

Global Real-Time Semaphore Protocols: A Survey, Unified Analysis, and Comparison

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Max
Planck
Institute
for
Software Systems

RTSS 2015

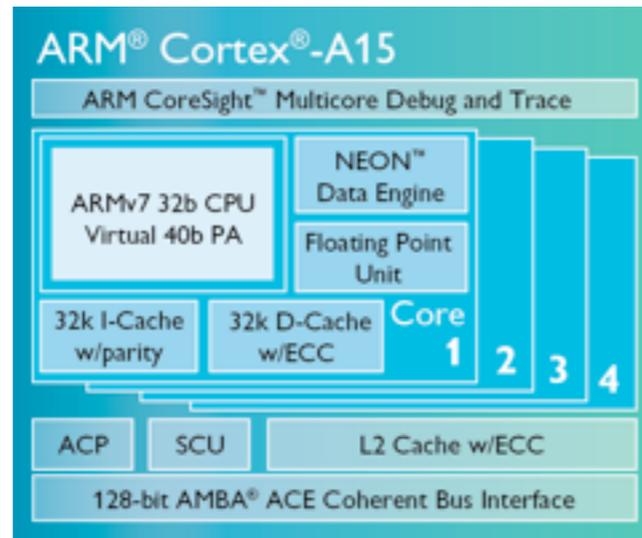
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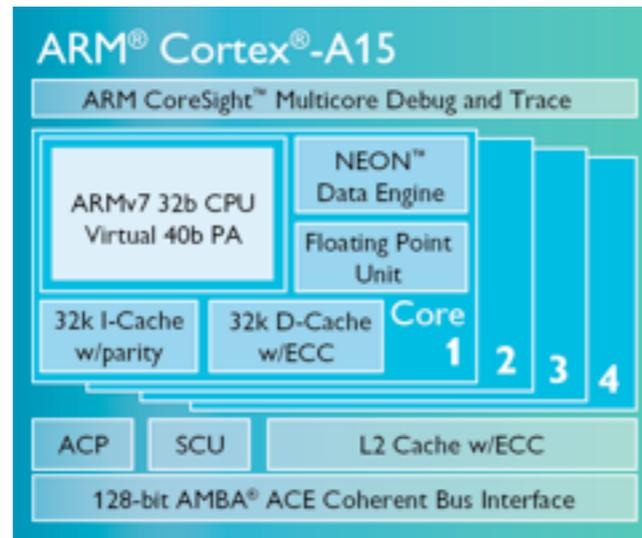


MAX-PLANCK-GESELLSCHAFT

Multicore is now a standard platform for deployment.



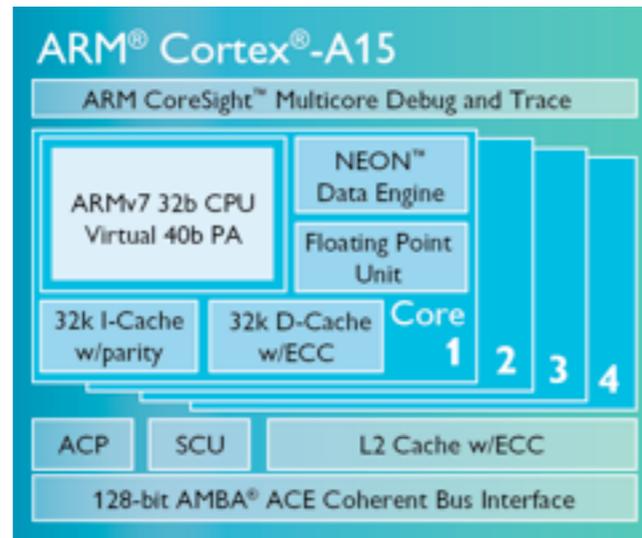
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Global fixed-priority scheduling is well understood.

default on VxWorks, QNX, Linux, ...

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Which **semaphore locking protocol** should be used for protecting **shared resources**?

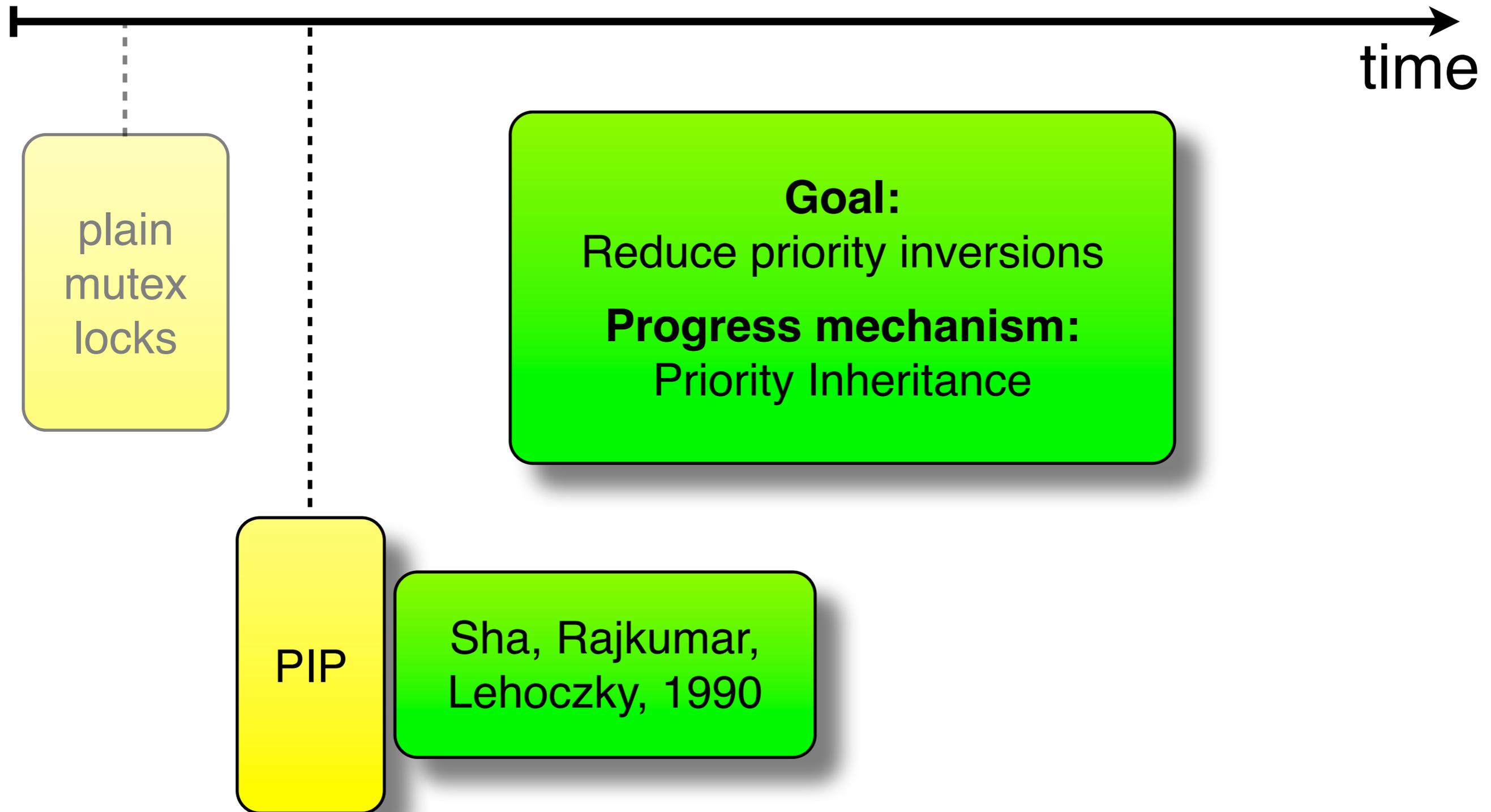
Locking Protocols for Global Scheduling



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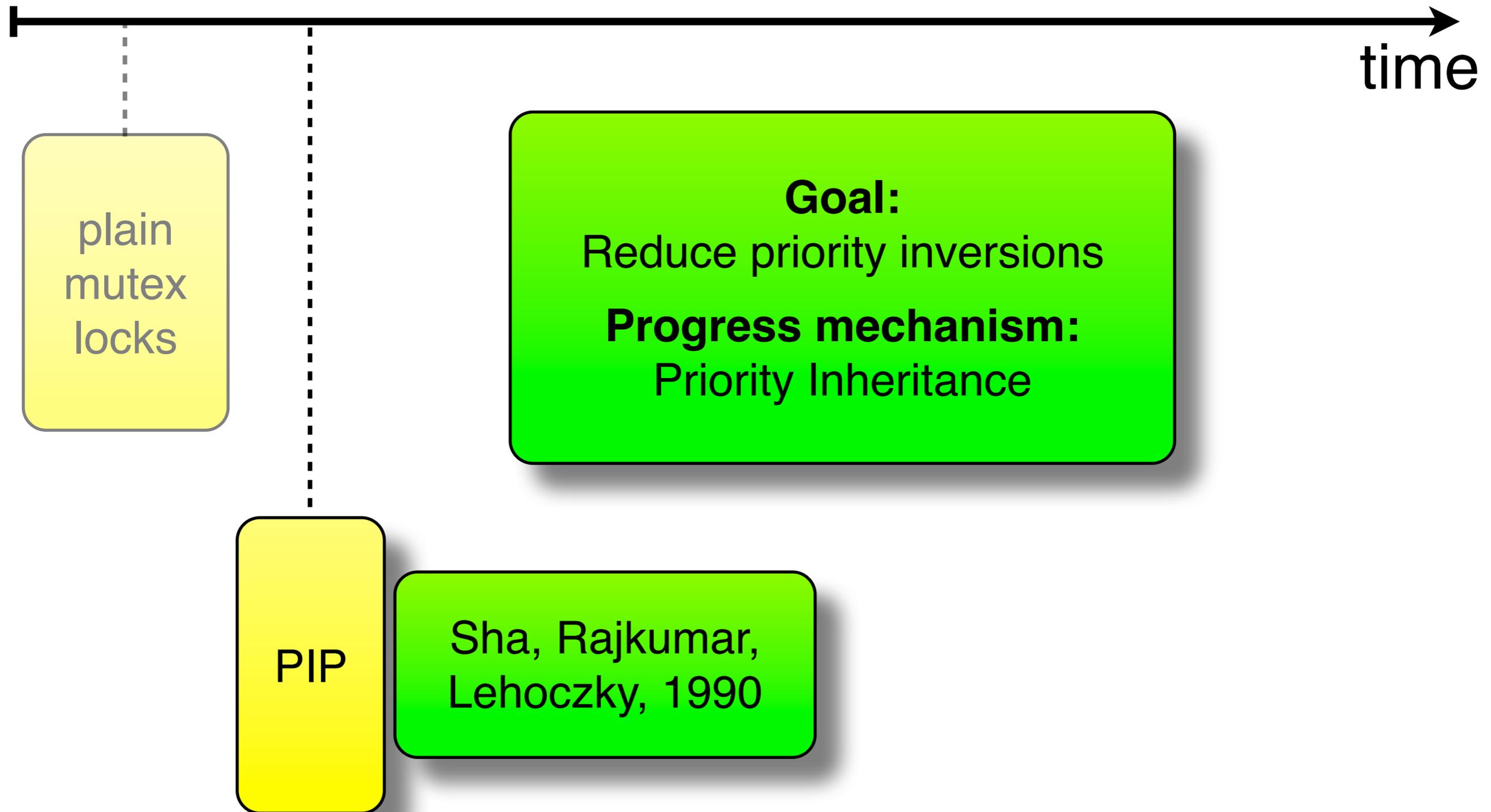


Progress Mechanism: Priority Inheritance (PI)

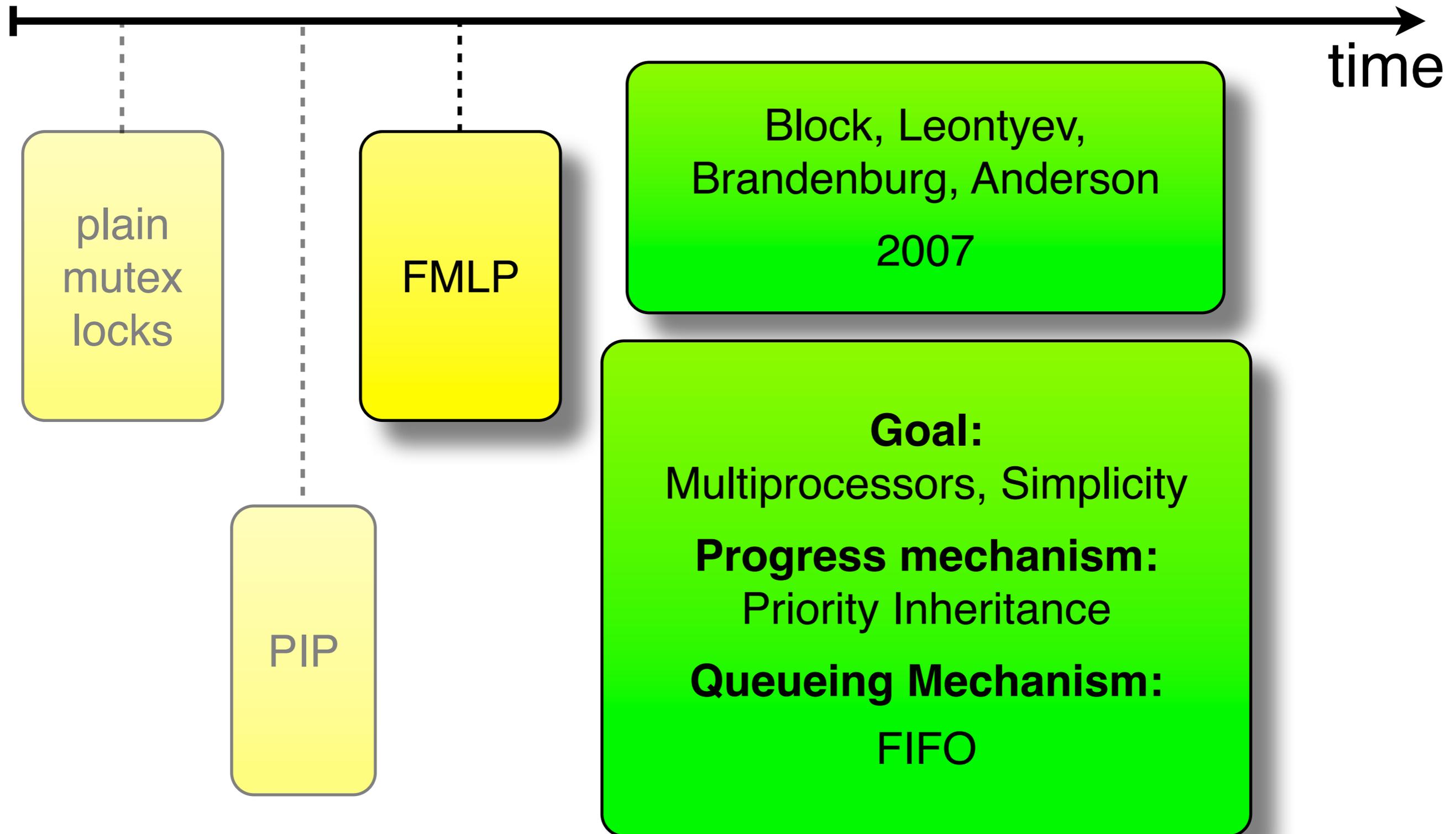
Priority Inheritance:

A resource-holding job
inherits the priority of a higher-priority
job blocked on the same resource.

