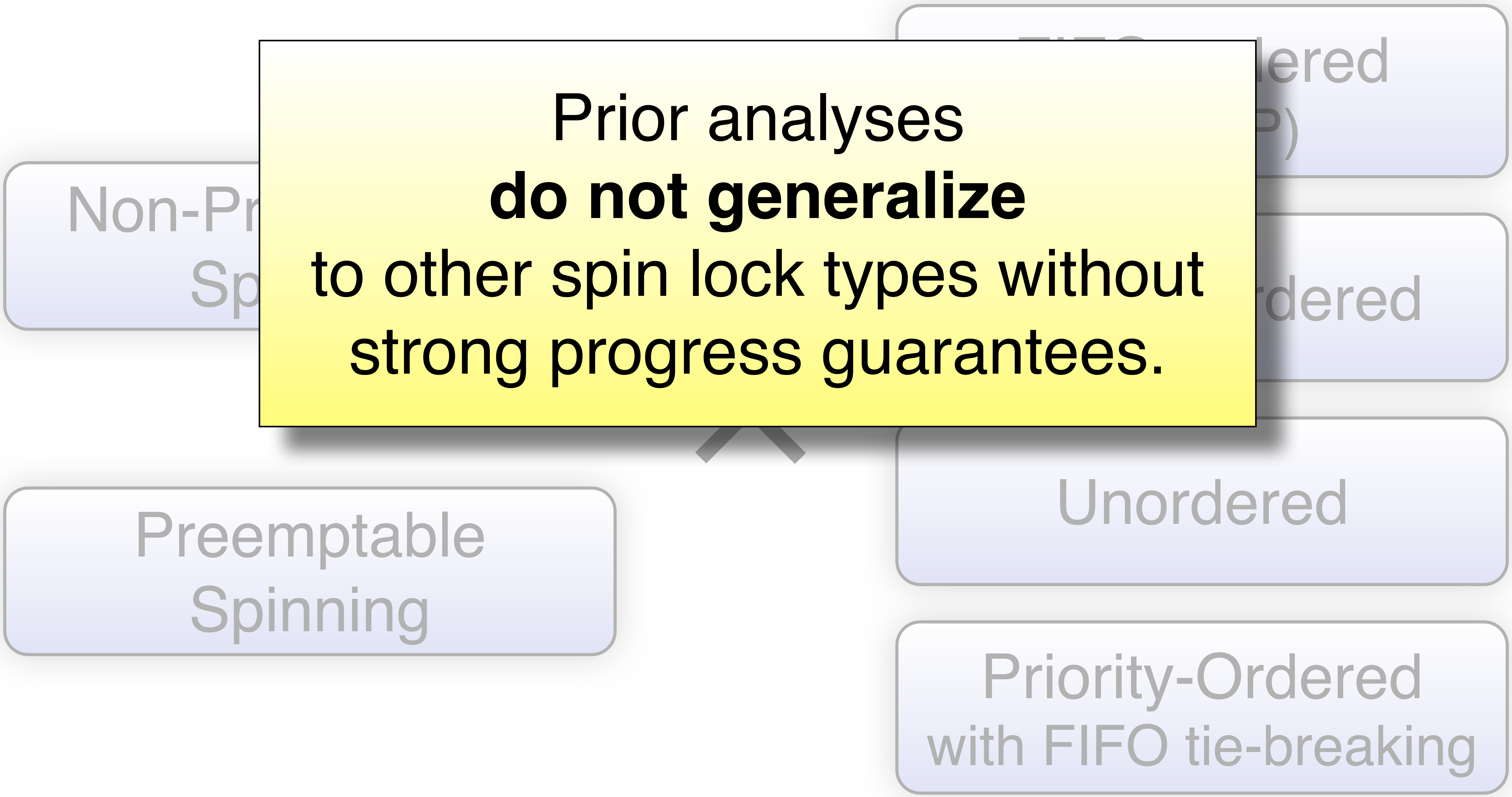
FIFO-ordered (MSRP)

Priority-Ordered

Unordered

Priority-Ordered with FIFO tie-breaking

# Spin Lock Types




Prior analyses
**do not generalize**
to other spin lock types without
strong progress guarantees.

# Prior Analyses Rely on Strong Progress Guarantees

FIFO-Ordering is analysis-friendly:

Each request can be blocked by
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FIFO-Ordering is analysis-friendly:

Each request can be blocked by **at most one request** for the same resource **from each other processor.**

**Prior analyses rely on strong progress guarantees** provided by FIFO-ordering.

# Prior Analyses Rely on Strong Progress Guarantees

Unordered spin locks:

Each request can be blocked by
**all other requests**
for the same resource.

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ILP formulation

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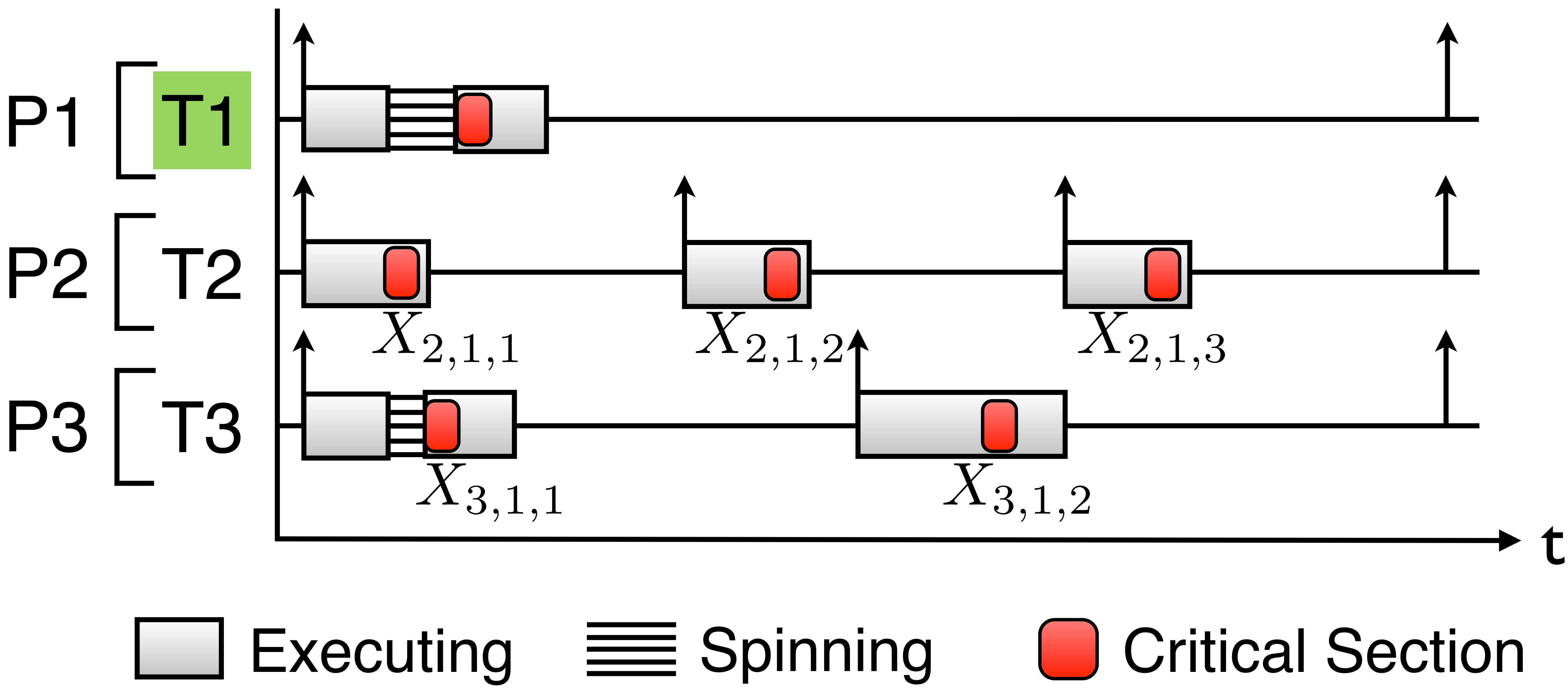
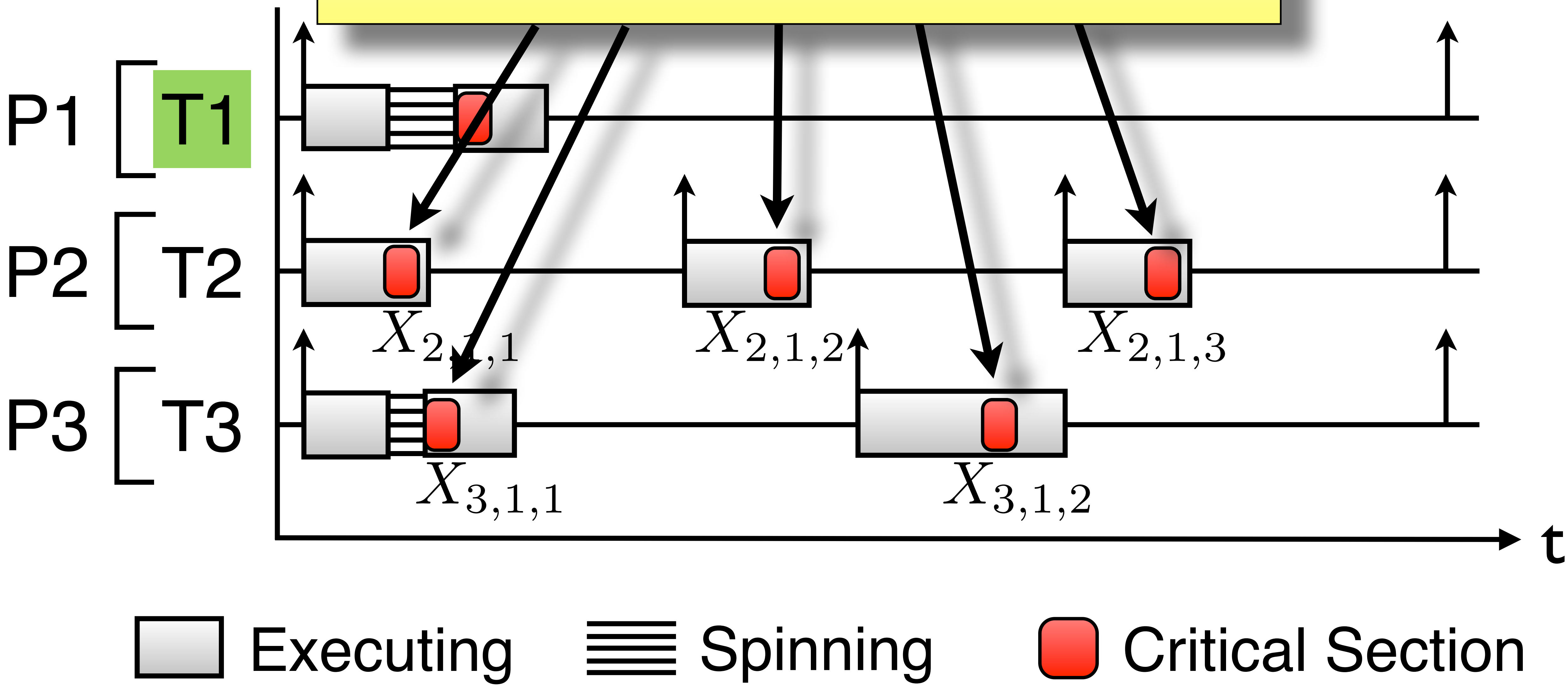
# Analysis of Unordered Spin Locks



# Analysis of Unordered Spin Locks

Can all of these really block T1's request?

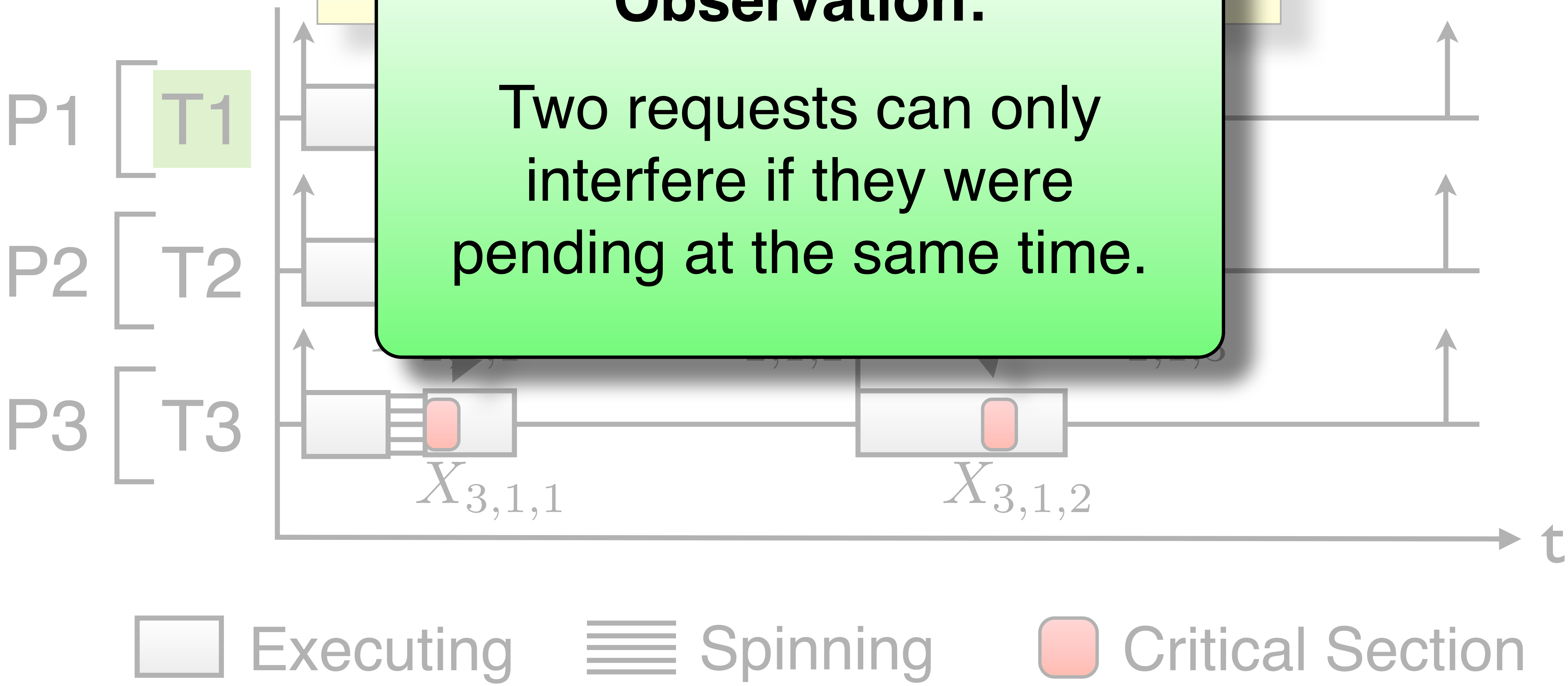


# Analysis of Unordered Spin Locks

Can all of these really

**Observation:**

Two requests can only interfere if they were pending at the same time.