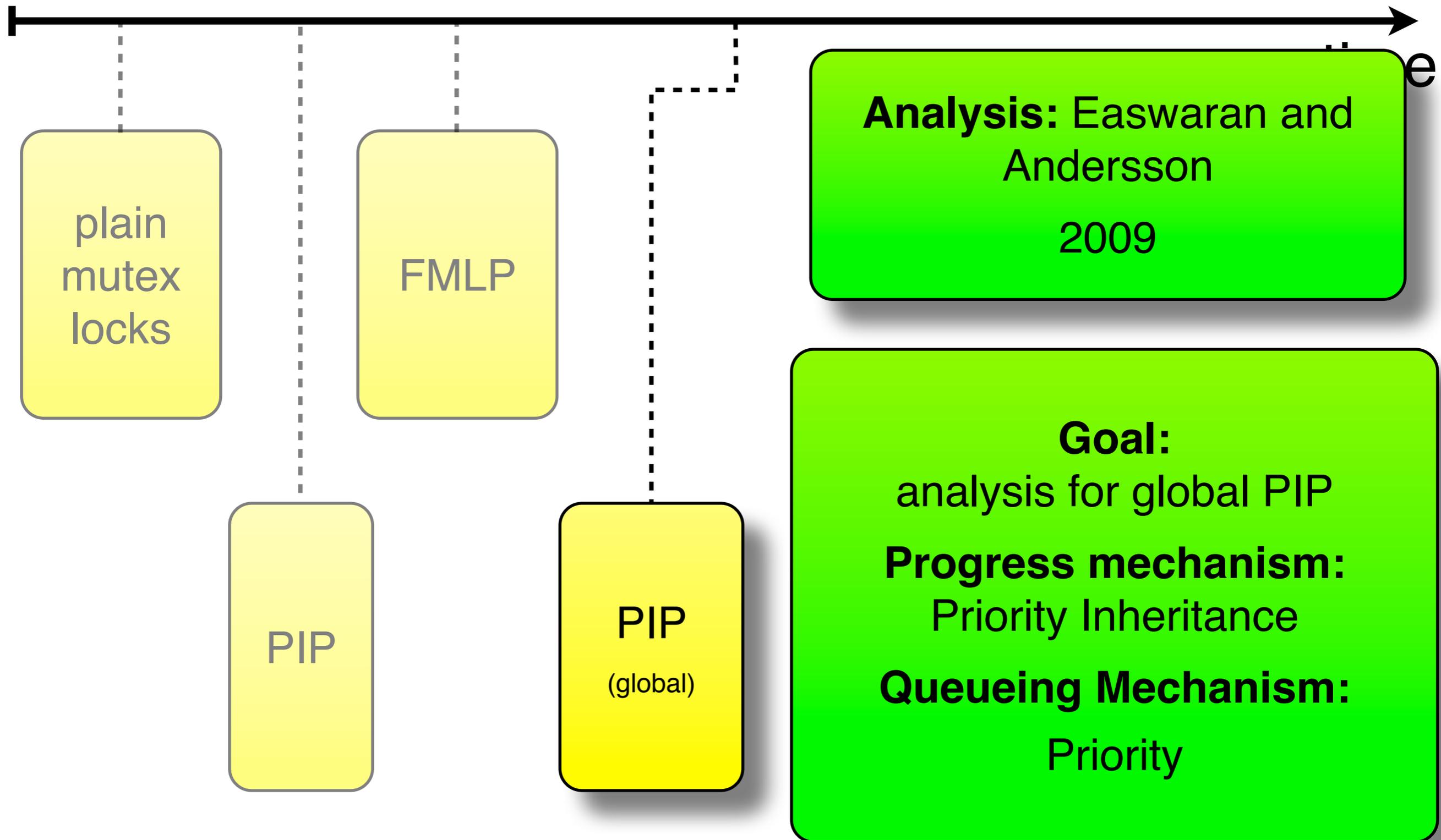
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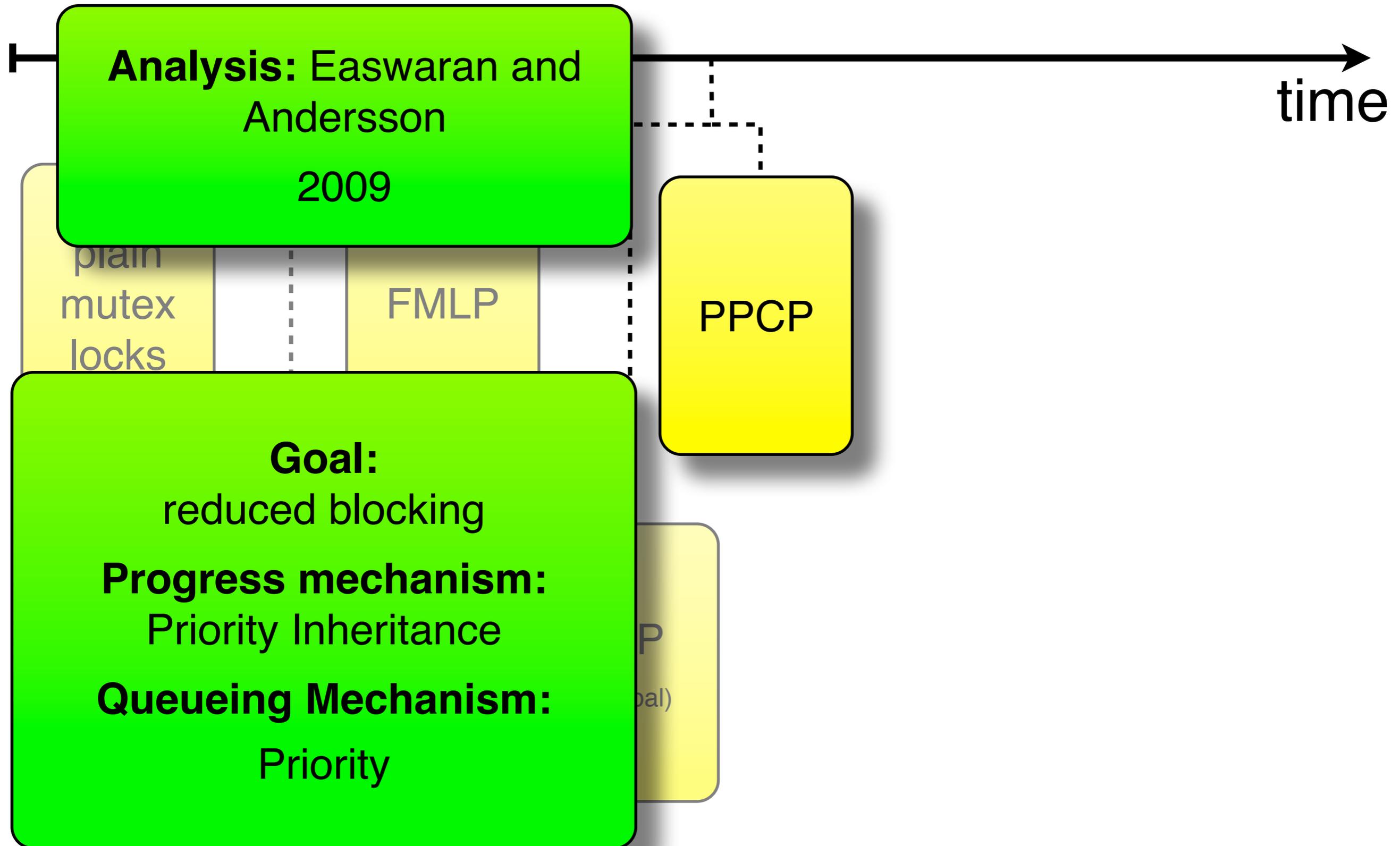
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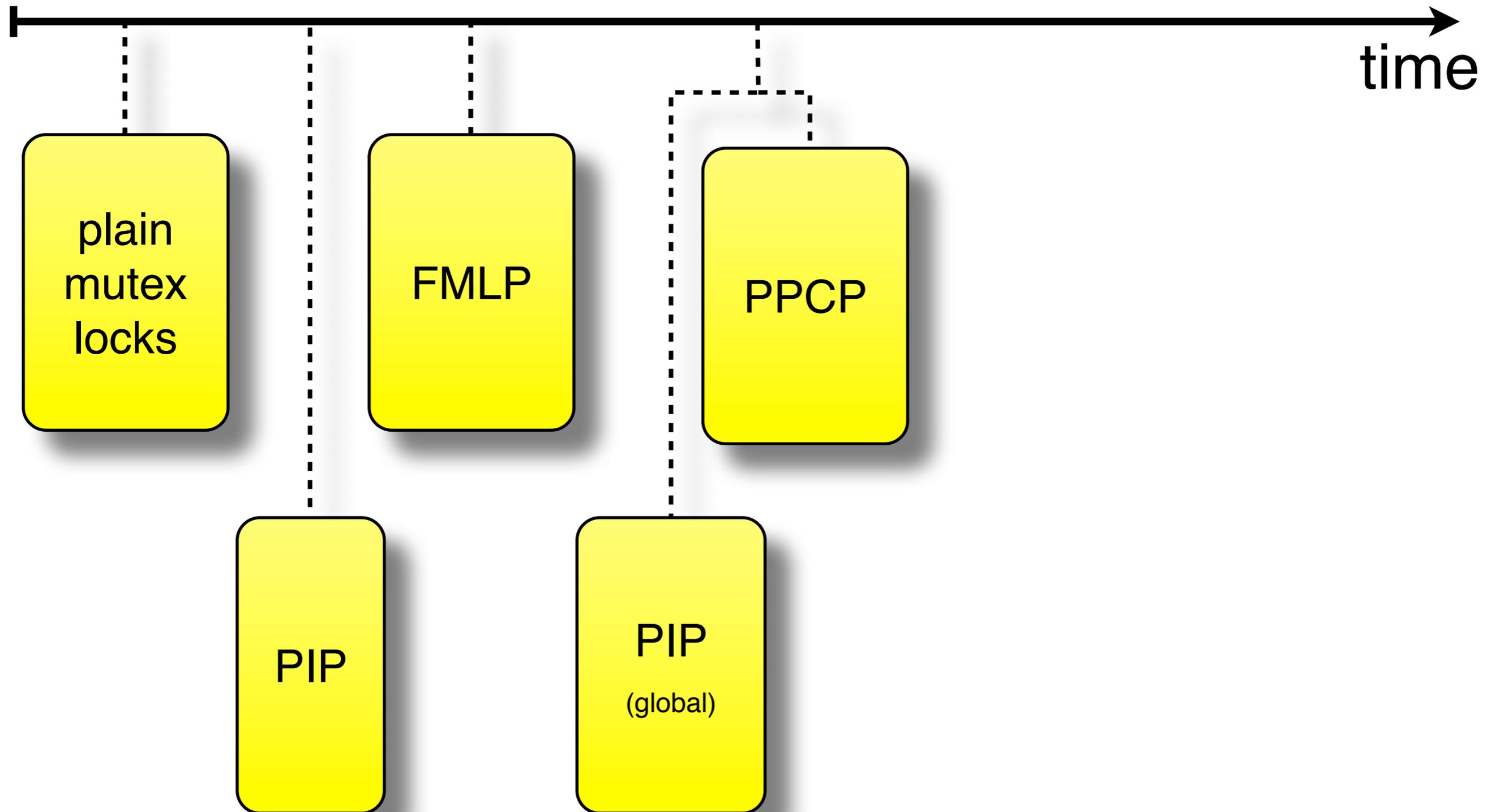
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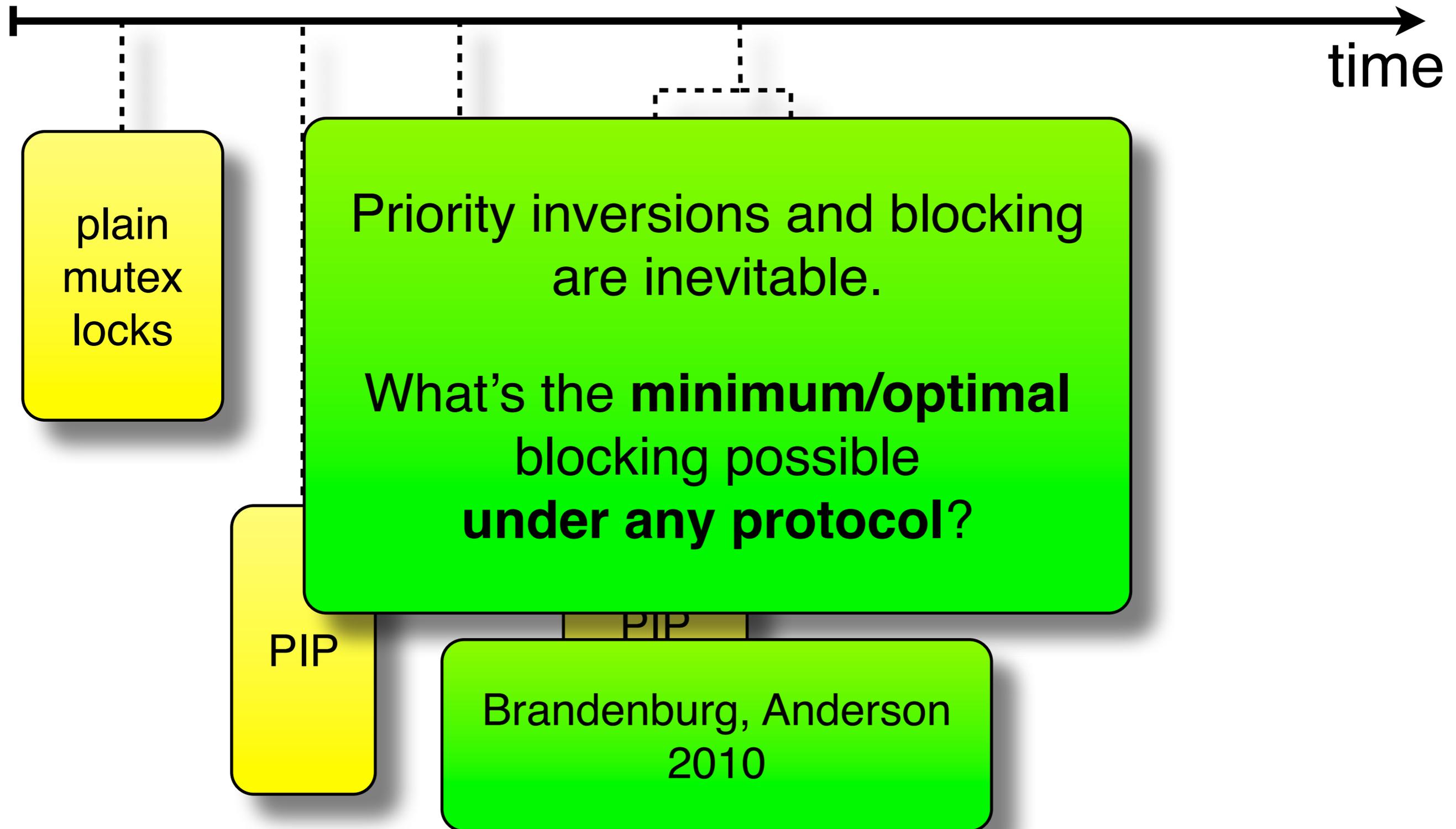
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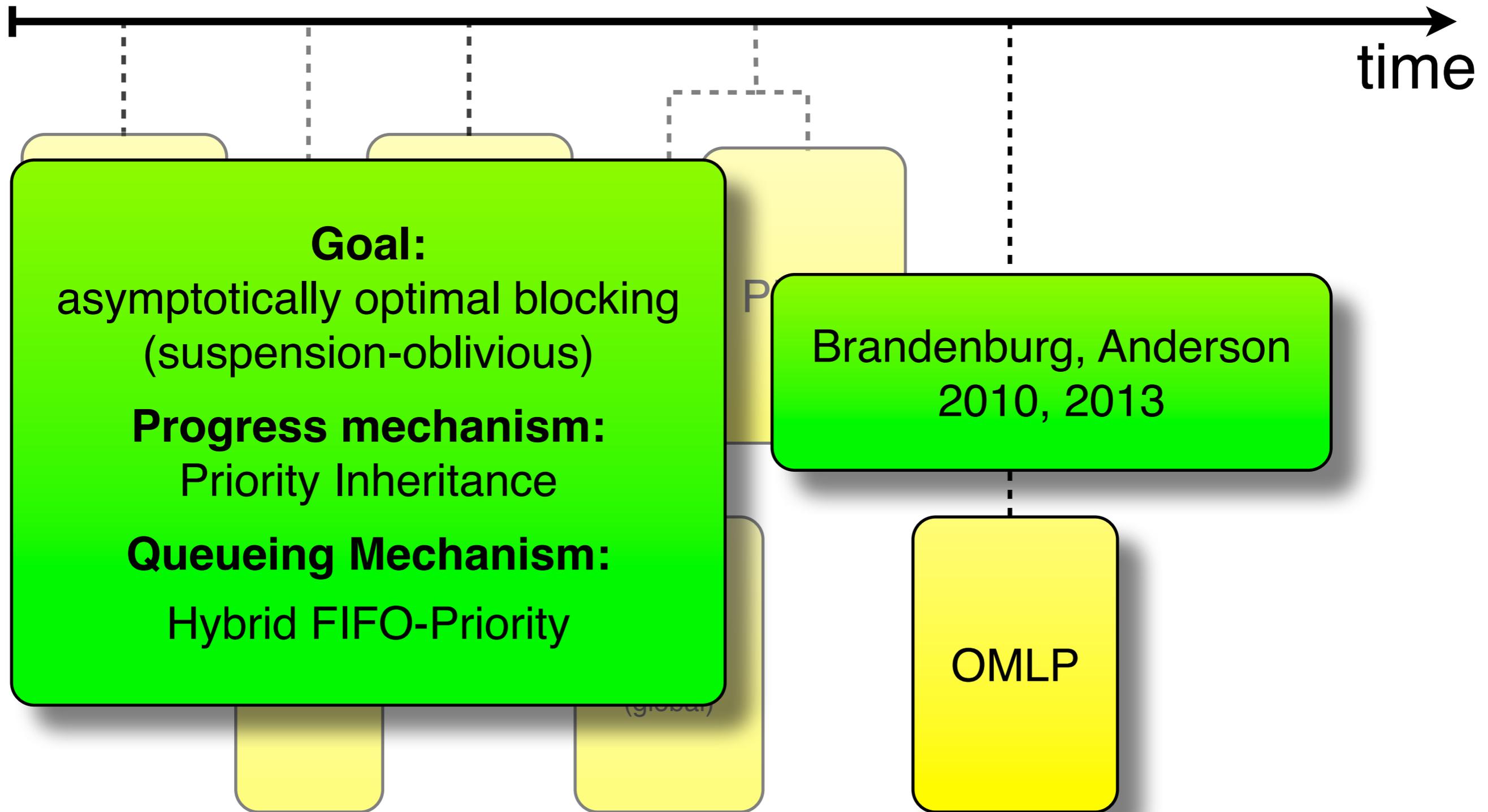
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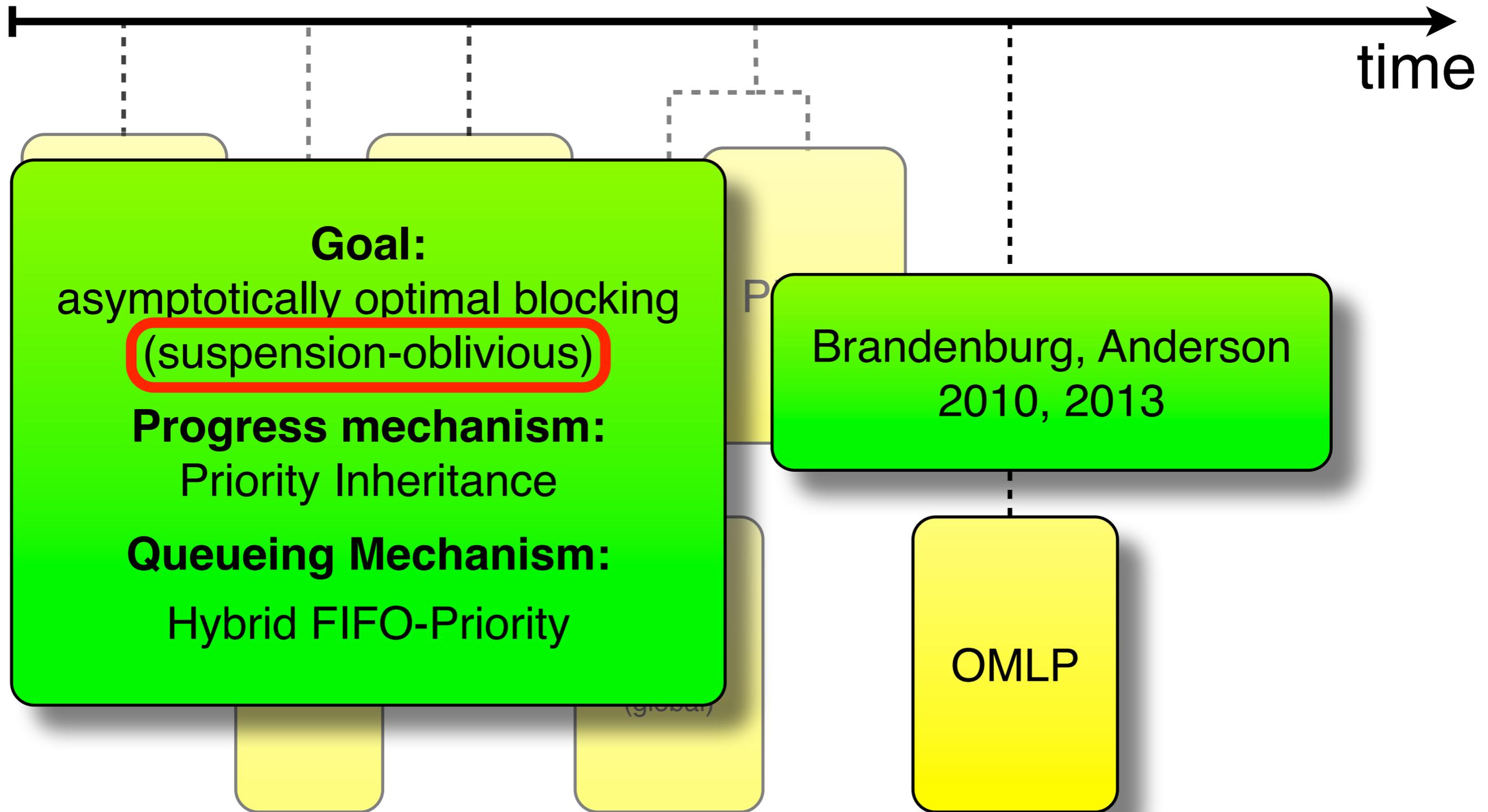