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# Per-Request Wait-Time Bounds

How many remote request can be pending while T1’s request is pending?

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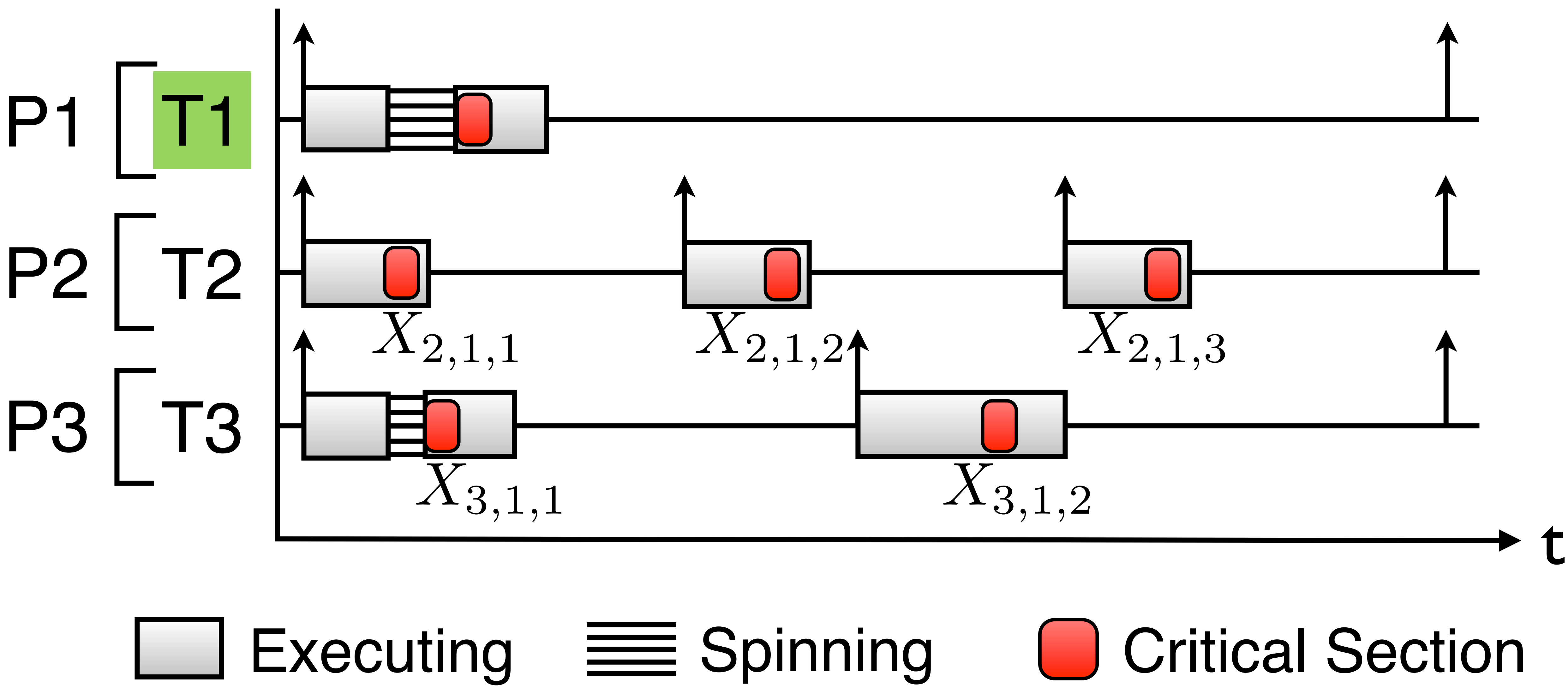
Bound **wait time** of T1's **request**. [1]

[1] K. Lakshmanan, D. Niz, and R. Rajkumar, "Coordinated task scheduling, allocation and synchronization on multiprocessors," in RTSS'09, 2009.

# Bounding the Wait Time of Requests



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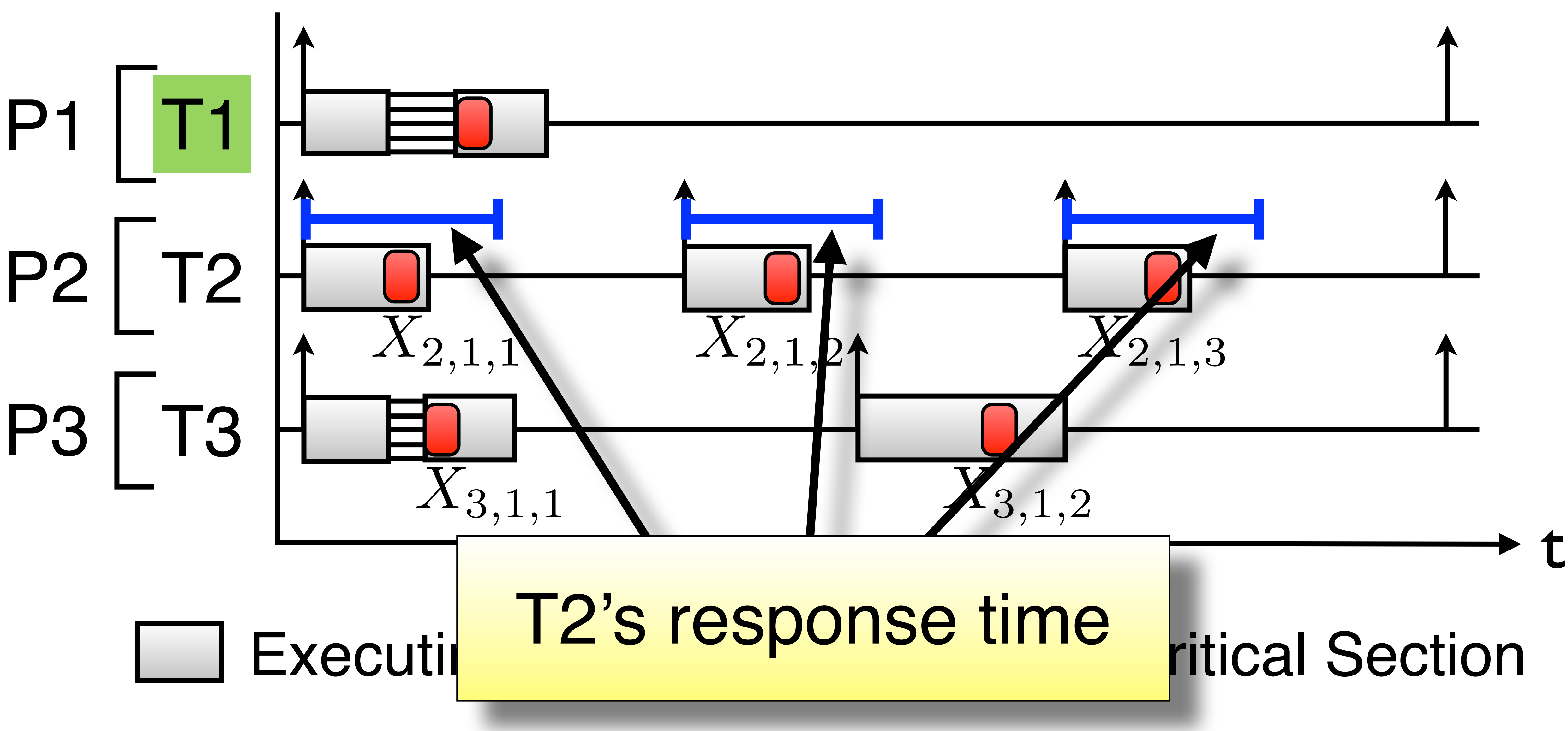

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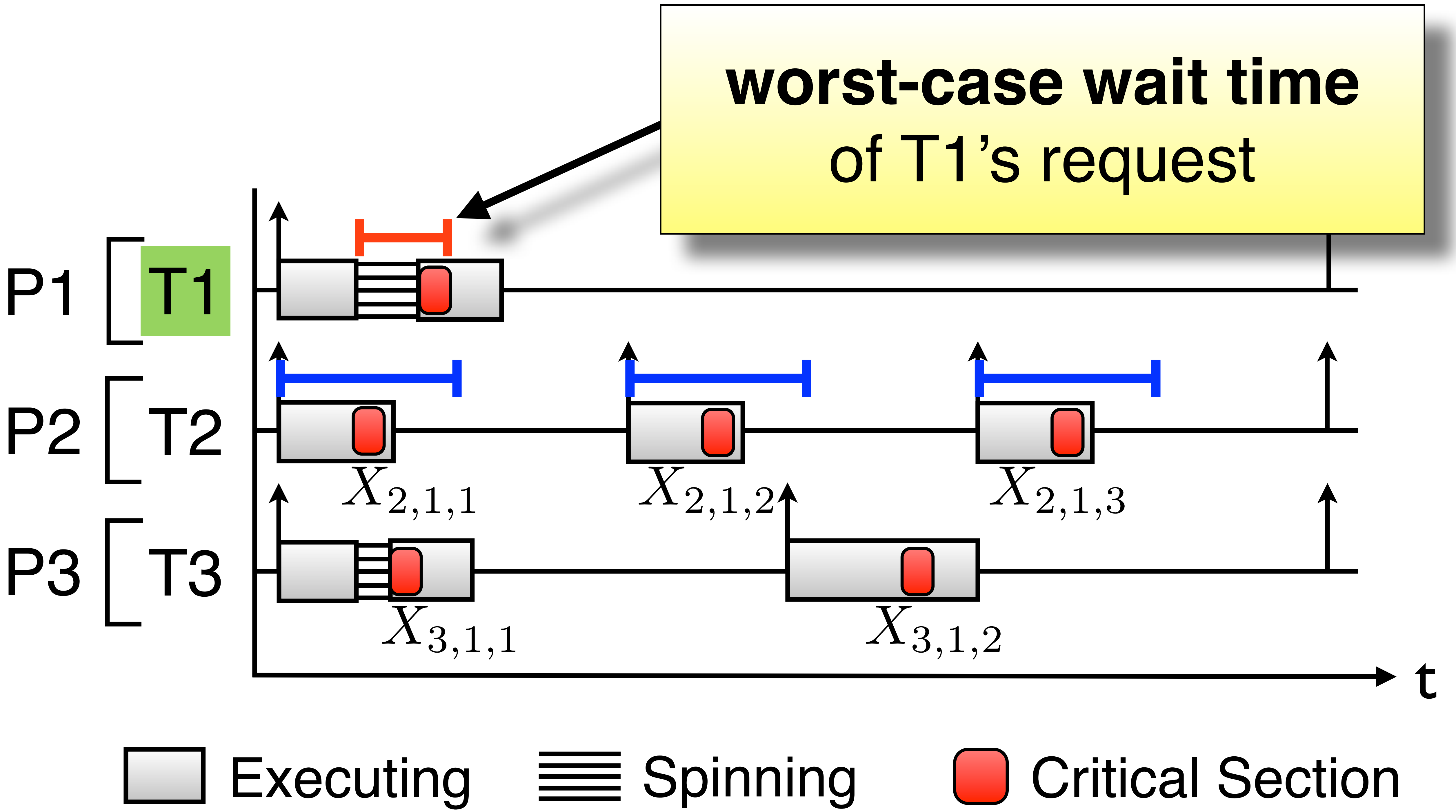

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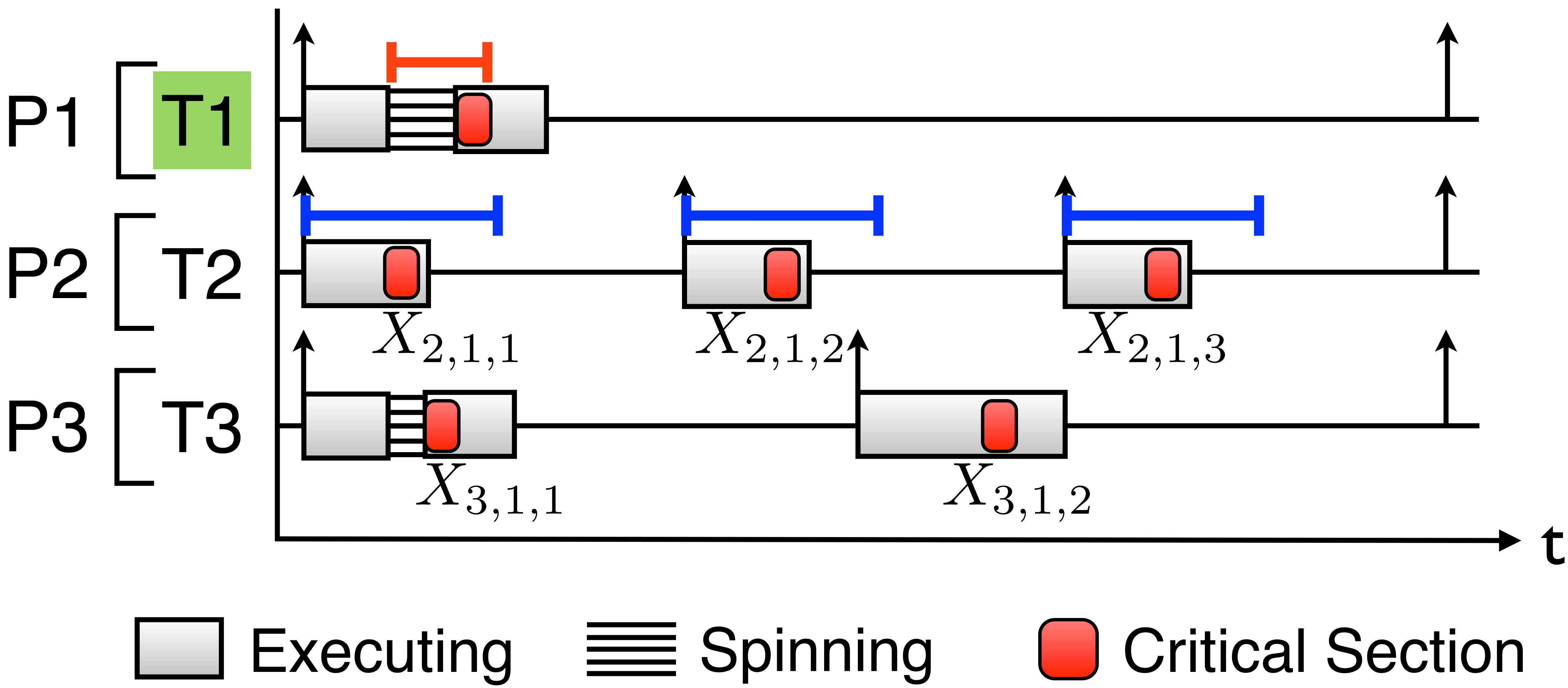

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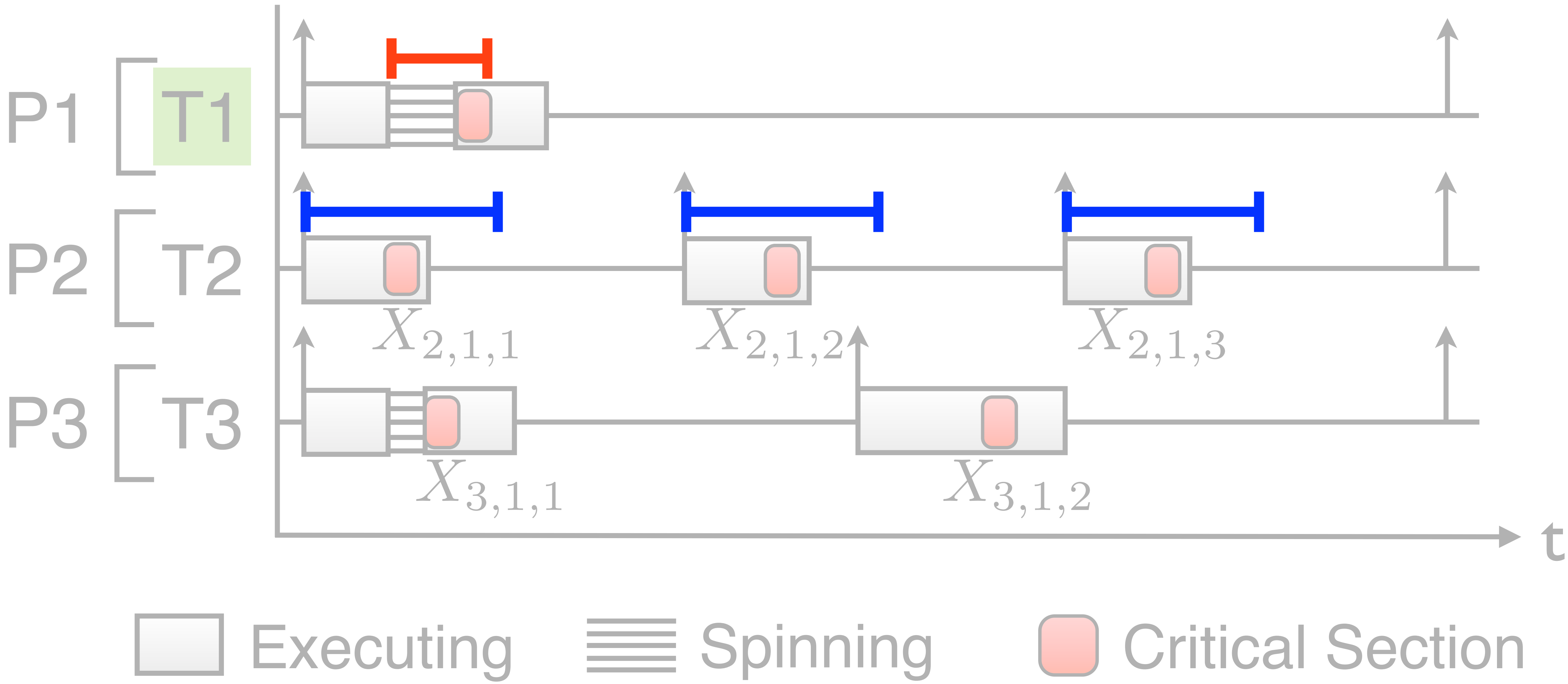

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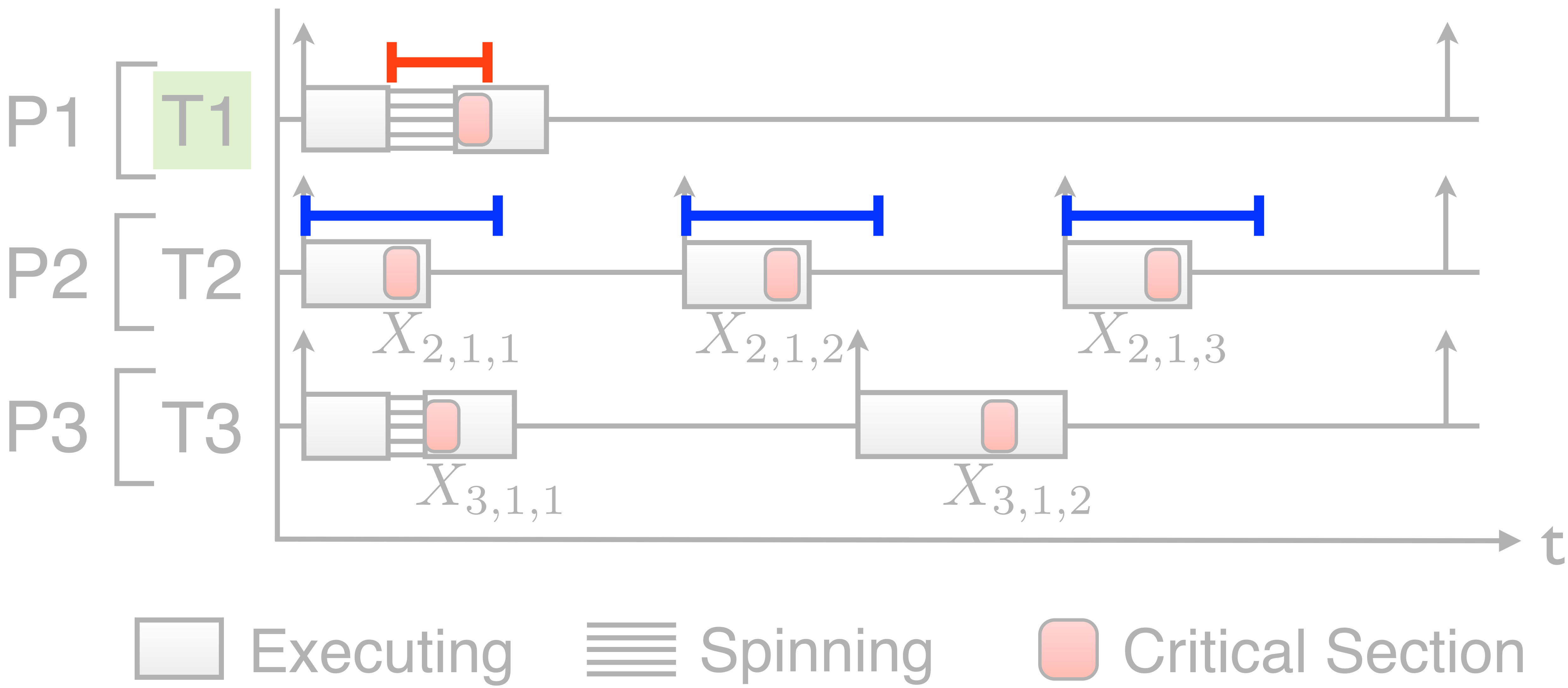

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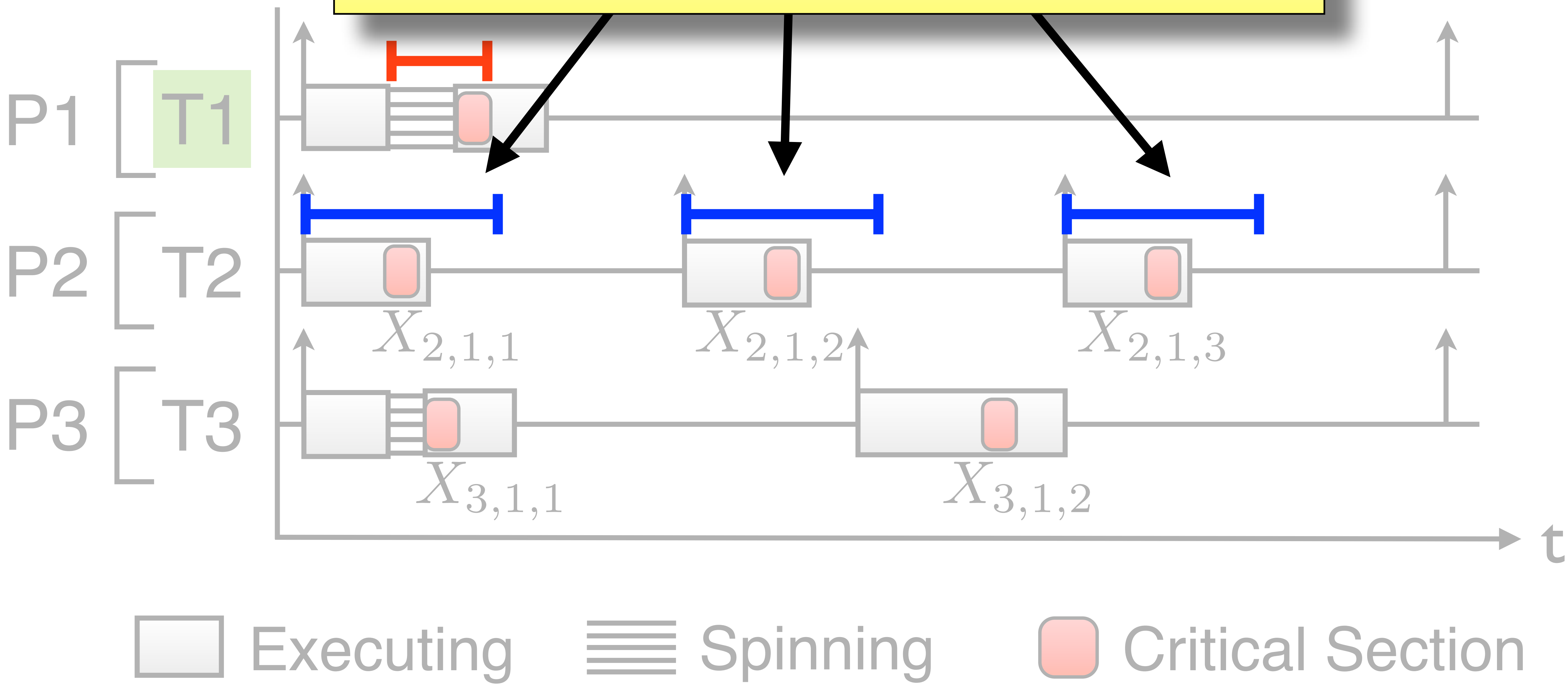
At most one of T2's jobs can overlap with T1's request.



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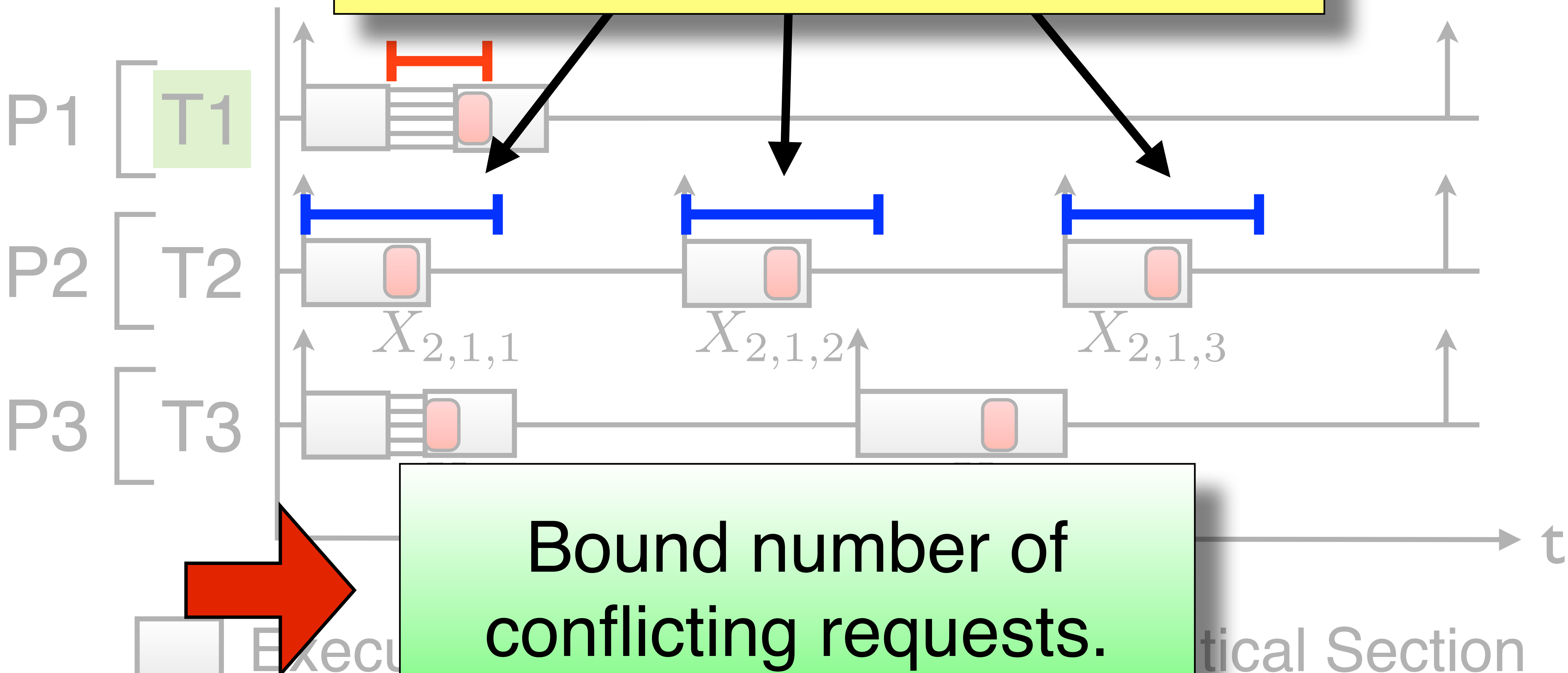
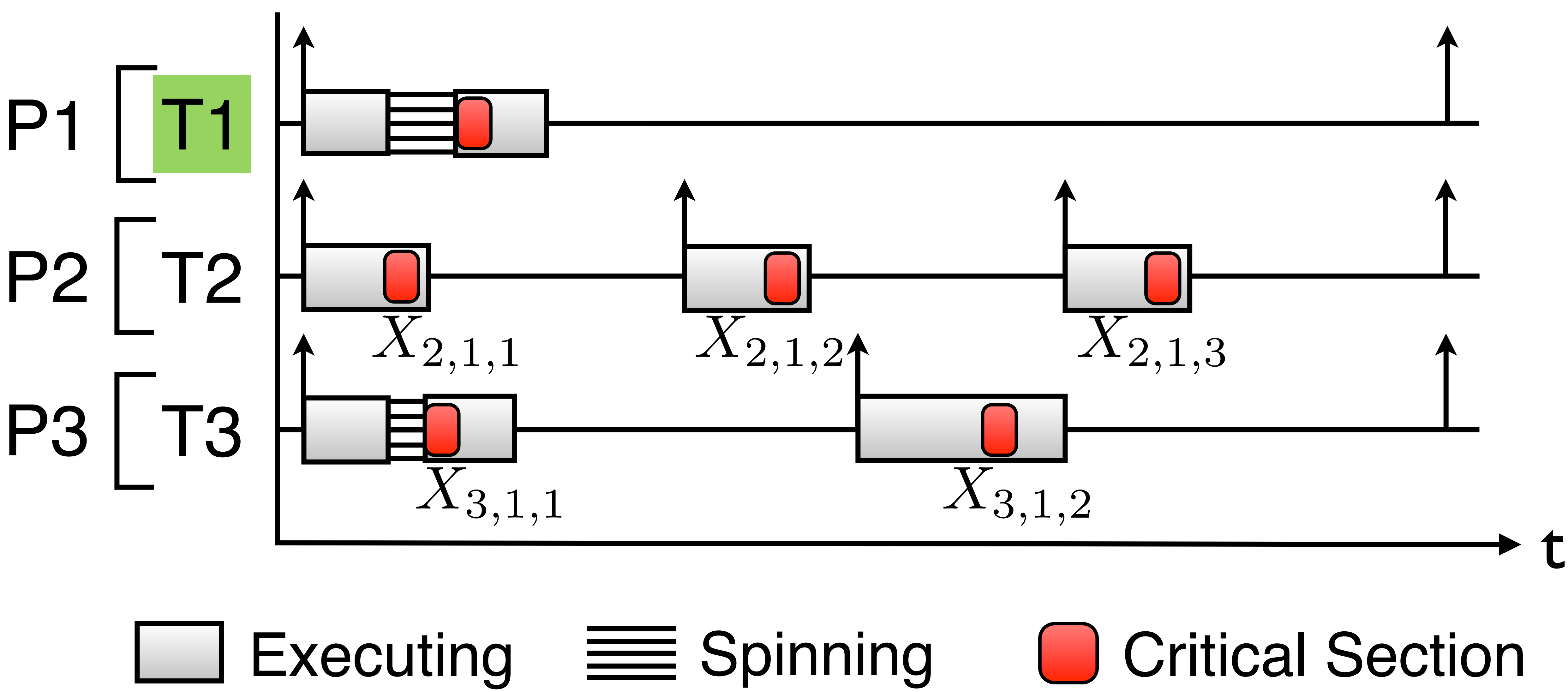