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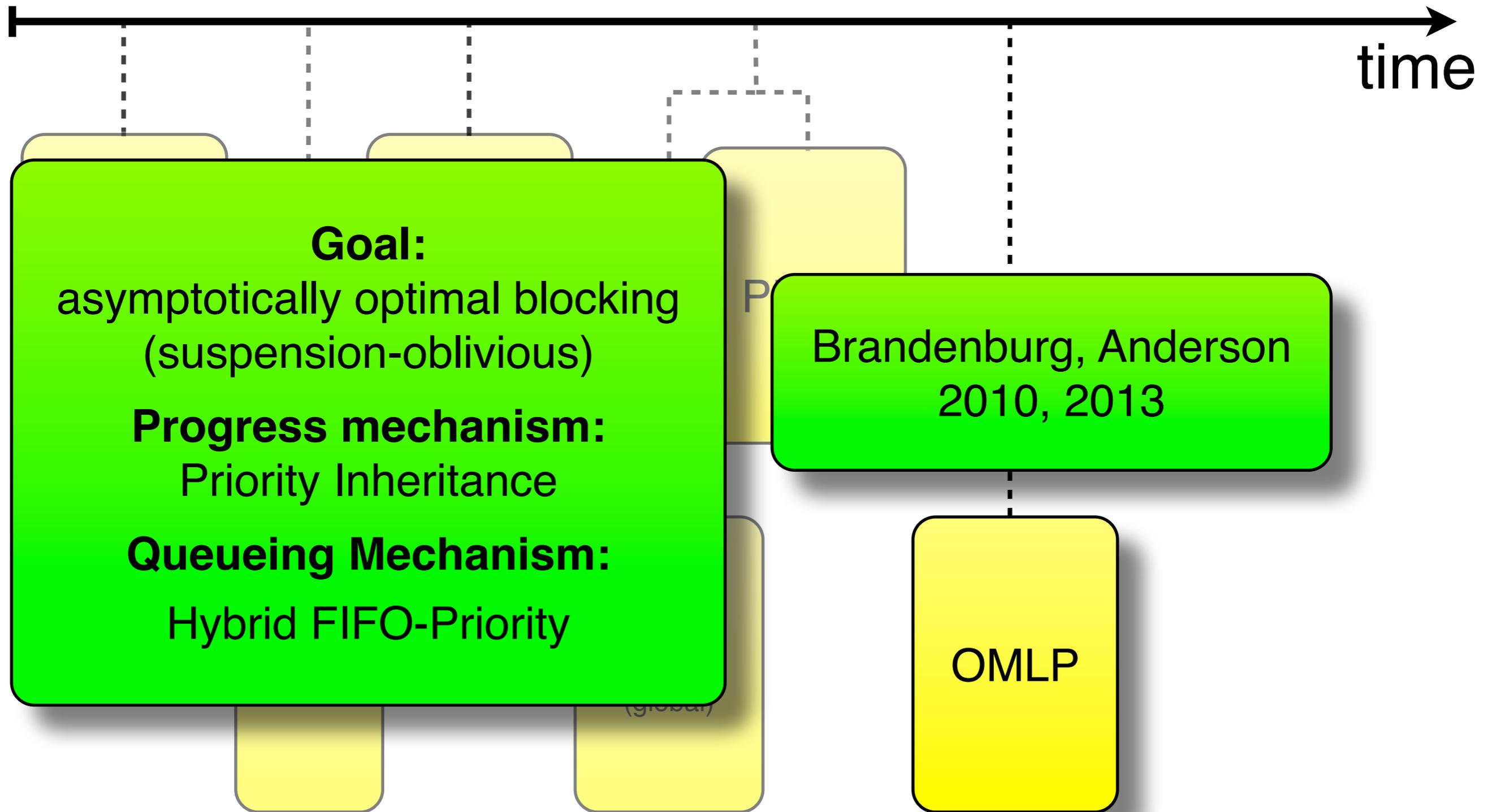
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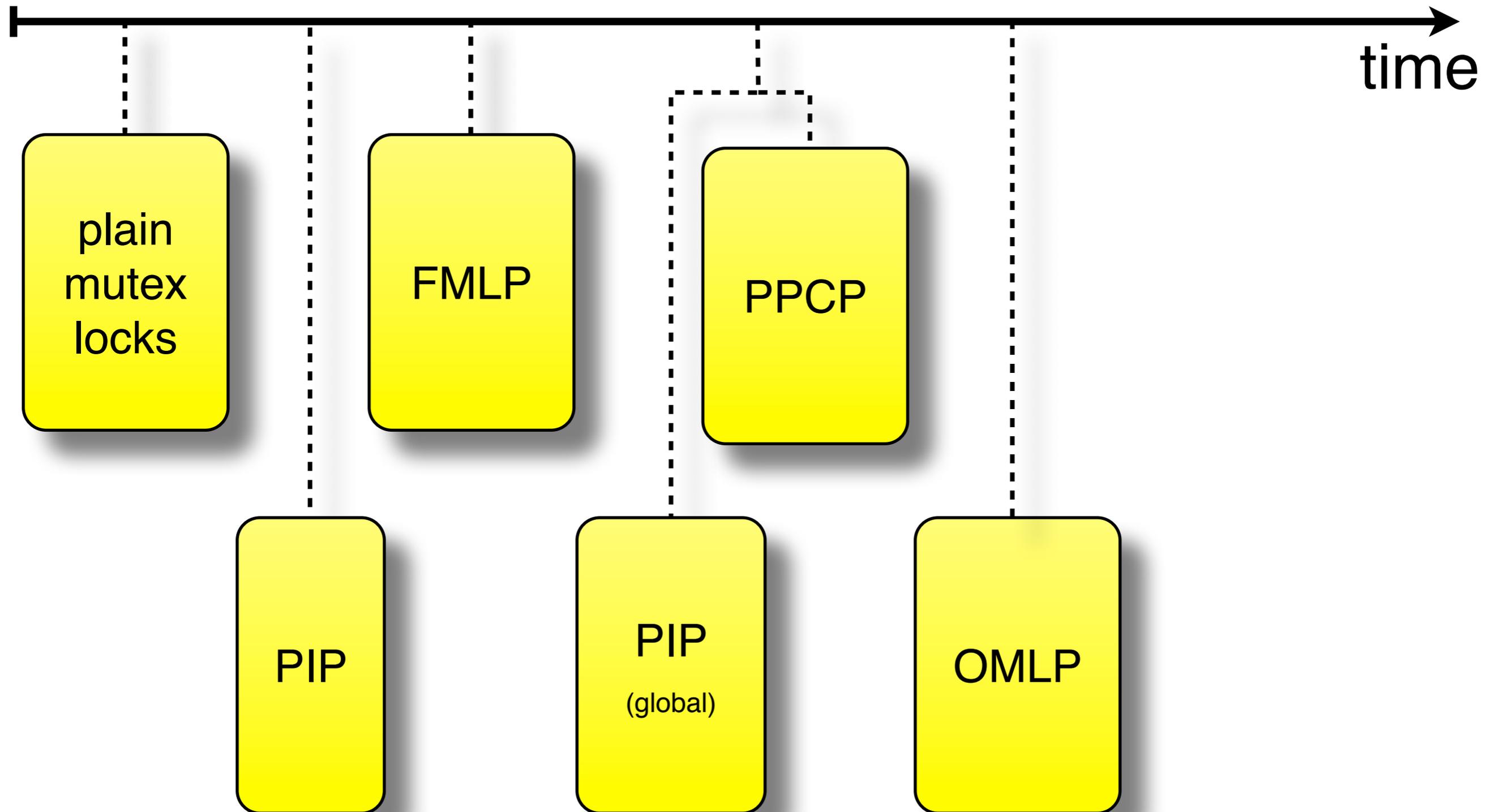
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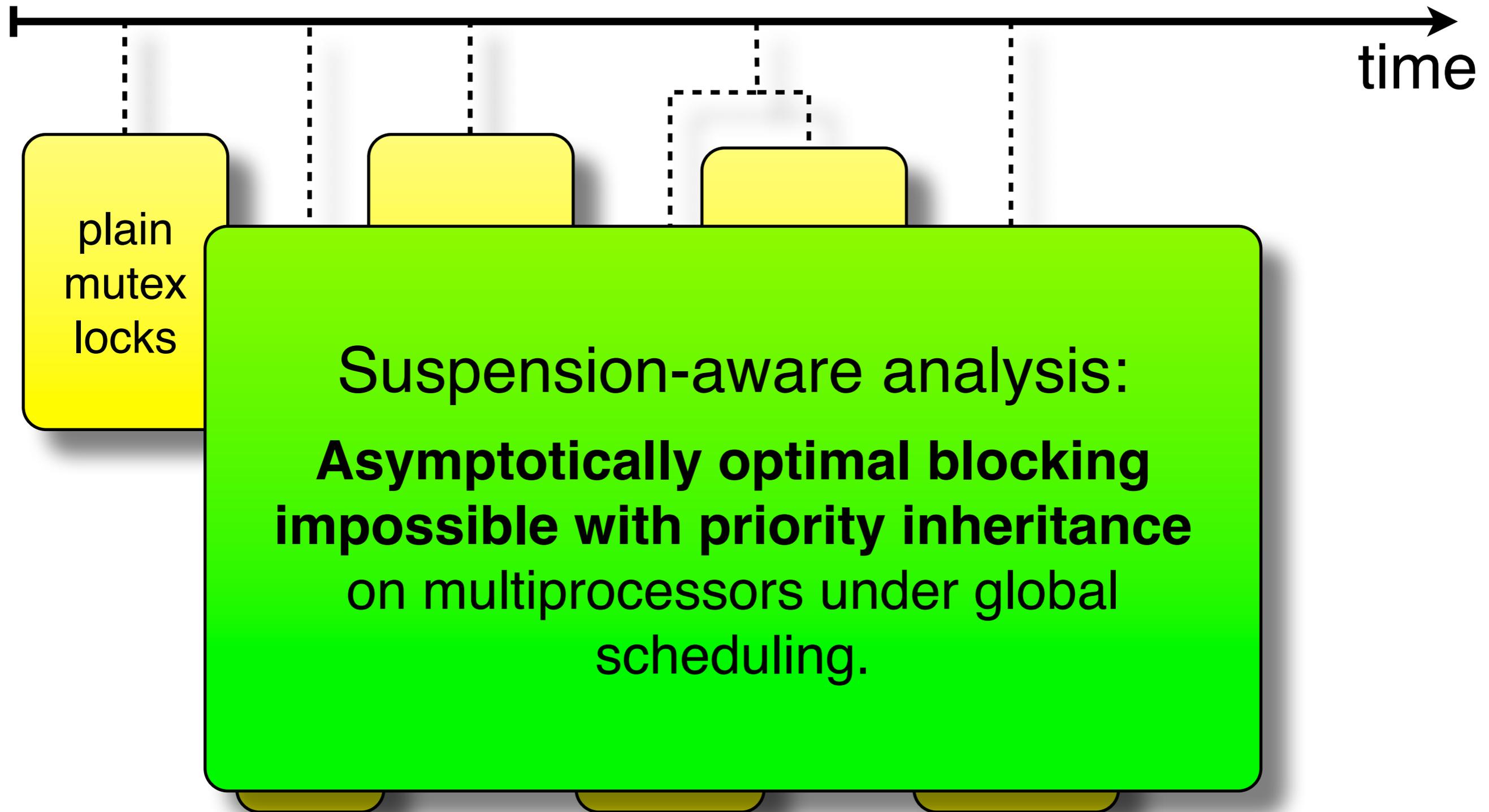
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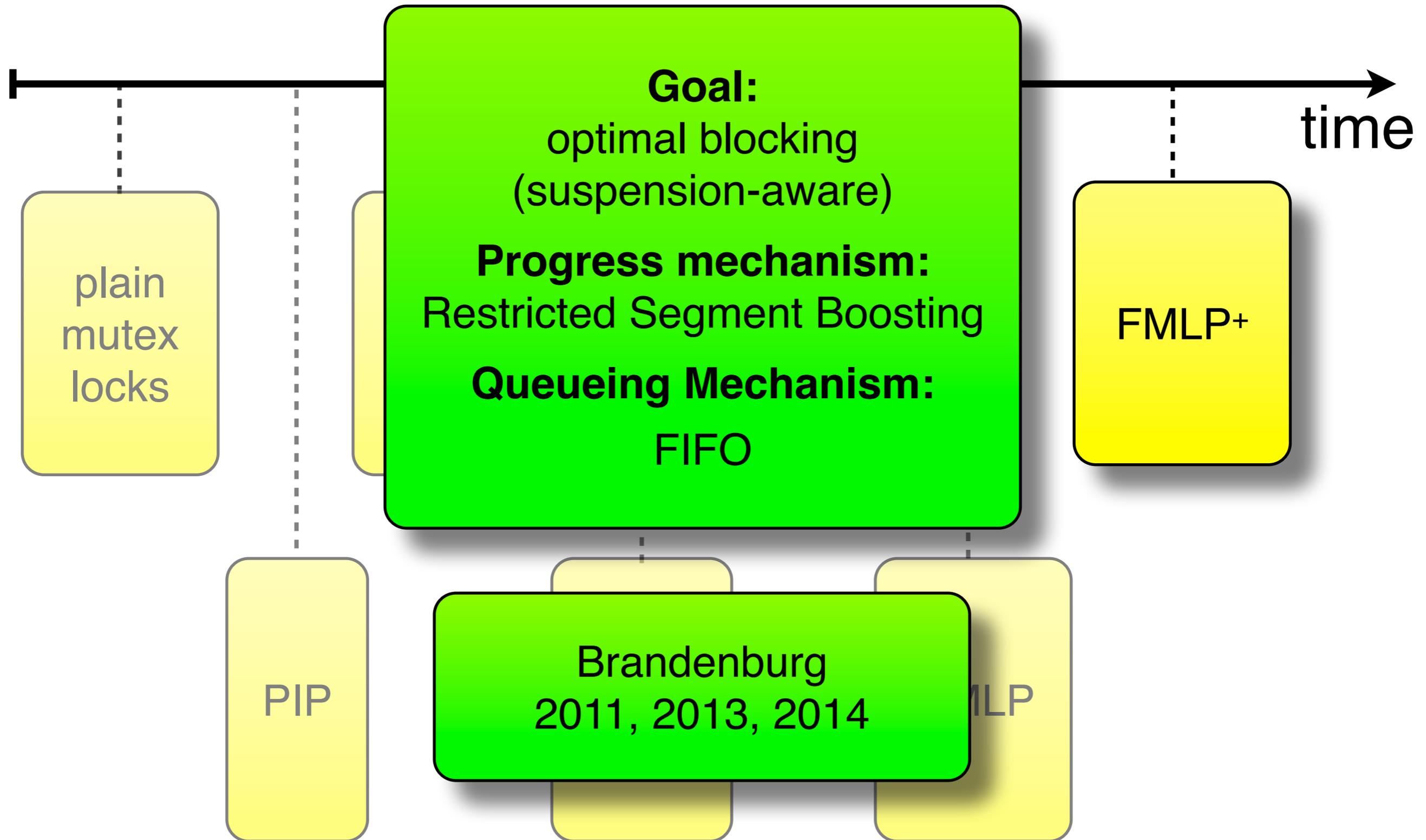
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Locking Protocols for Global Scheduling