Bound number of conflicting requests.

# ILP Constraints
# Unordered Spin Locks



# ILP Constraints
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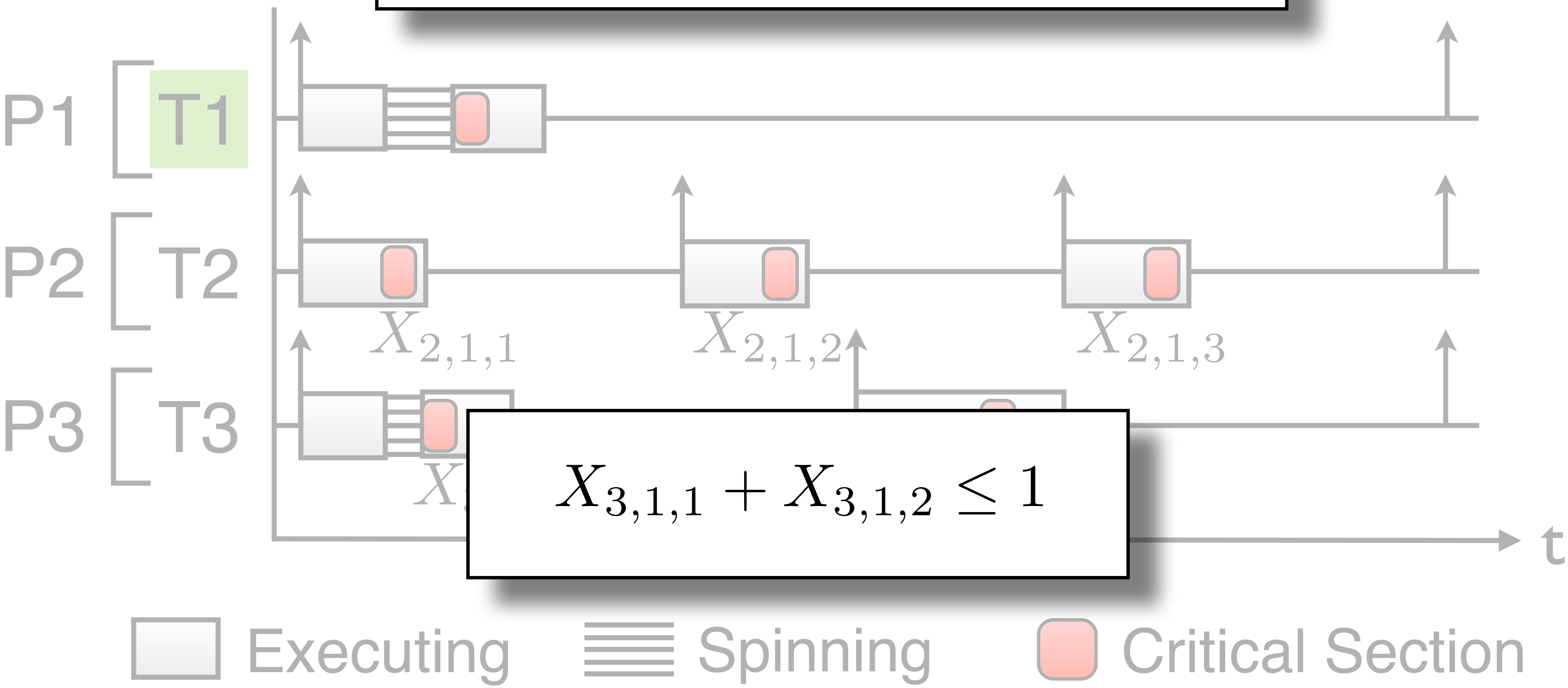
$$X_{2,1,1} + X_{2,1,2} + X_{2,1,3} \leq 1$$

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# ILP Constraints
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**Same constraints** for **unordered** and **FIFO**-ordered spin locks.

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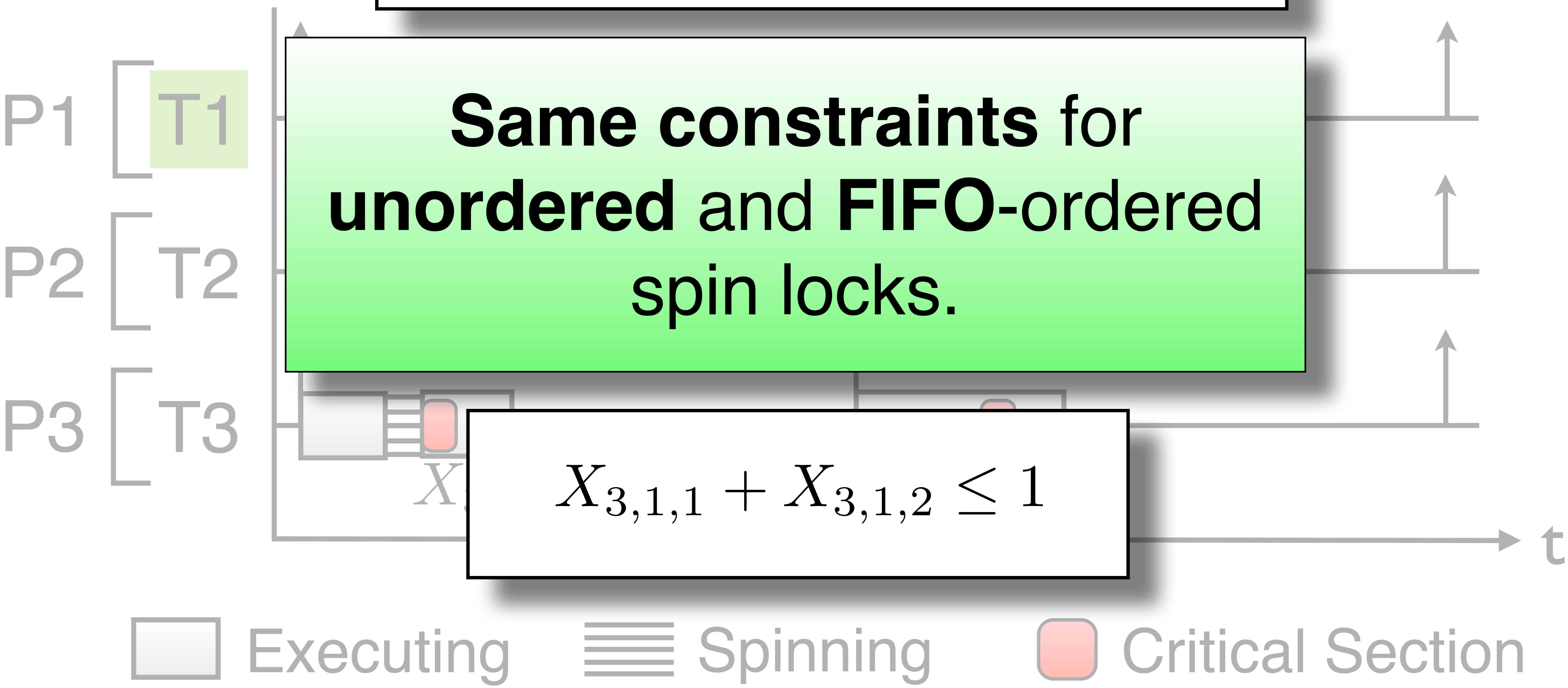

# Challenges

Prior analysis is **pessimistic due to inflation**.

Explicit blocking terms
ILP formulation

Prior analysis is **specific to non-preemptable FIFO-ordered** spin locks.

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# Evaluation

# Evaluation

Non-Preemptable Spinning

Preemptable Spinning

×

FIFO-ordered (MSRP)

Priority-Ordered

Unordered

Priority-Ordered with FIFO tie-breaking

# Evaluation

Could we **reduce pessimism**?

FIFO-ordered (MSRP)

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Could we **reduce pessimism**?

Does the spin lock type matter at all?

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FIFO-ordered
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**Which type**
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Preemptable
Spinning

Unordered

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Could we **reduce pessimism**?

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Does the spin lock type matter at all?

**Which type** should we use?

Unordered

**When** can **unordered** locks be used?

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# Evaluation

Could we **reduce pessimism**?

FIFO-ordered

Does the spin lock type matter at all?

**Which type** should we use?

**When** can **unordered** locks be used?

Should spinning be **preemptable or non-preemptable?**

# Evaluation

**Large-scale schedulability experiments:**

- number of processors $m$: 4, 8, 16
- average task utilization: 0.1, 0.2, 0.3
- critical section lengths: $[1\mu s, 15\mu s]$, $[1\mu s, 100\mu s]$
- number of resources: $m/2,\ m,\ 2m$
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- resource sharing factors: 0.1, 0.25, 0.4, 0.75

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**Large-scale schedulability experiments:**

1296 different configurations

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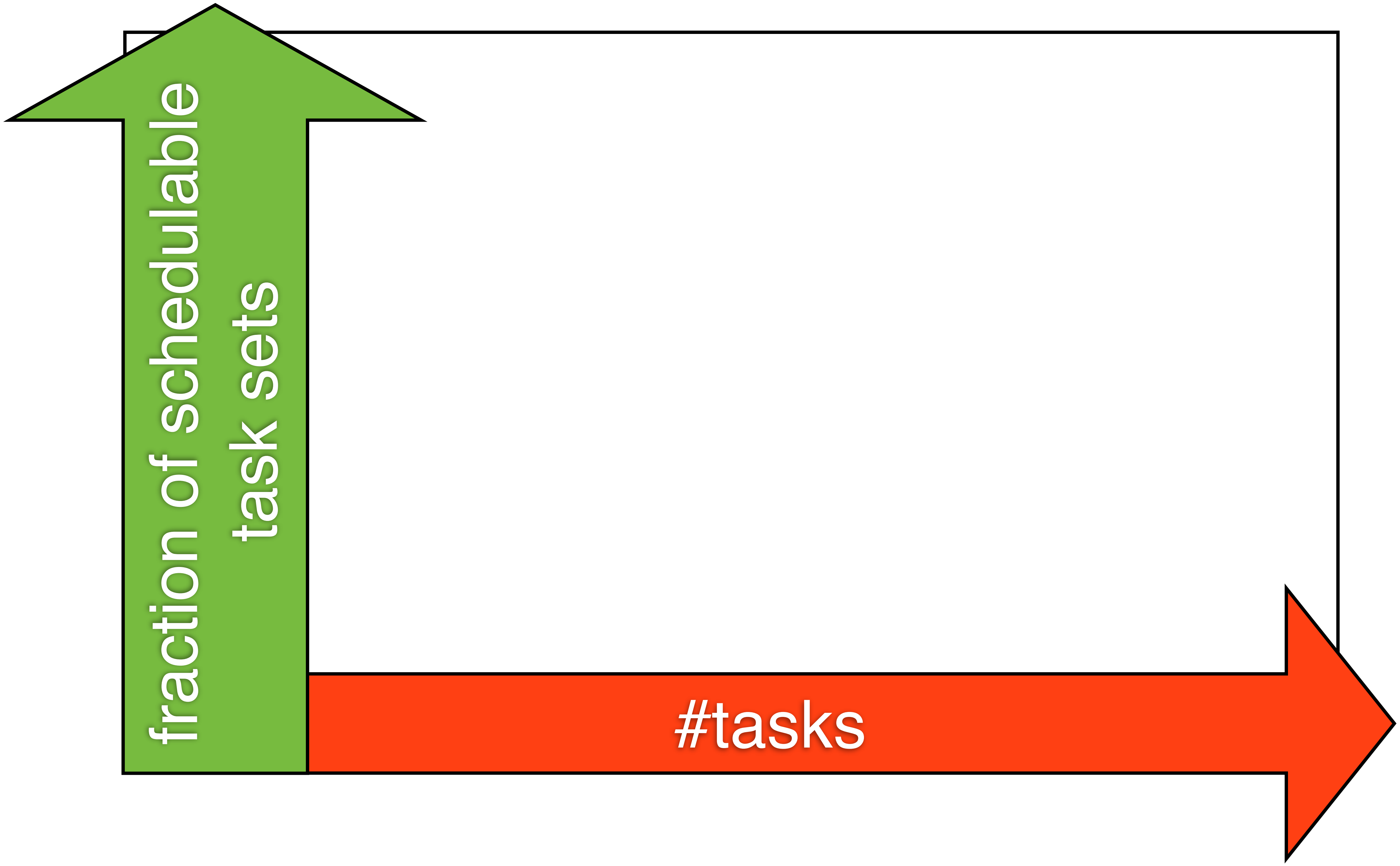
- number
- resource 0.4, 0.75

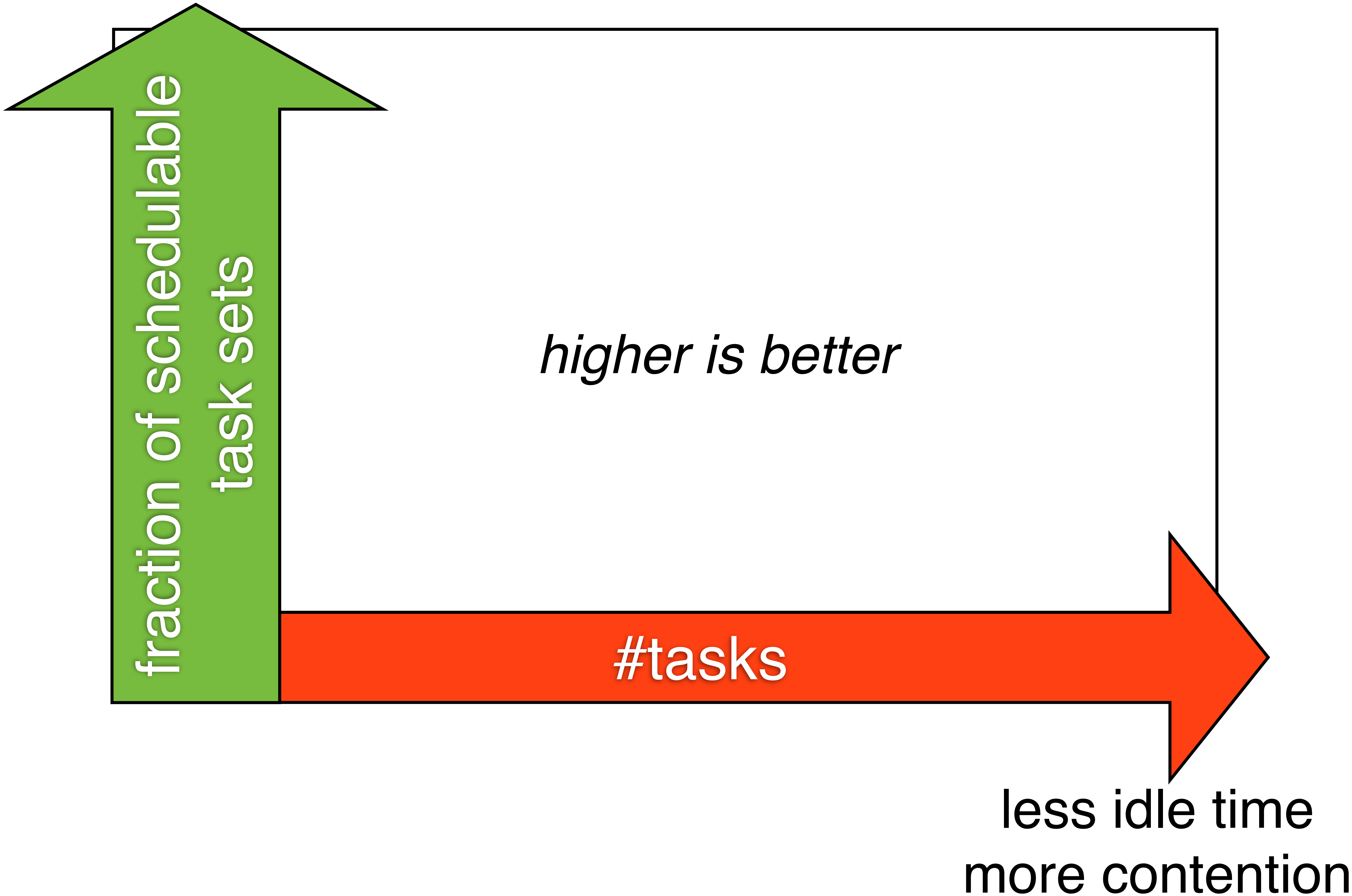
≥1000 samples
per data point
in each configuration

# Schedulability Experiments




less idle time
more contention

# Schedulability Experiments



# Notation

$$F \mid N$$

# Notation

**F**/N

FIFO-ordered

# Notation

F|**N**

Non-preemptable

# Notation

| **Type** | **Ordering** |
|---|---|
| F\|N | FIFO-ordered non-preemptable |
| P\|N | Priority-ordered non-preemptable |
| U\|N | Unordered non-preemptable |
| PF\|N | Priority-ordered non-preemptable with FIFO tie-breaking |

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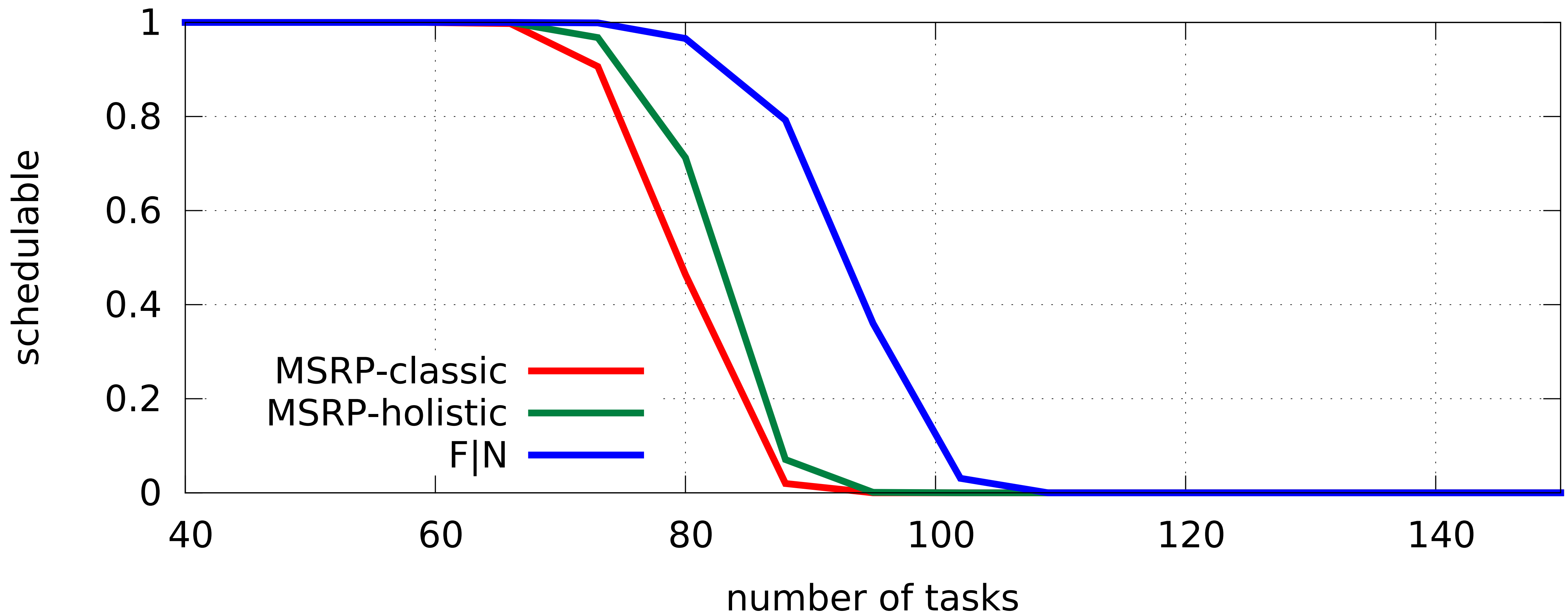


Configuration: 16 CPUs, avg. utilization: 0.1, 16 shared resources, CS lengths $[1\mu s, 15\mu s]$, at most 2 requests per resource, contention = 0.4

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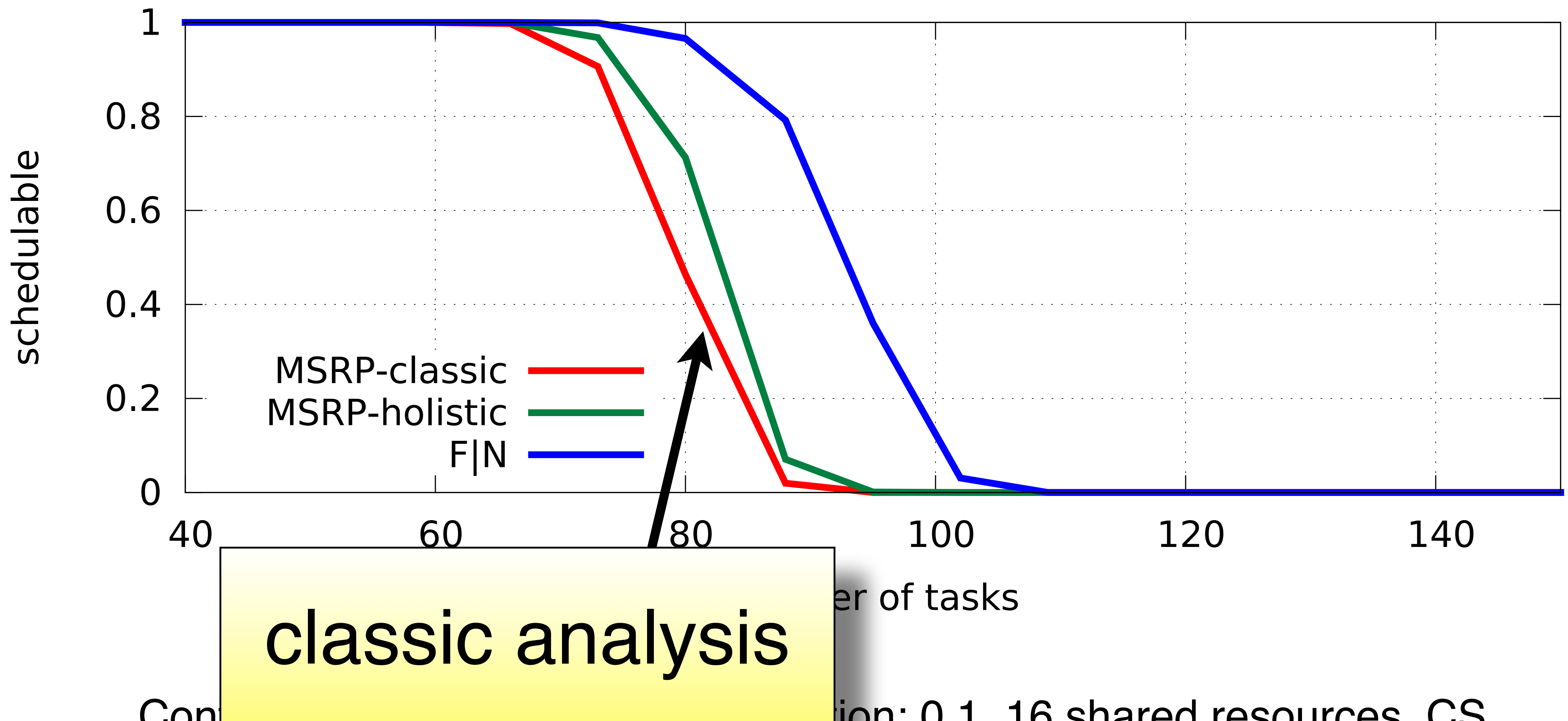


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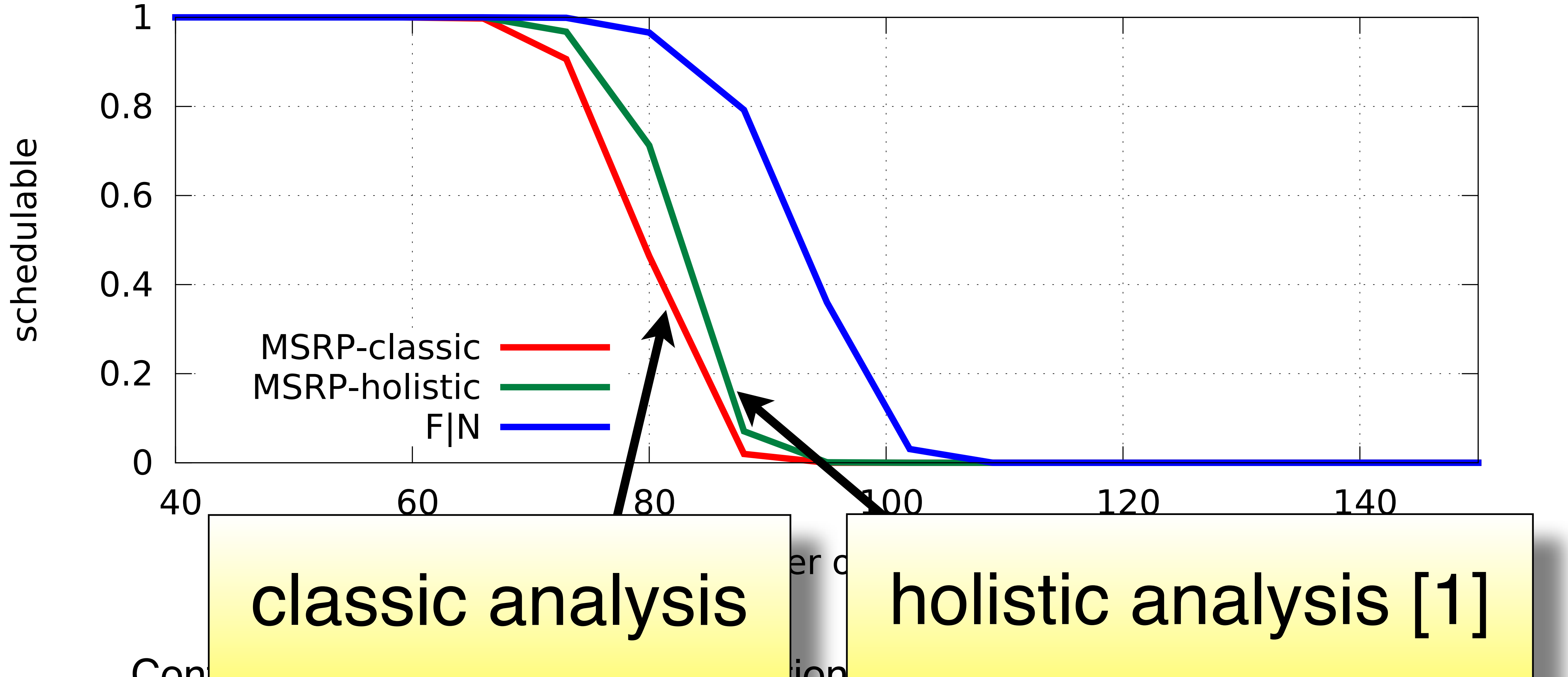