Progress Mechanism: Restricted Segment Boosting (RSB)

Restricted Segment Boosting

Job execution split into
independent segments and **request segments**.

Job in request segment with earliest request segment start time is **priority boosted**.

Up to $m - 1$ jobs in independent segment with higher priority are **co-boosted**.

Progress Mechanism: Restricted Segment Boosting (RSB)

Restricted Segment Boosting

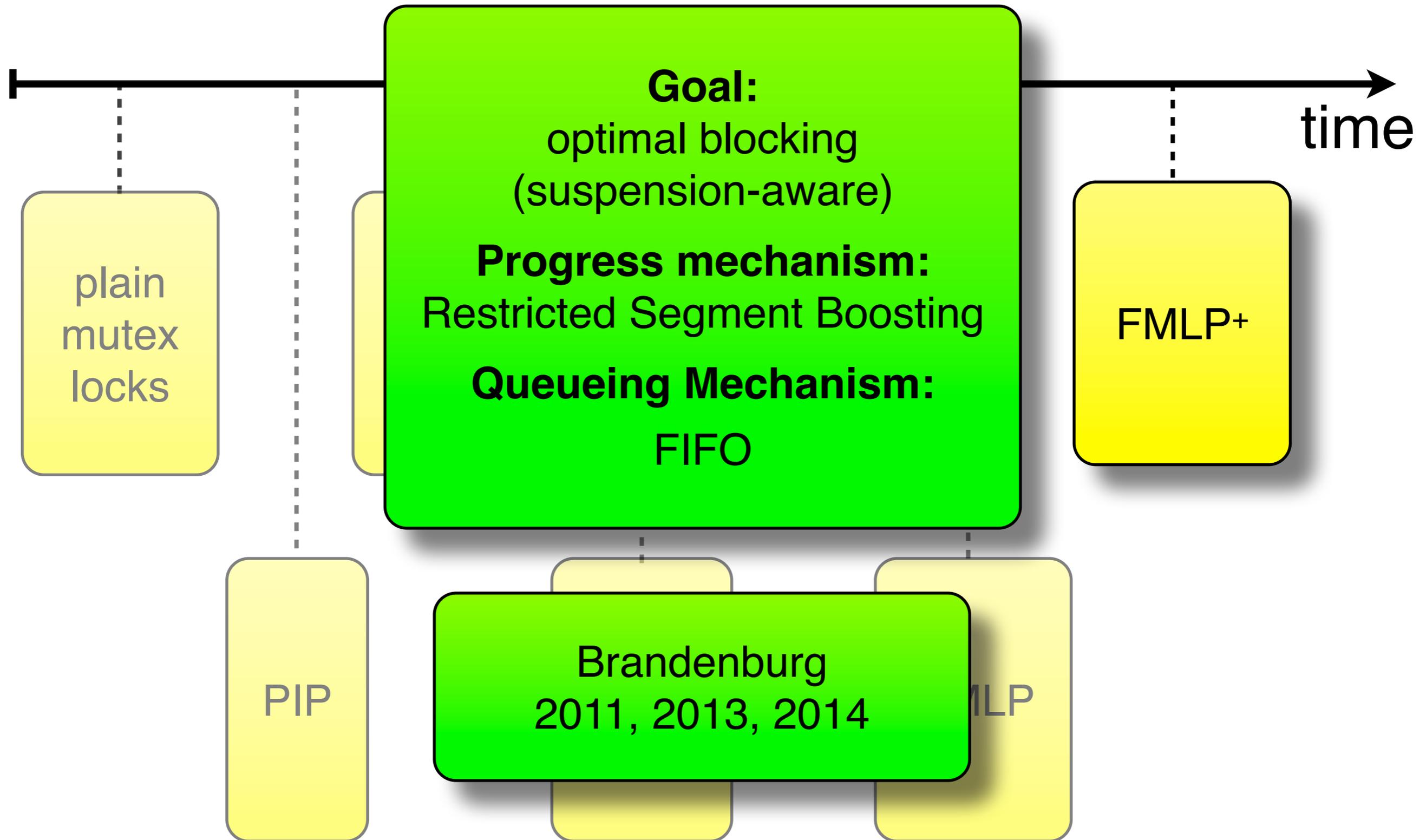
Job execution
independent

**required to obtain
asymptotic optimal blocking
in face of pathological cases**

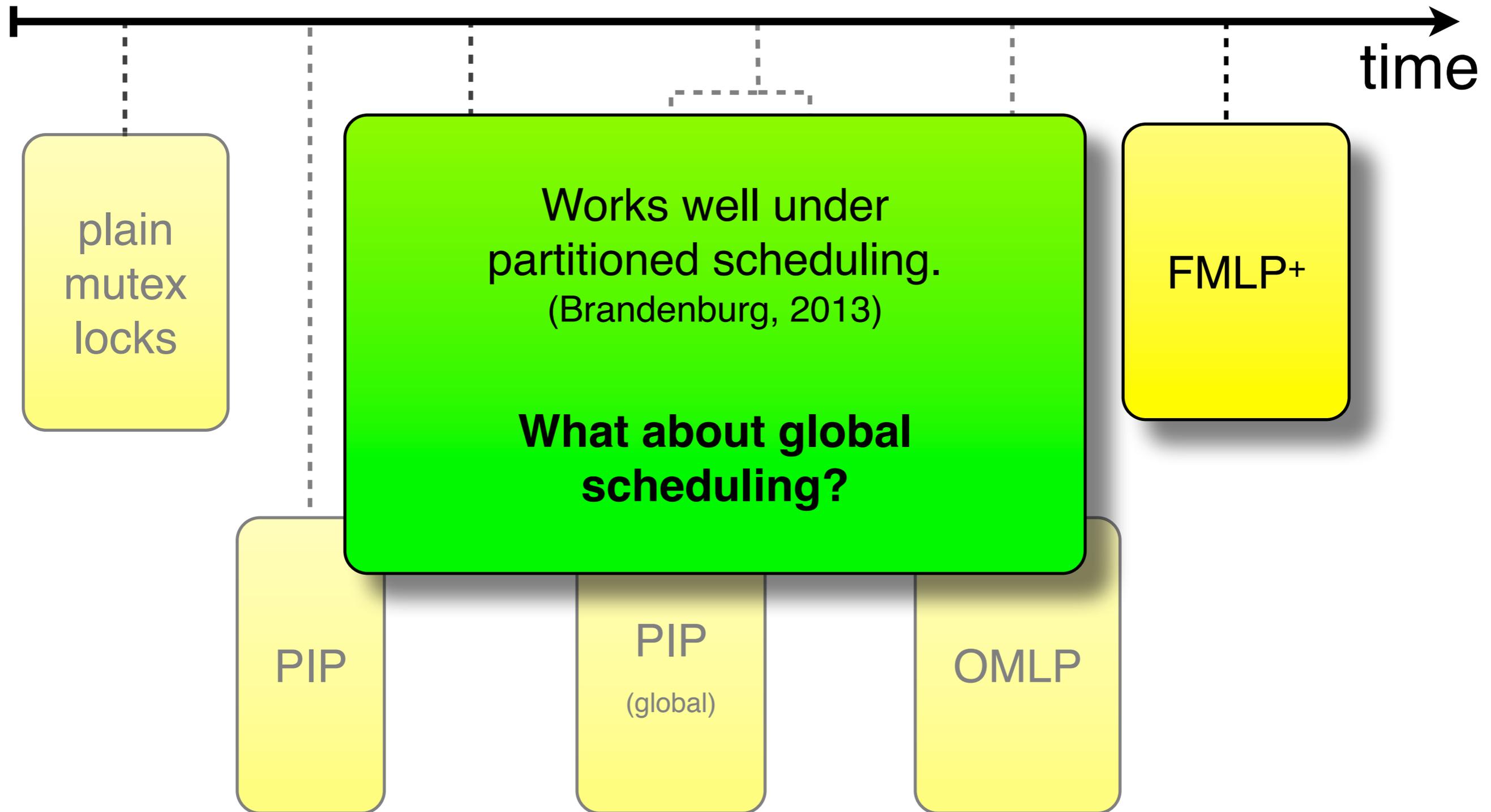
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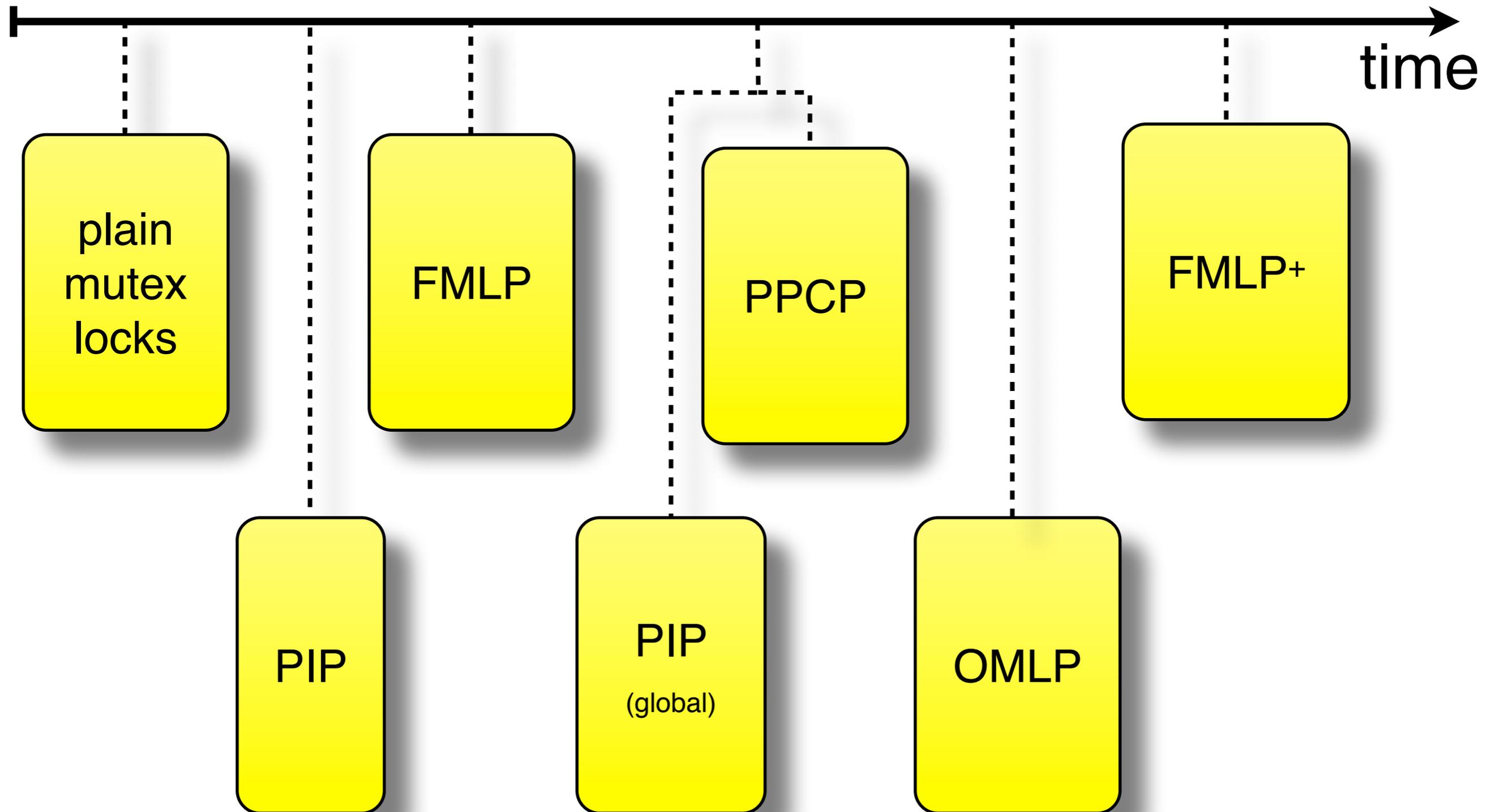
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no progress mechanism
FIFO or priority ordering

Locking Protocols for Global Scheduling

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Priority-RSB:
variant of FMLP+ with
RSB and priority ordering

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Locking Protocols for Global Scheduling

Which locking protocols would be reasonable default choices?

| FMLP | PI | FIFO |
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Locking Protocols for Global Scheduling

Which locking protocols would be reasonable default choices?

No comprehensive comparison in prior work!

| | FMLP | PI | FIFO |
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Locking Protocols for Global Scheduling

Which locking protocols would be reasonable default choices?

No comprehensive comparison in prior work!

Analysis techniques improved!

Our solution:

Unified
Suspension-Aware
Blocking Analysis
Framework
for Global Scheduling

providing **higher accuracy** with
state-of-the-art analysis methods

Locking Protocols for Global Scheduling

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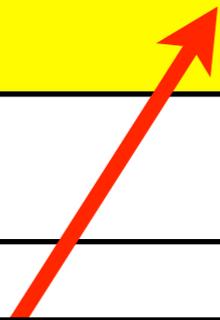
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Which locking protocols would be reasonable default choices?



Outline

~~Intro~~

Unified Analysis Framework

Evaluation Results

Summary and Conclusion

LP-Based Blocking Analysis

Prior work:

Successfully applied to suspension-based and spin-based locks under partitioned scheduling.

LP-Based Blocking Analysis

Key idea: Blocking analysis modeled as a linear optimization problem (LP).

- **objective:** maximize blocking to obtain safe bound
- **constraints:** encode locking protocol invariants
- **variables:** enumerate all critical sections that might contribute to blocking

LP-Based Blocking Analysis

Benefits:

- **no need to identify or characterize worst case**
- **no double counting**: each critical section is accounted for at most once
- **simple composable constraints**: constraints specified and proven independently for each protocol invariant or property
- **constraints rule out impossible scenarios** rather than capturing worst-case behavior
- **generic LP solver used** to obtain safe bound

LP-Based Blocking Analysis

Example constraint:

FIFO queuing:

Each job can have at most one pending request.

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

LP-Based Blocking Analysis

Example constraint: task T_i under analysis

Constraint 8: When using FIFO queues:

$$\forall \ell_q, \forall T_x \in \tau^i : \sum_{v=1}^{N_{x,q}^i} X_{x,q,v}^D \leq N_{i,q}.$$

LP-Based Blocking Analysis

Example constraint: task T_i under analysis

Constraint 8: When using FIFO queues:

for each resource $\forall \ell_q, \forall T_x \in \tau^i : \sum_{v=1}^{N_{x,q}^i} X_{x,q,v}^D \leq N_{i,q}$

for each other task

all requests issued by T_x while one job of T_i is pending

blocking variable for direct blocking

max. #requests for ℓ_q issued by a single job of T_i

The diagram illustrates the constraint equation $\forall \ell_q, \forall T_x \in \tau^i : \sum_{v=1}^{N_{x,q}^i} X_{x,q,v}^D \leq N_{i,q}$. Red arrows point from explanatory text to parts of the equation: 'for each resource' points to $\forall \ell_q$; 'for each other task' points to $\forall T_x \in \tau^i$; 'all requests issued by T_x while one job of T_i is pending' points to the summation $\sum_{v=1}^{N_{x,q}^i}$; 'blocking variable for direct blocking' points to $X_{x,q,v}^D$; and 'max. #requests for ℓ_q issued by a single job of T_i ' points to $N_{i,q}$.

LP-Based Blocking Analysis

Example constraint: task T_i under analysis

Constraint 8: When using FIFO queues:

$$\forall \ell_q, \forall T_x \in \tau^i : \sum_{v=1}^{N_{x,q}^i} X_{x,q,v}^D \leq N_{i,q}.$$

generic and reusable:
constraint used for all
protocols with FIFO-queueing

LP-Based Blocking Analysis for Global Scheduling

Challenge #1: Account for new sources of blocking arising under global scheduling and RSB.

Requires additional blocking types that have to be

- abstract and generic,
- expressive, and
- disjoint.

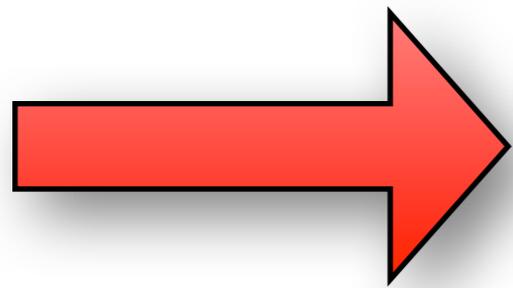
LP-Based Blocking Analysis for Global Scheduling

Challenge #2: LP-based analysis for partitioned scheduling did not need to account for regular interference.

Global scheduling:

Interference and blocking need to be analyzed together to avoid excessive inaccuracy!