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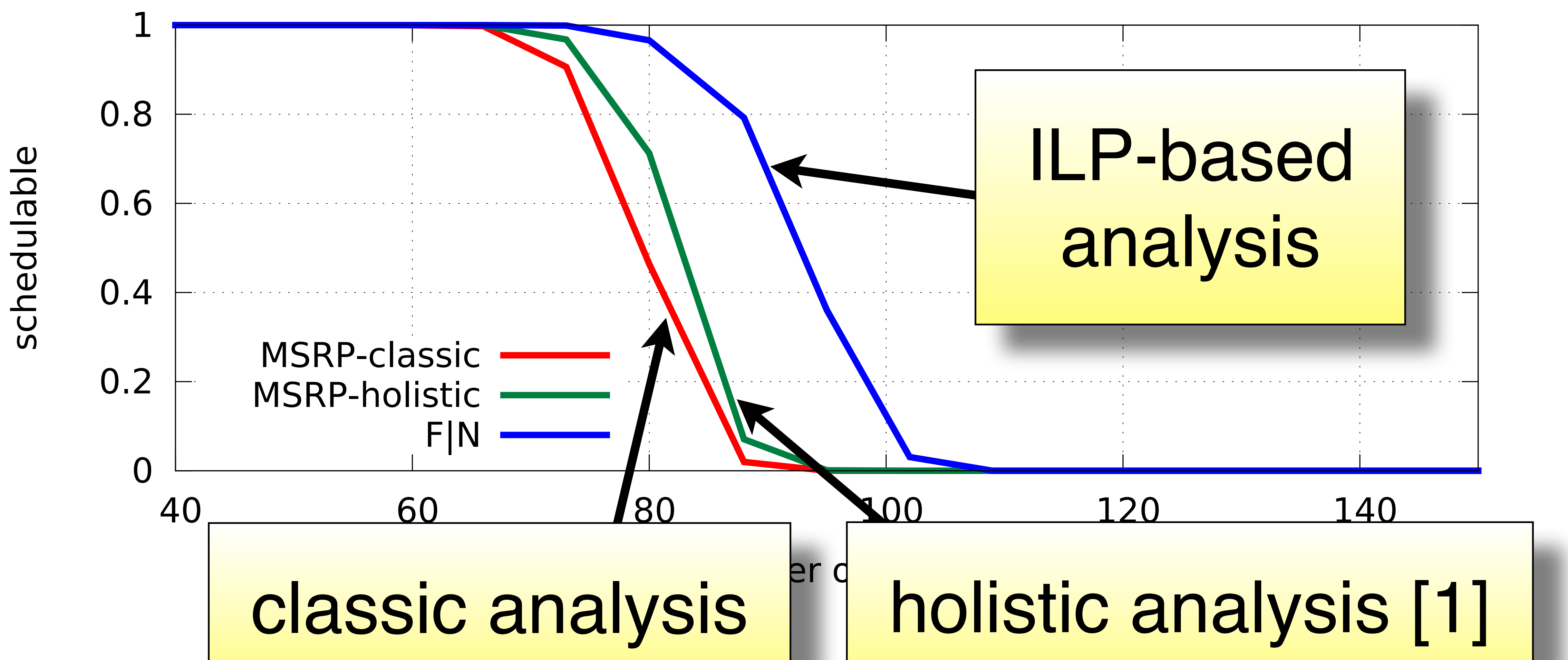


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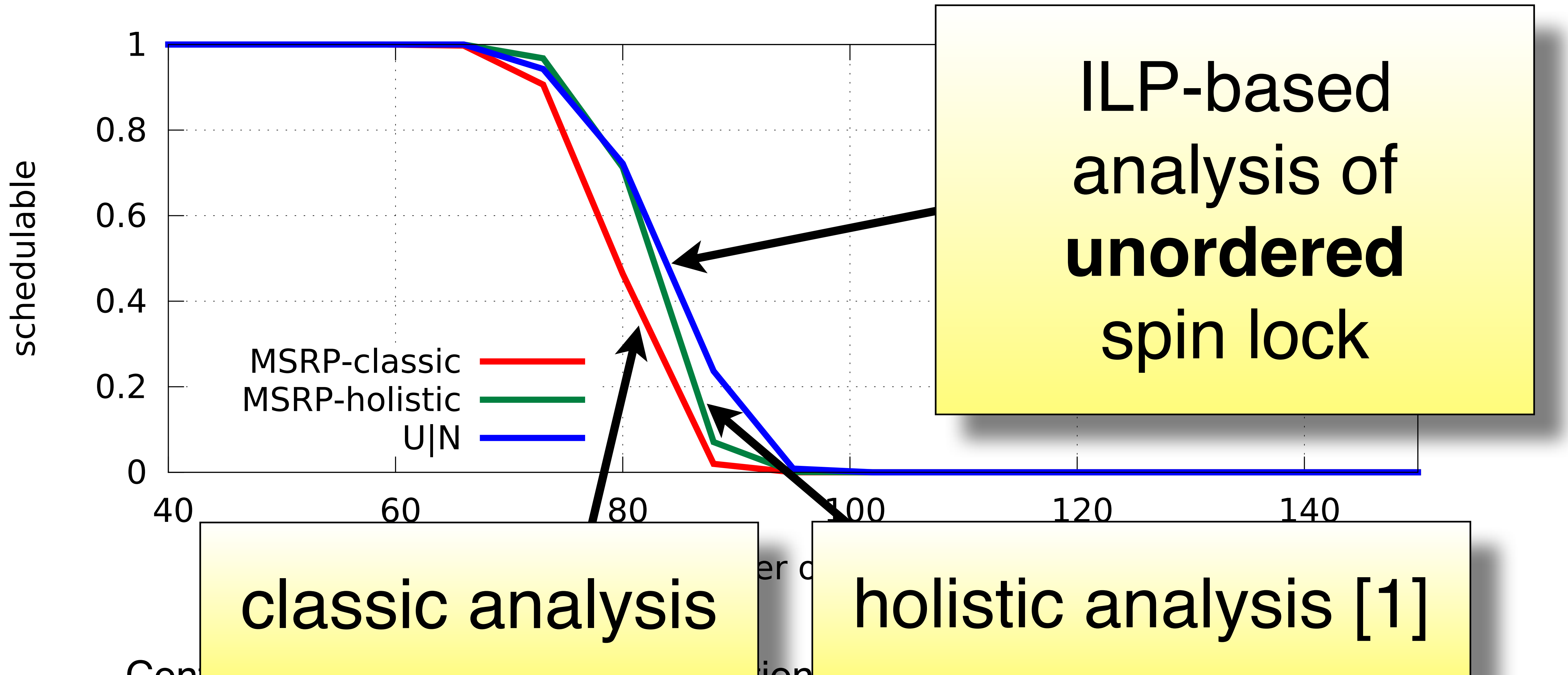


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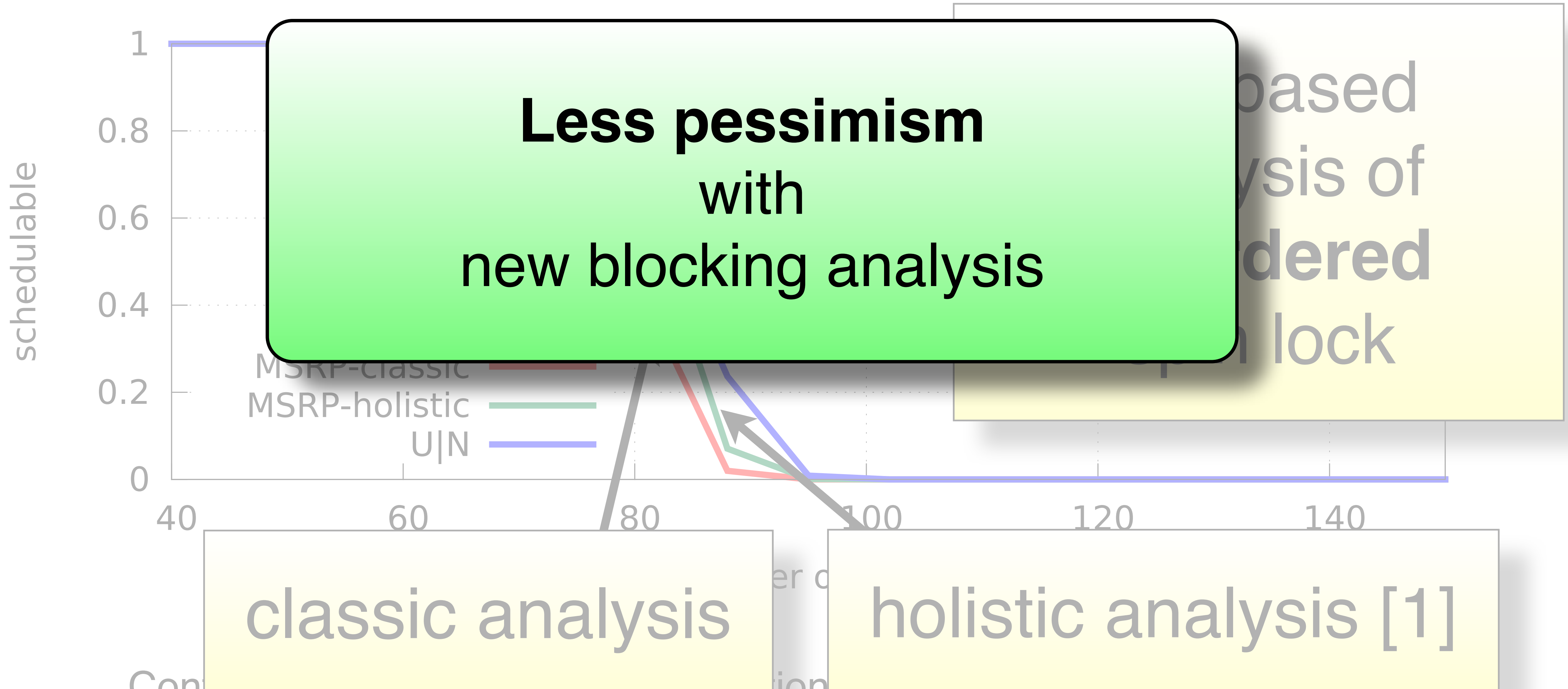


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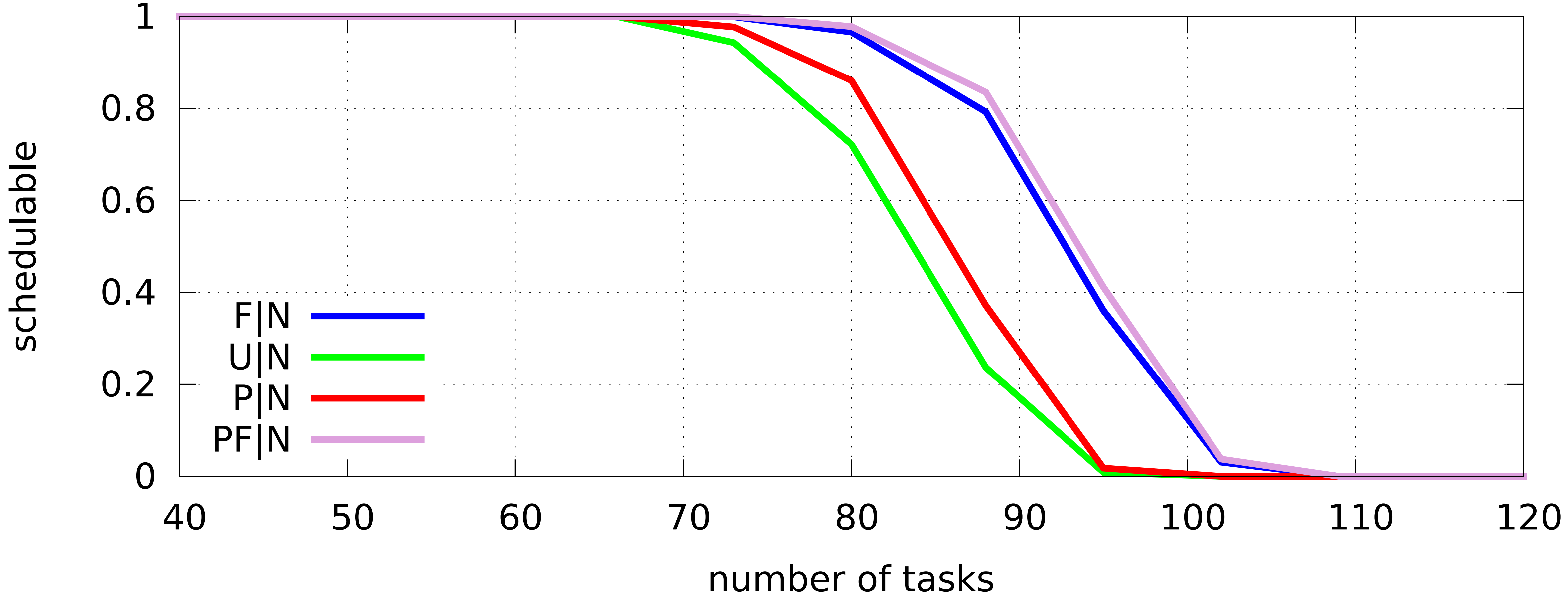

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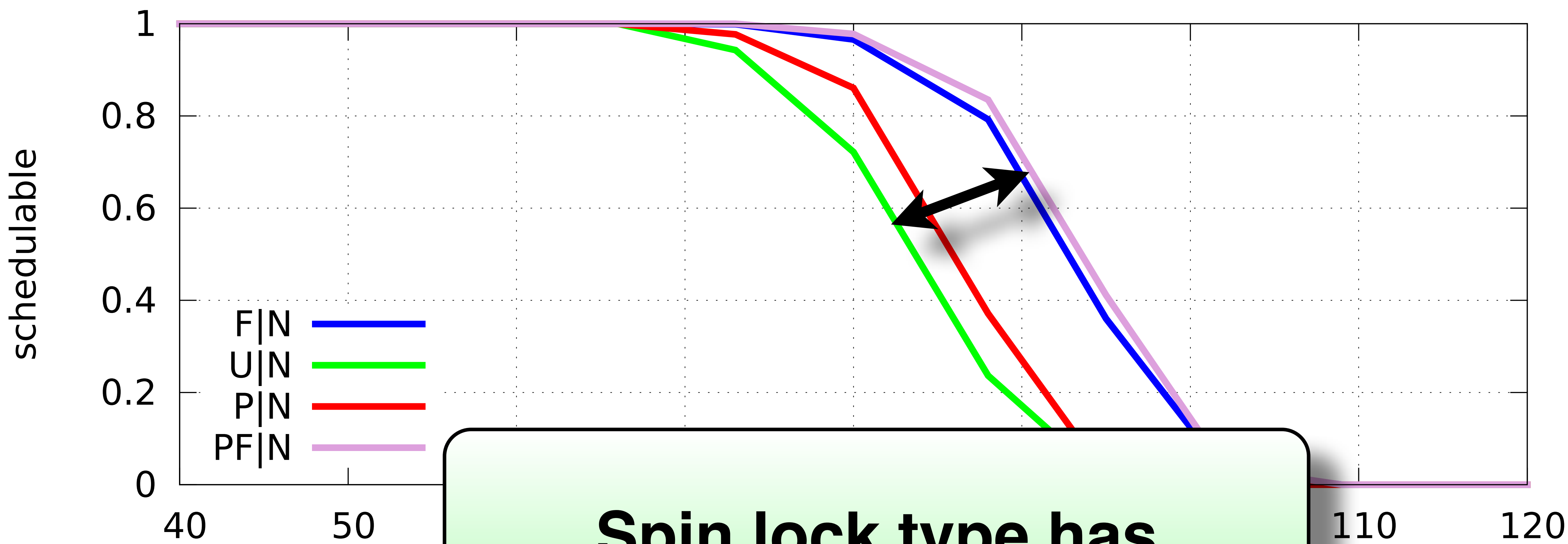


**Spin lock type has significant impact** on schedulability.

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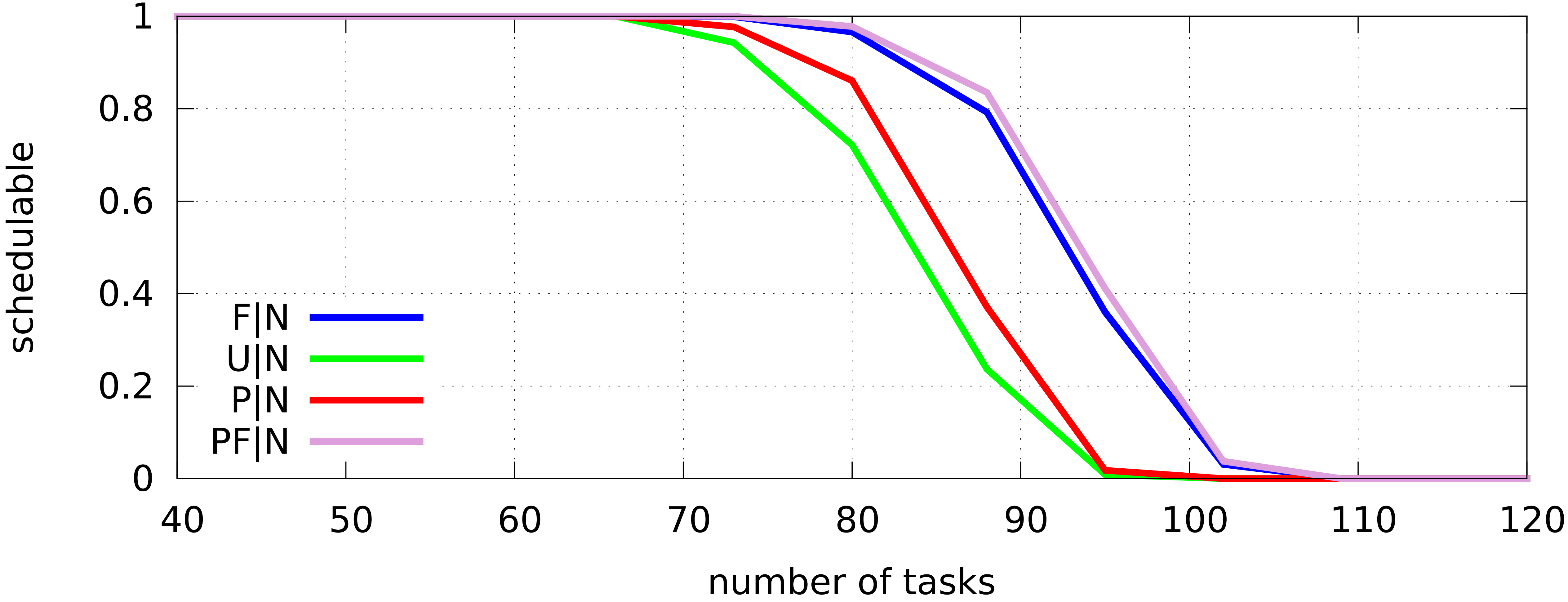

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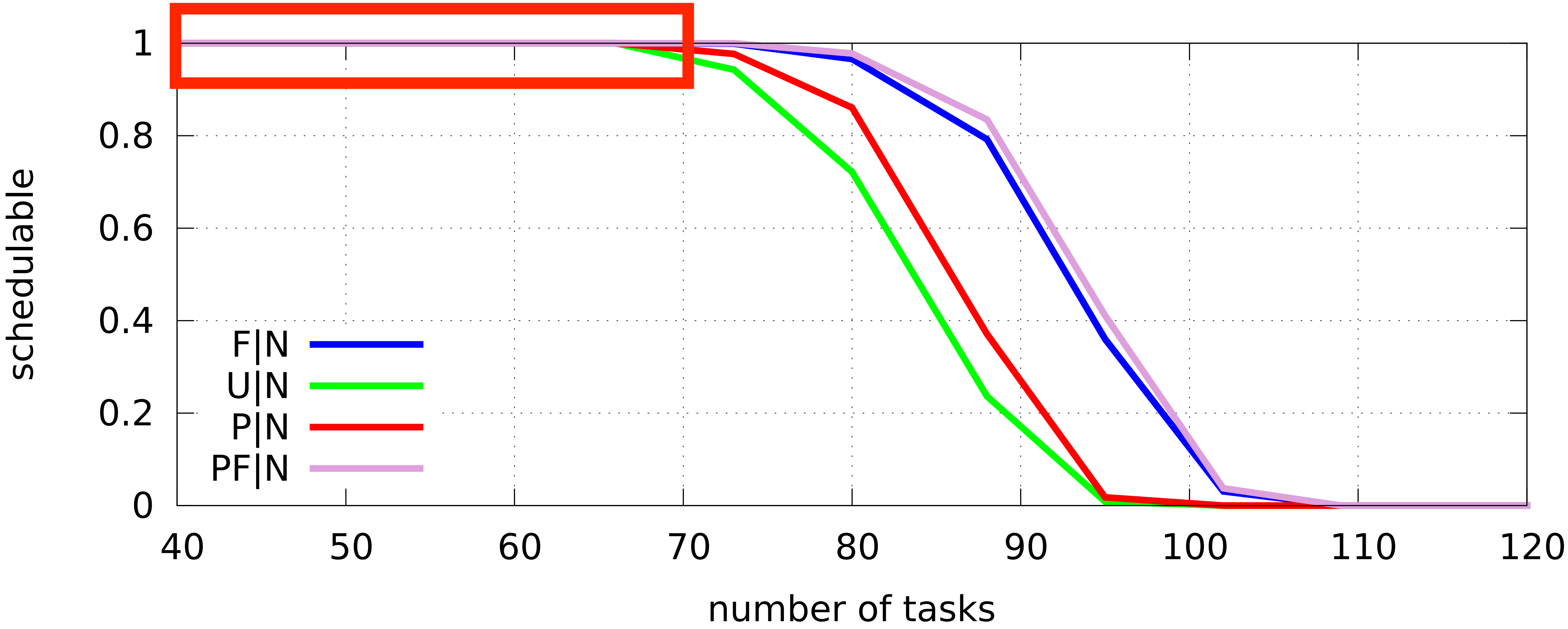

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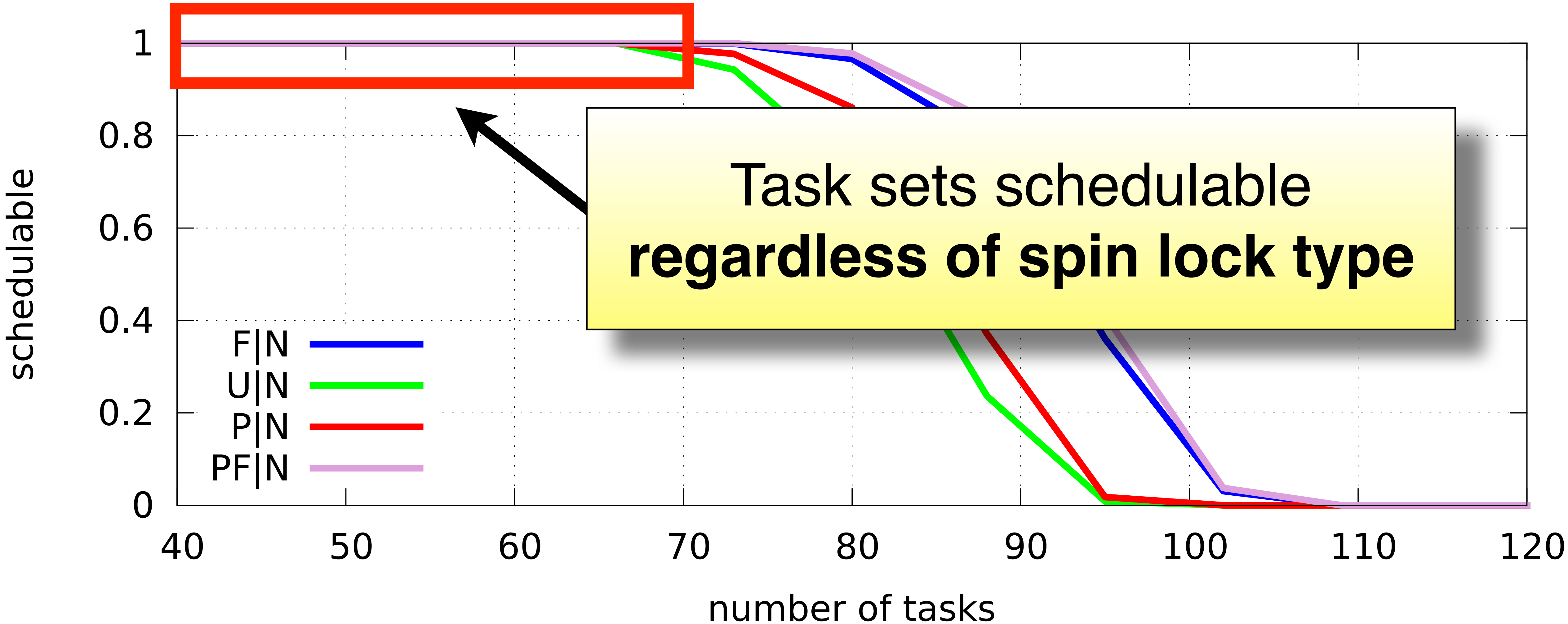

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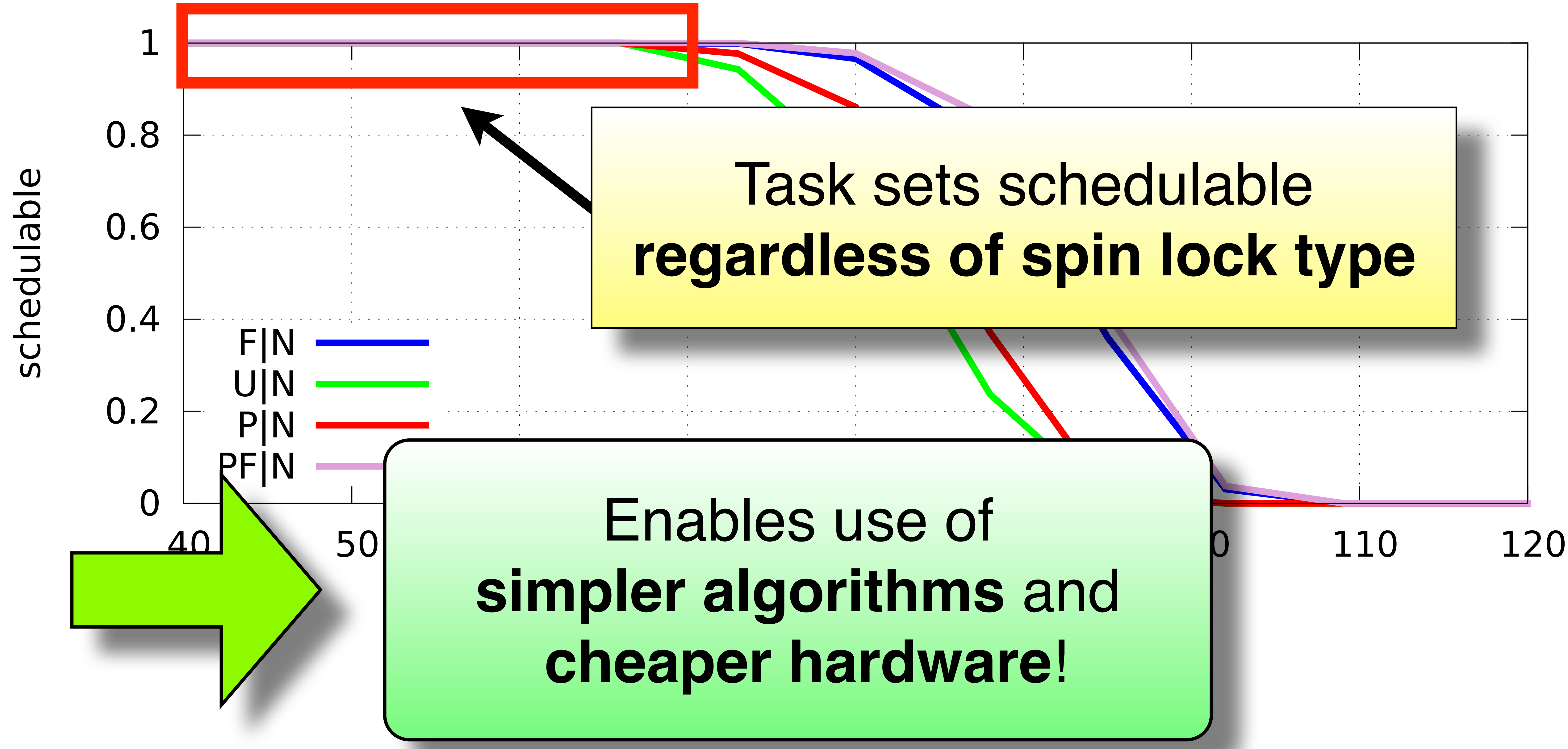


Task sets schedulable **regardless of spin lock type**

Enables use of **simpler algorithms** and **cheaper hardware**!