LP-Based Blocking Analysis for Global Scheduling



Details in paper

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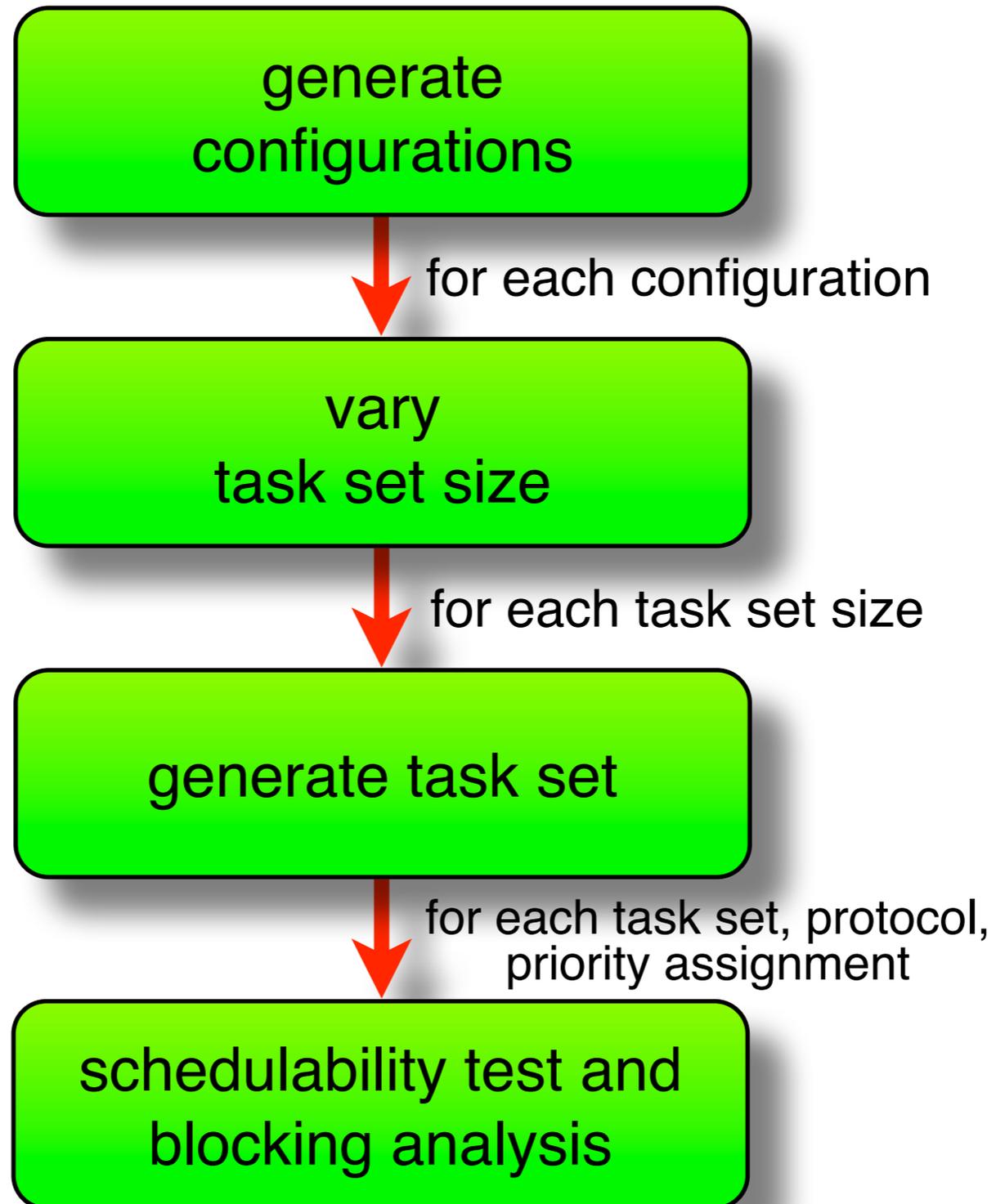
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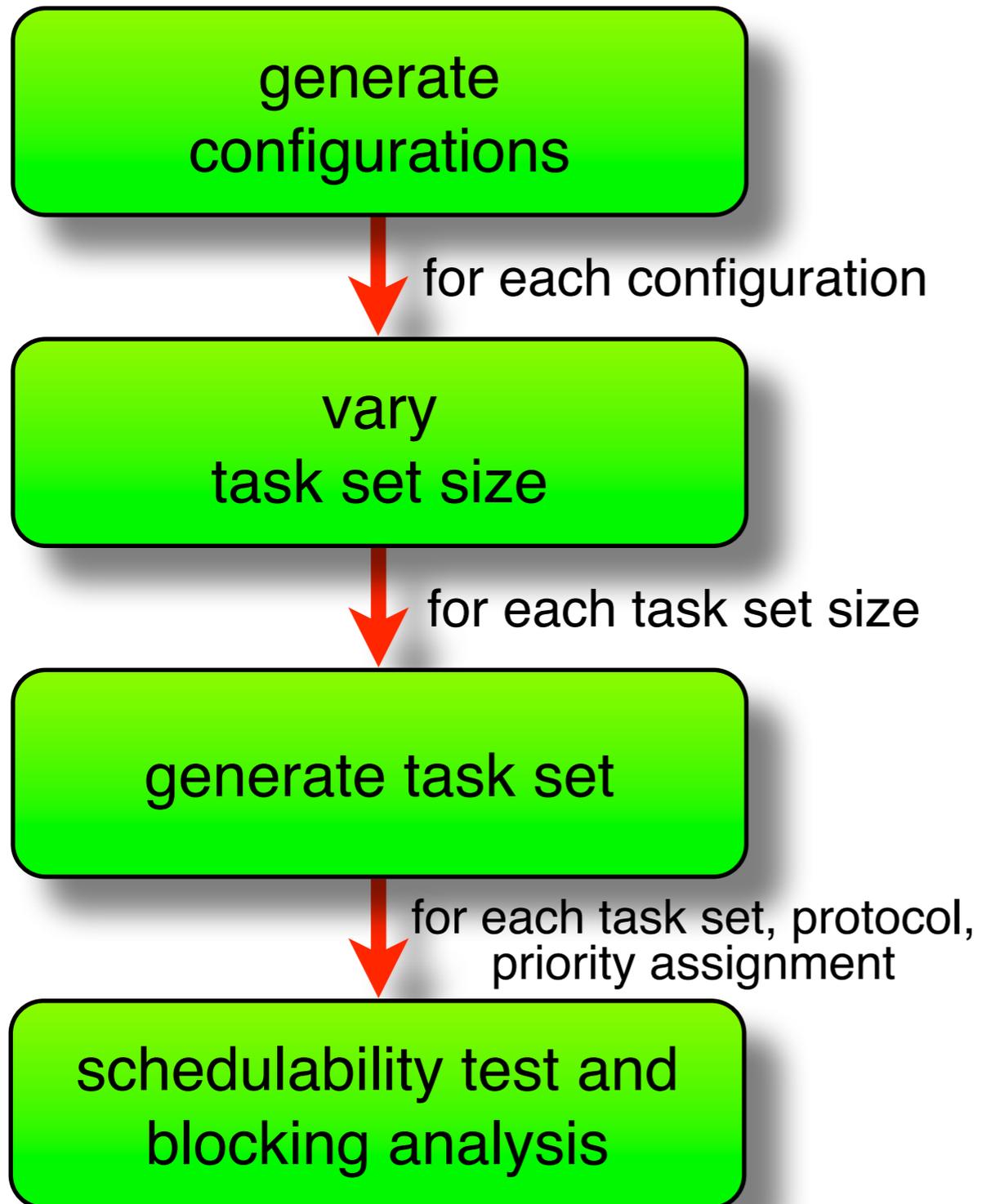
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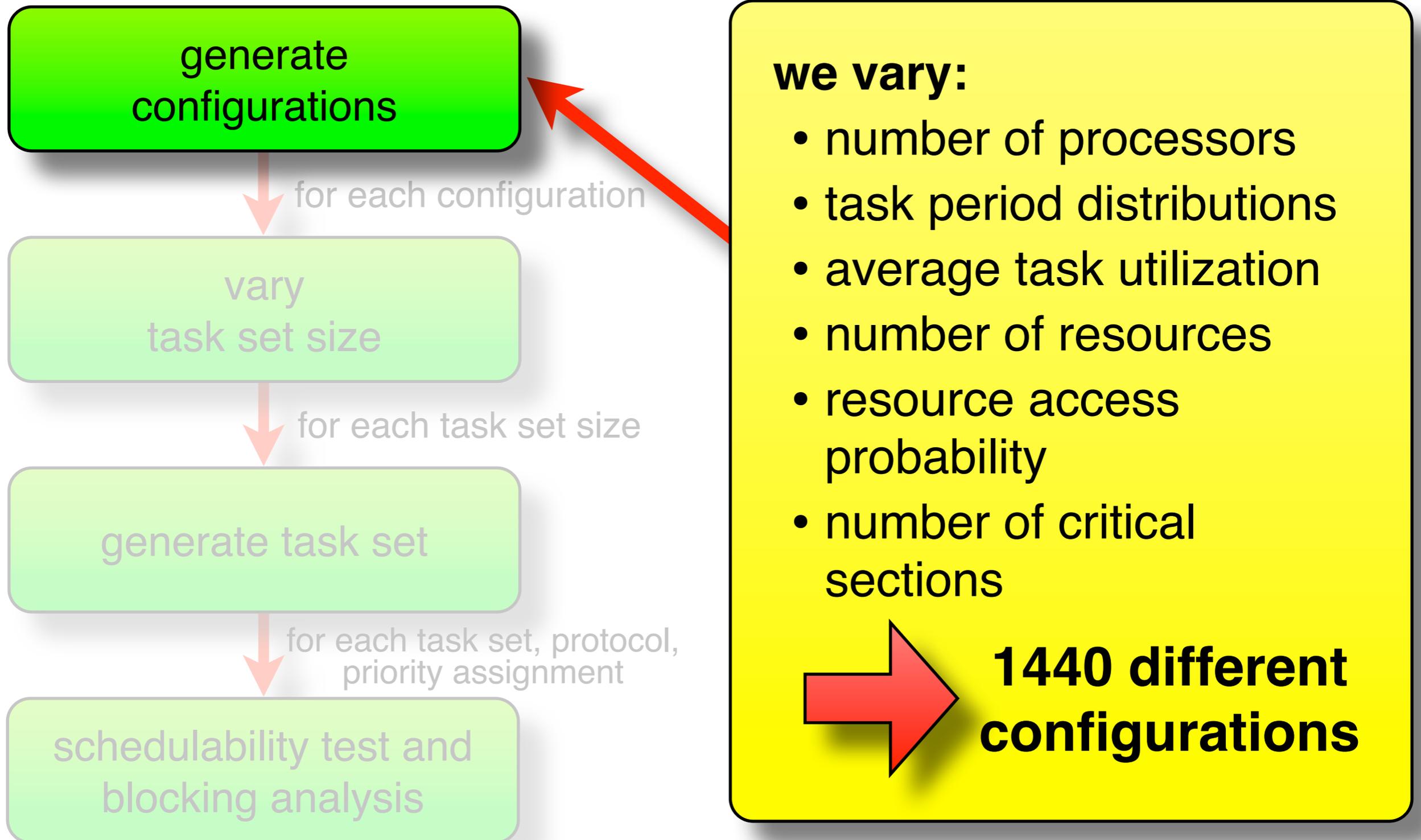