# Handling
# Unknown Spin Lock Types

Analysis for unordered spin locks
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Analysis for unordered spin locks **applicable for unknown types!**

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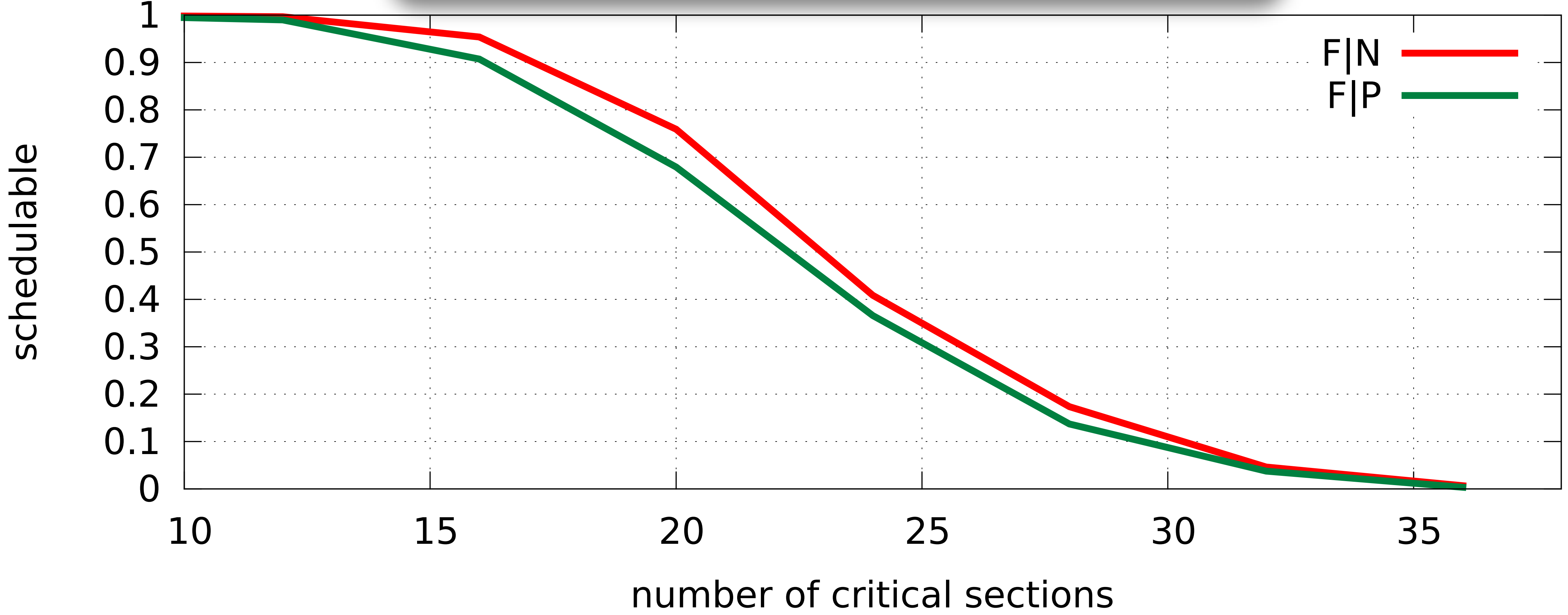

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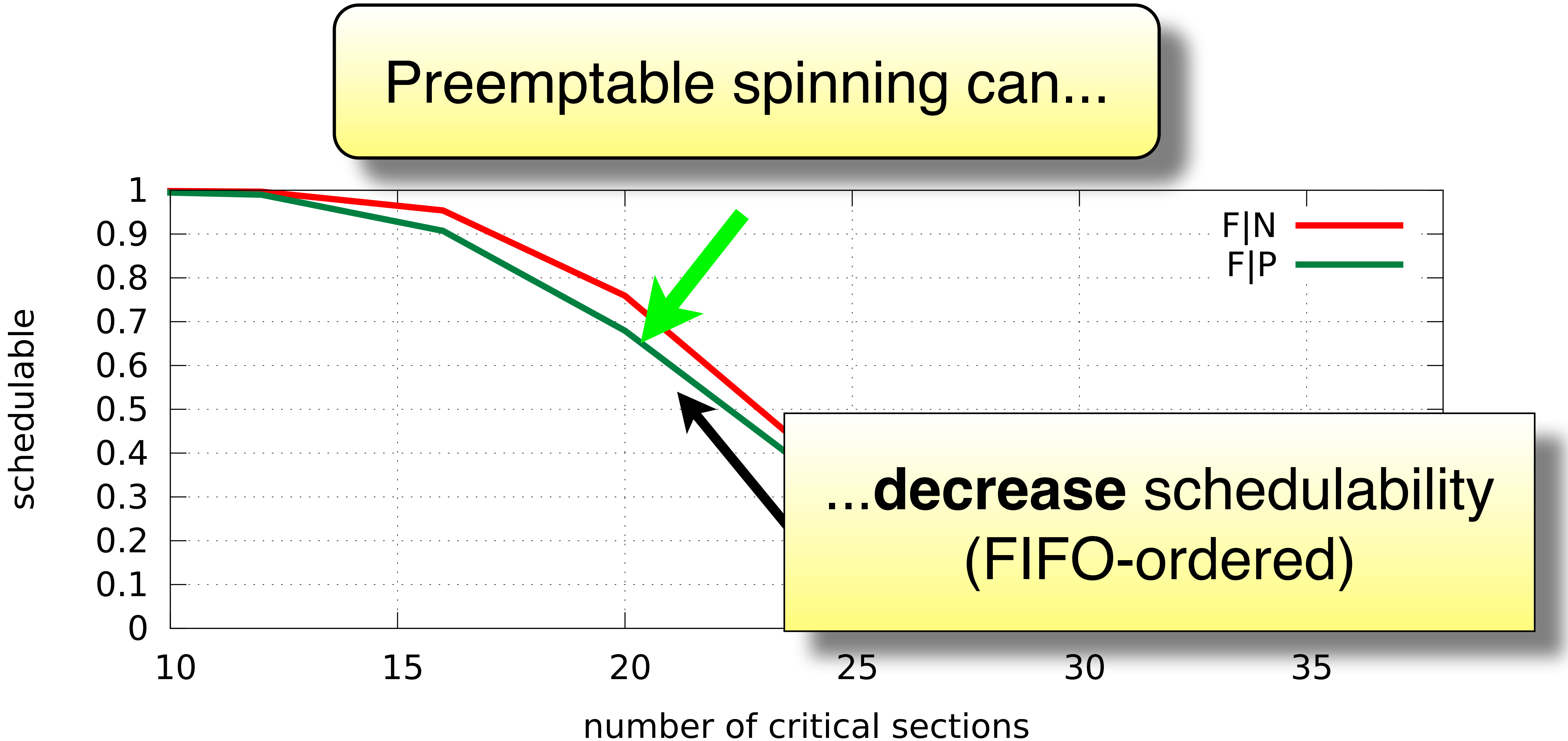

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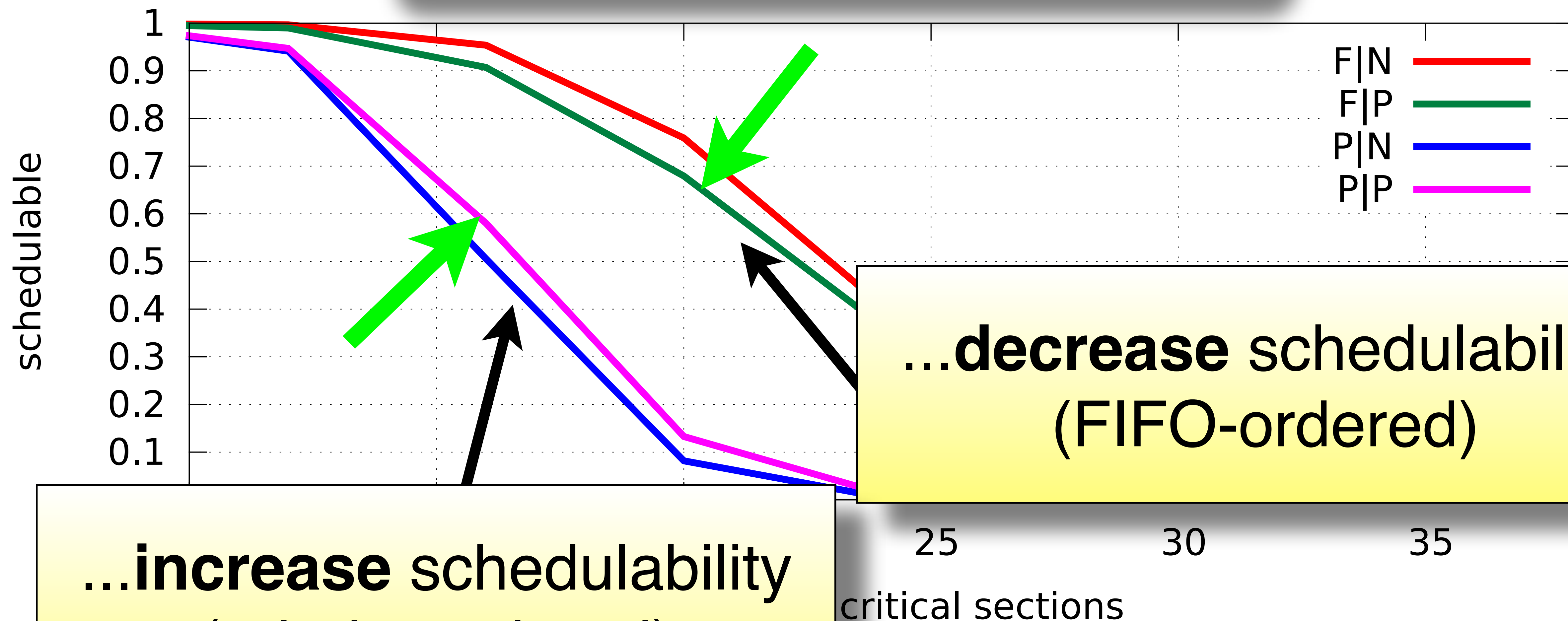


...**decrease** schedulability (FIFO-ordered)

...**increase** schedulability (priority-ordered)

# Summary and Conclusions

# Suggested AUTOSAR API changes

Spin lock type has significant impact on schedulability.

→

**Specify spin lock type**

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**Support FIFO and priority ordering** in AUTOSAR

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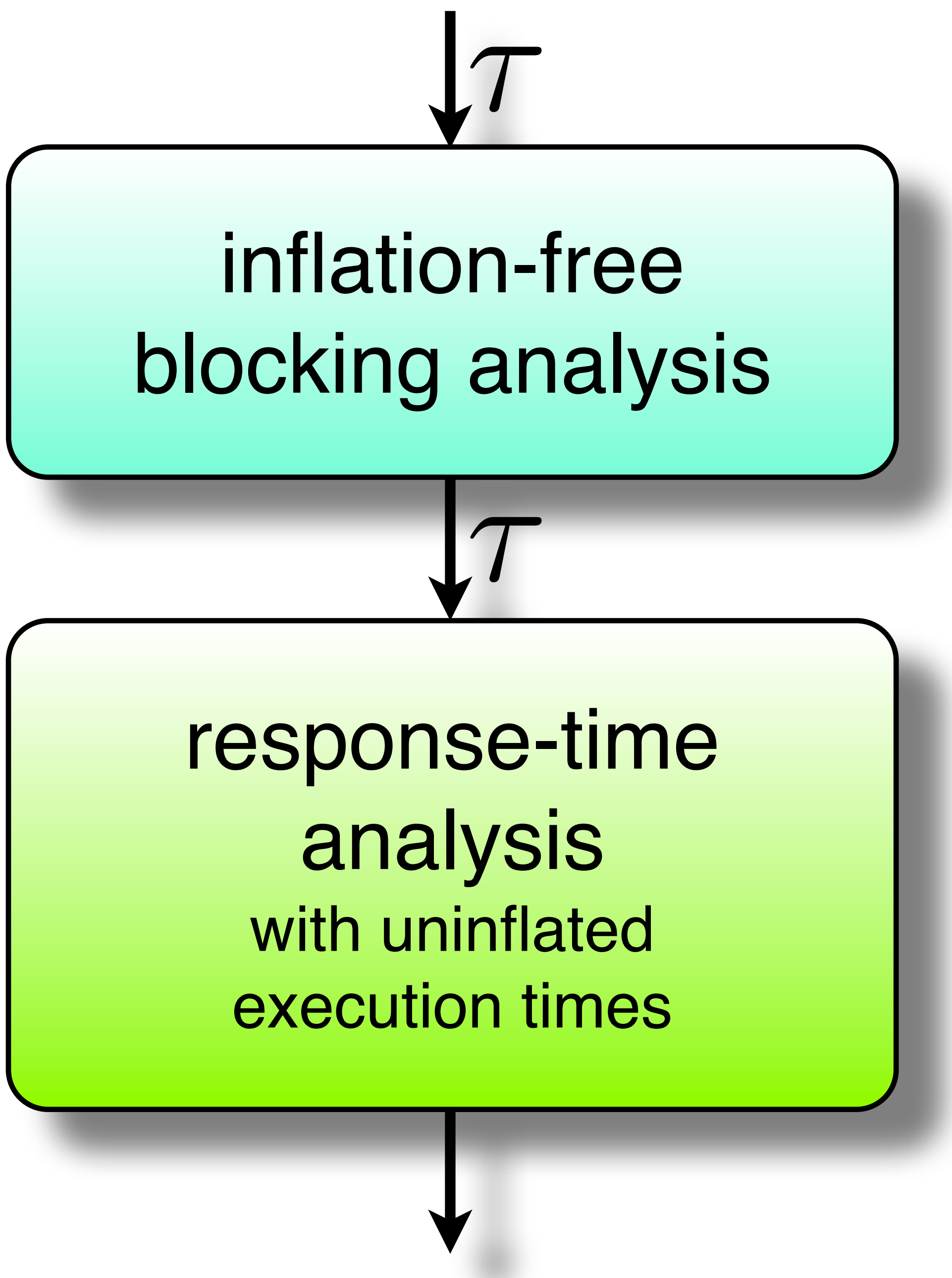
**Support FIFO and priority ordering** in AUTOSAR

Preemptable spinning can improve schedulabiliy.

Support **preemptable spinning with ordering guarantees**

# Summary

Novel blocking analysis
for spin locks:



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suggestions for AUTOSAR

# Future Work

Current analysis assumes non-nested critical sections.

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Nested critical sections:
**work in progress**

*Fin*