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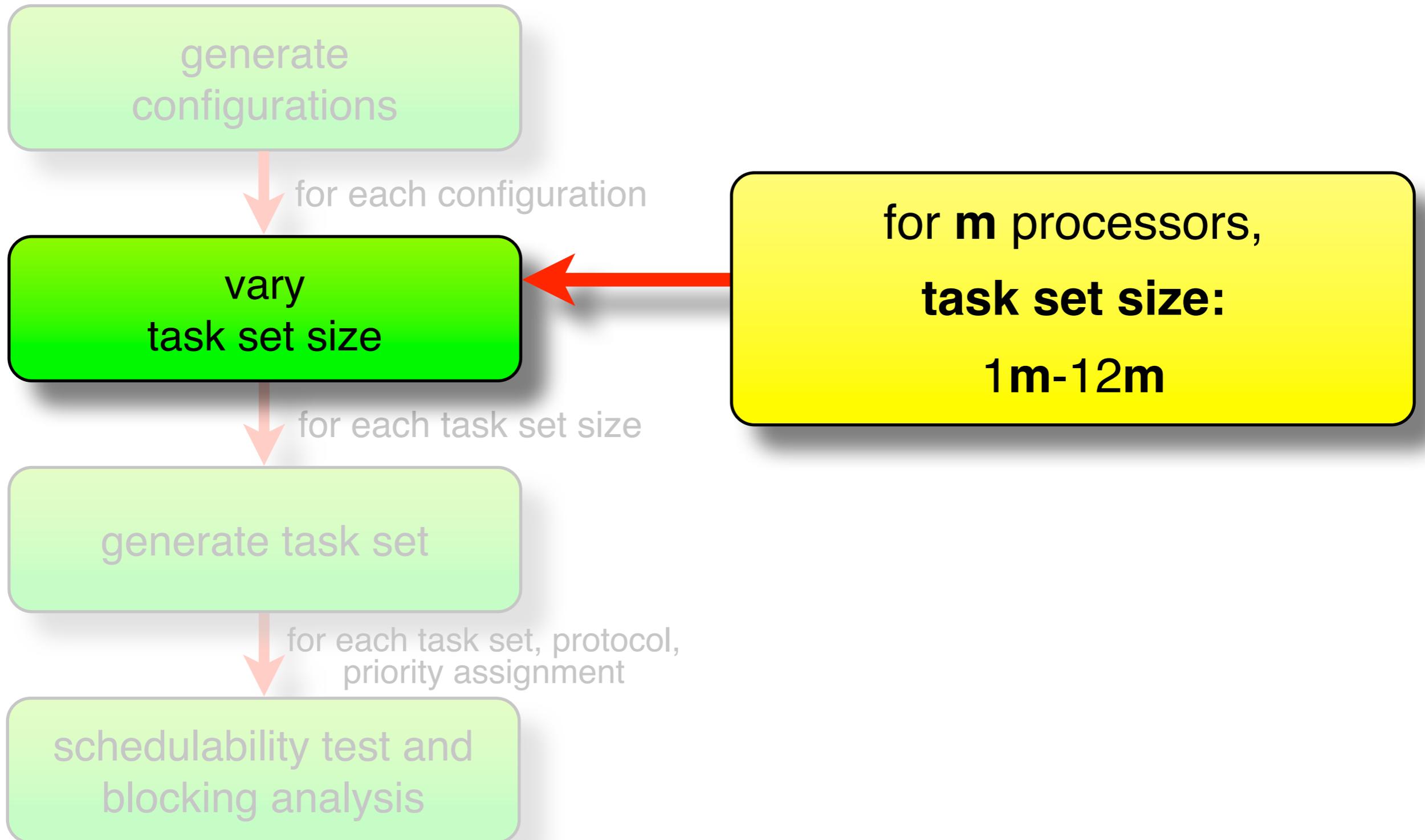
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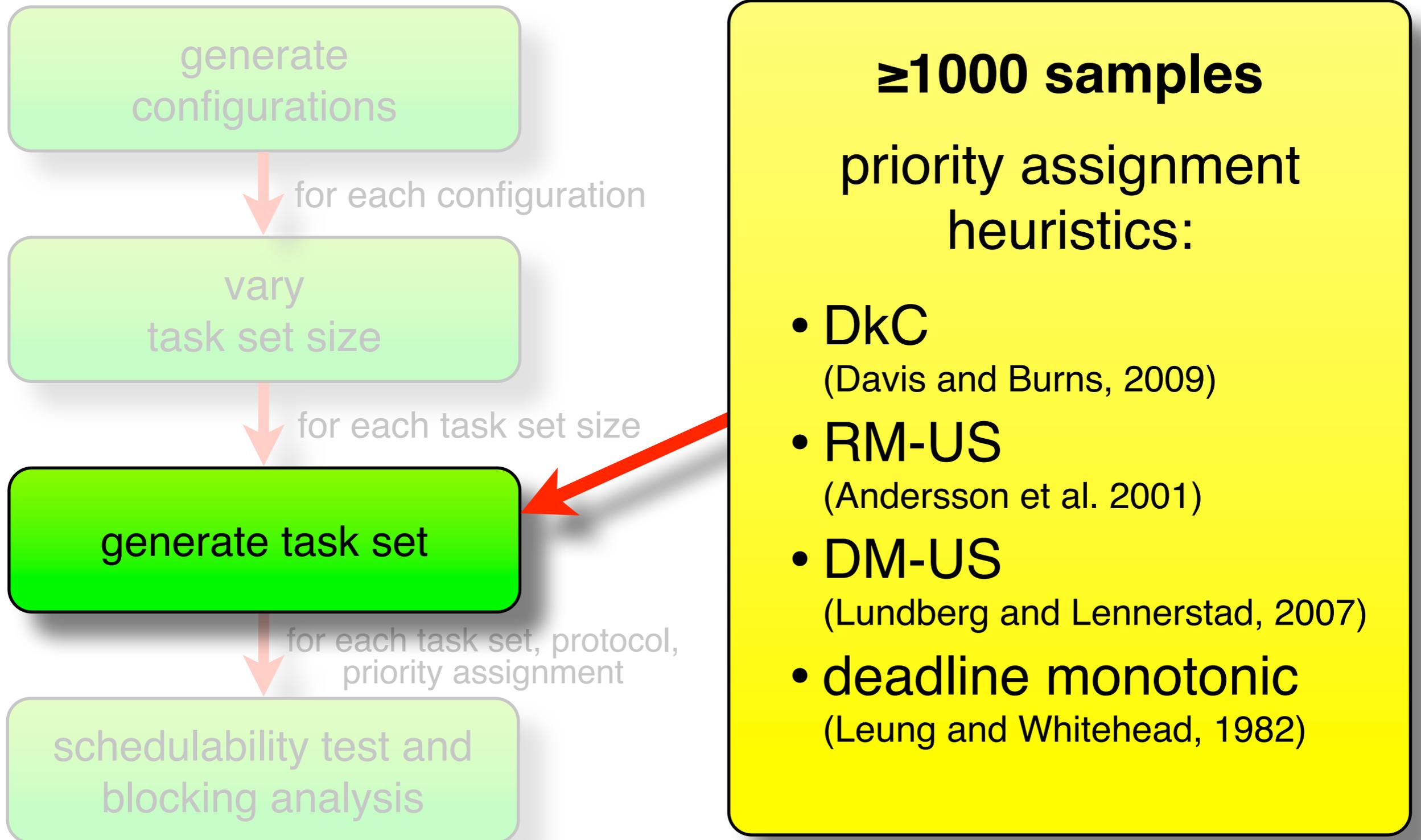
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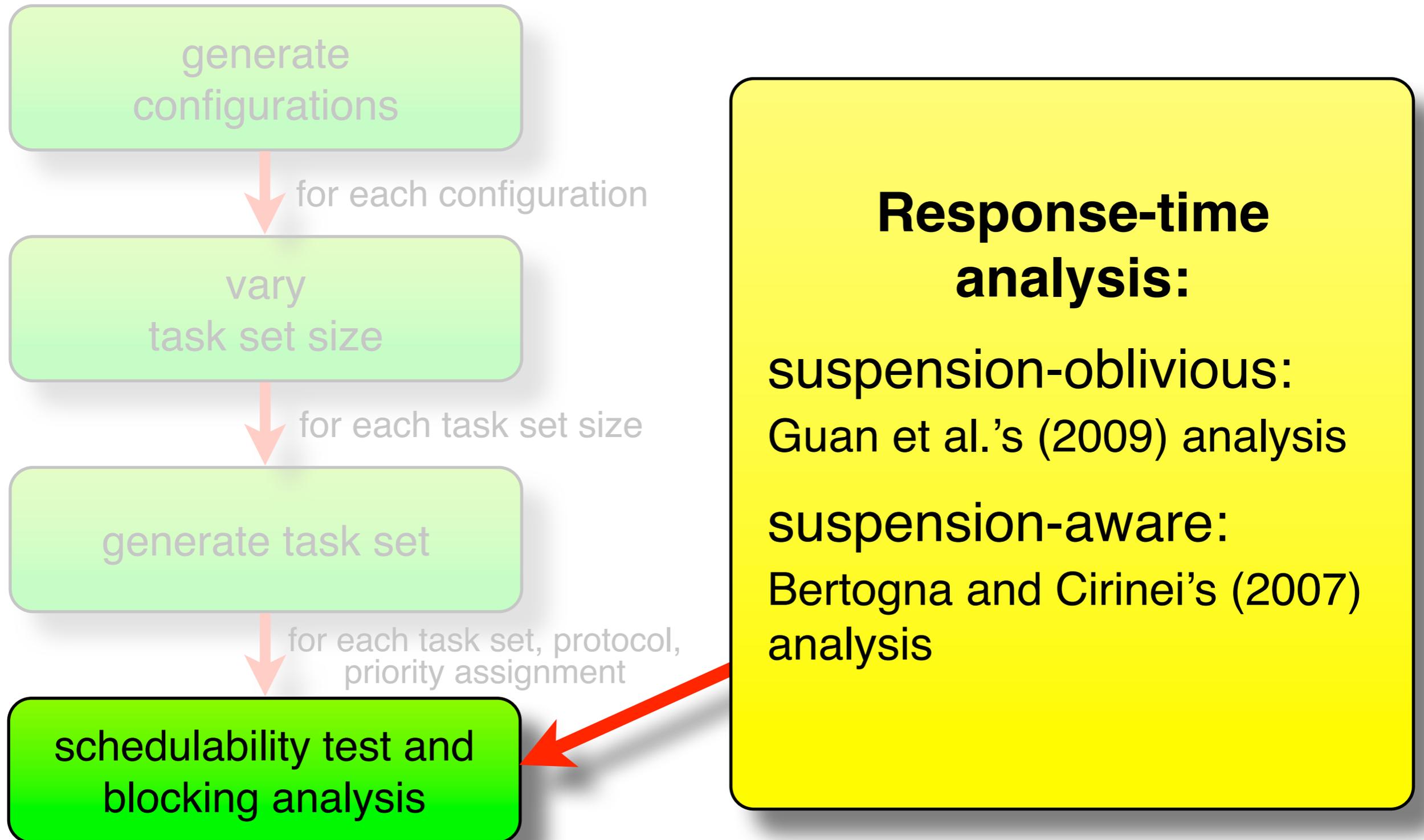
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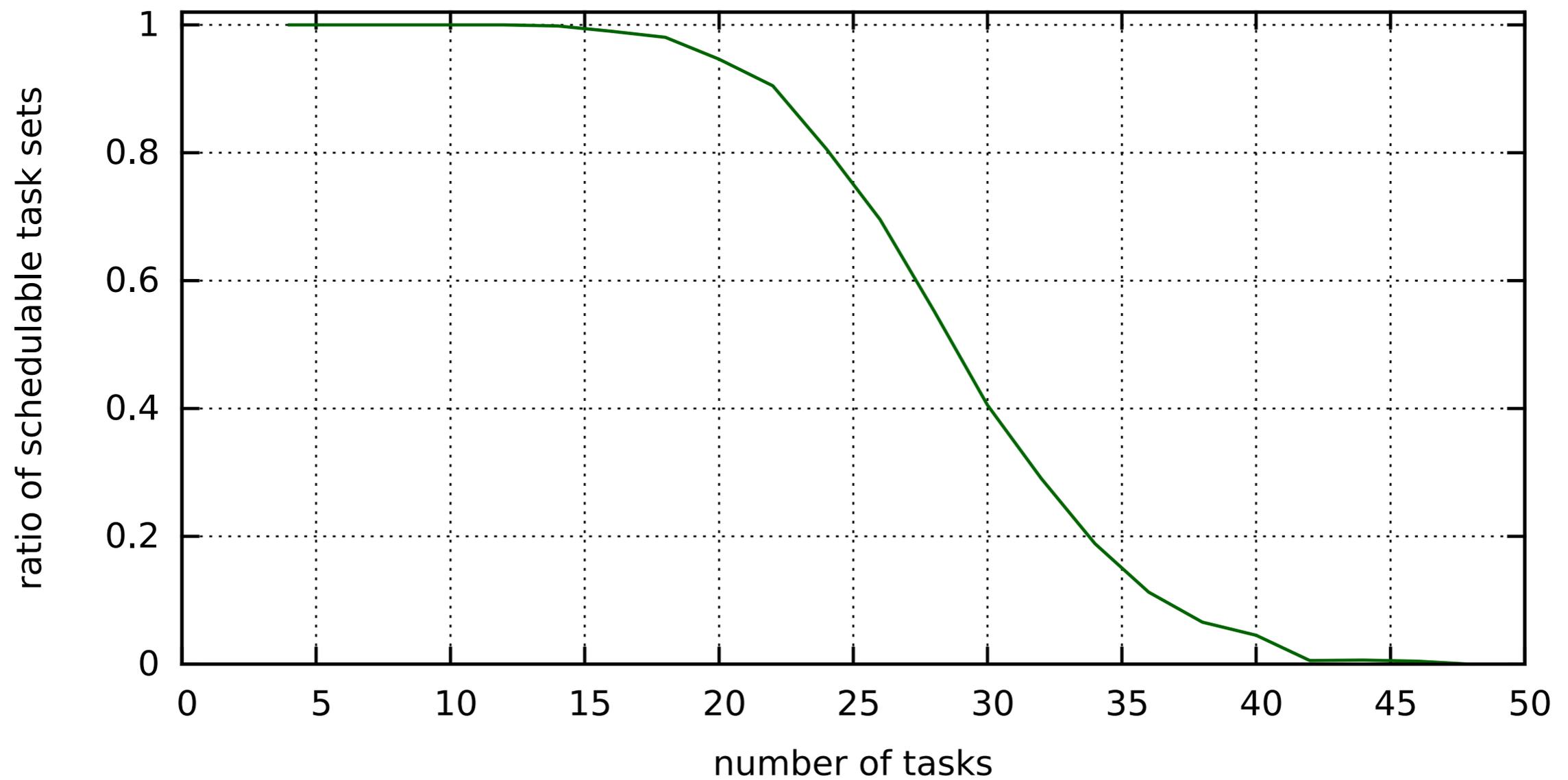


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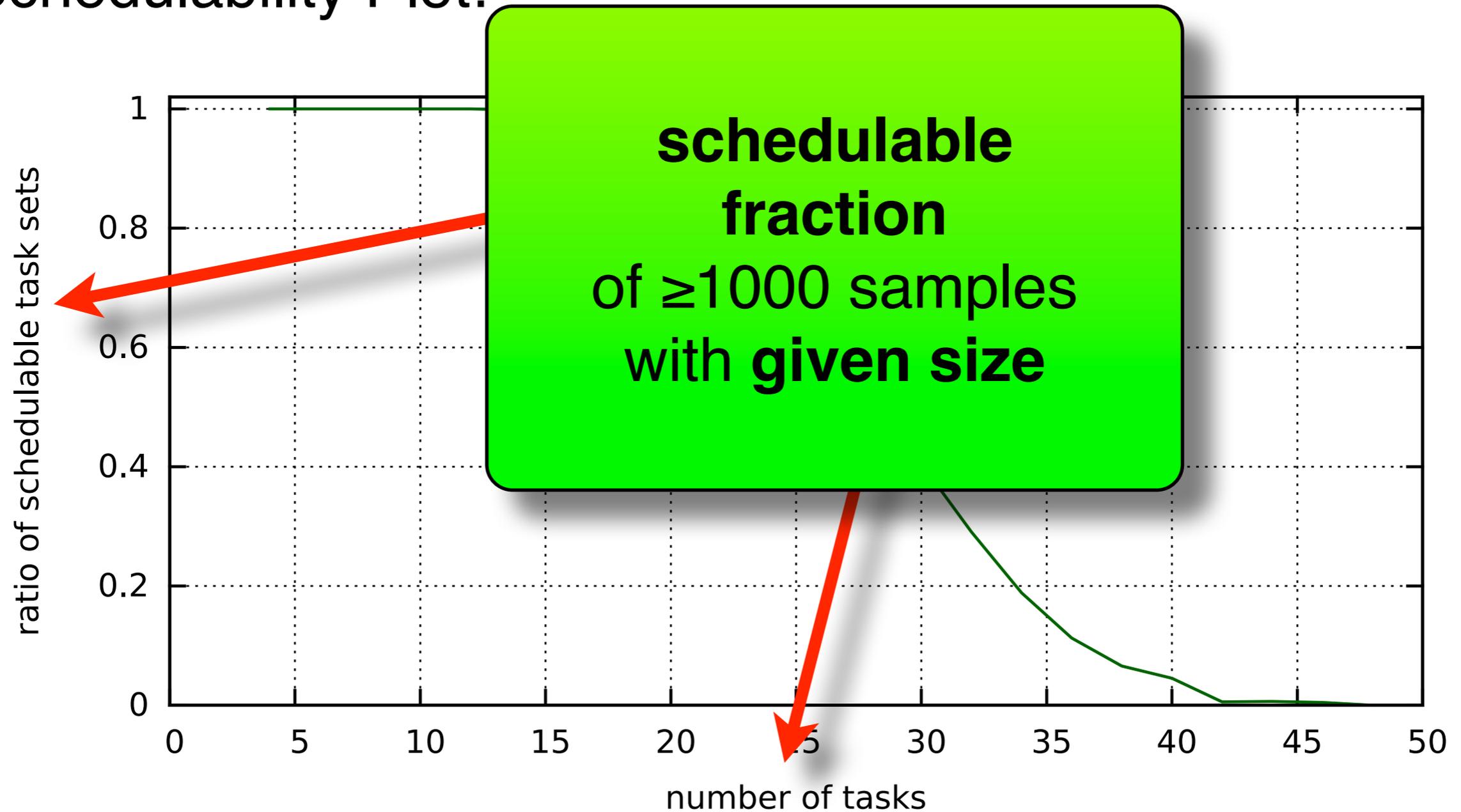
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Schedulability Plot:



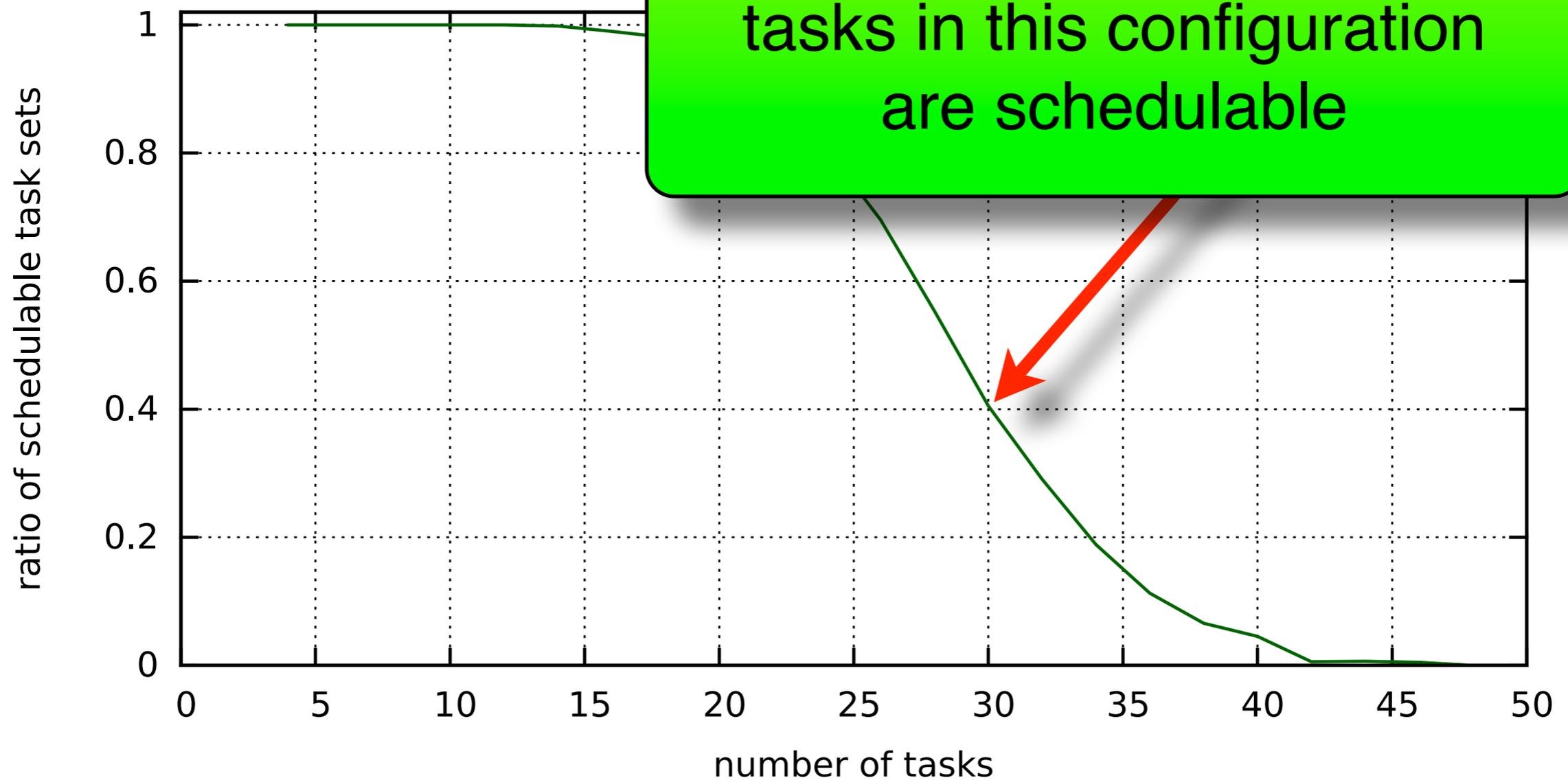
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Schedulability Plot:



Evaluation

Schedulability Plot:



40% of task sets with 30 tasks in this configuration are schedulable

Evaluation

Our findings:

- The choice of protocol does matter!
- LP-based analysis increases schedulability.
- PIP and FMLP perform best.
- PPCP results don't justify complexity.
- PI performs better than RSB under global scheduling.

Evaluation

Representative configuration:

| | |
|-------------------------|------------------|
| processors | 4 |
| periods | 10...100ms |
| #resources | 4 |
| utilization | 0.1 |
| access probability | 0.5 |
| critical section length | 25...100 μ s |
| #requests | 5 |

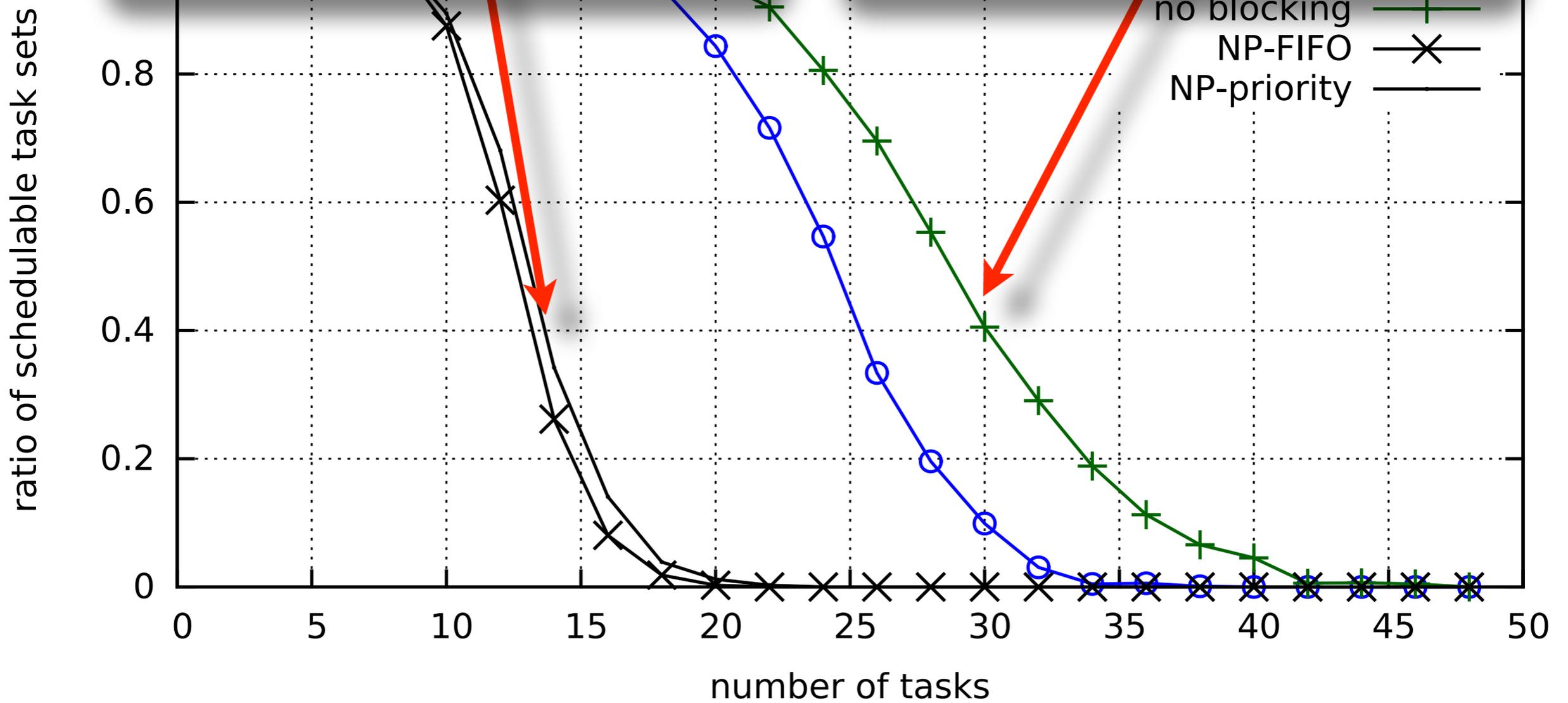
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The choice of protocol does matter!

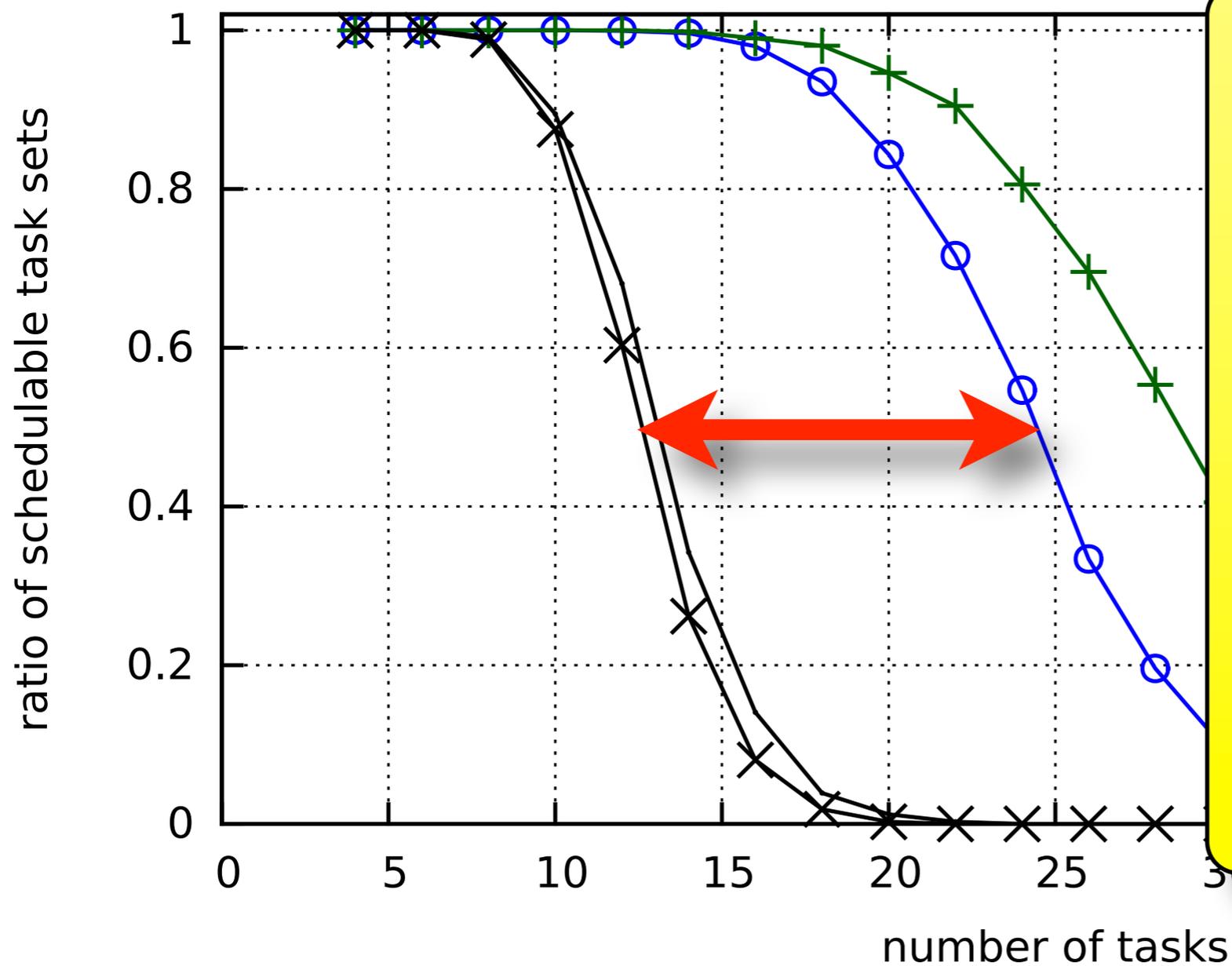
lower bound:
locks without
progress mechanism

upper bound:
schedulability
without any blocking



Evaluation

The choice of protocol does matter!



average #tasks supported at schedulability ratio 0.5:

worst: 12

vs.

best: 24

Evaluation

The unified LP-based analysis results in higher schedulability.

Locking Protocols for Global Scheduling

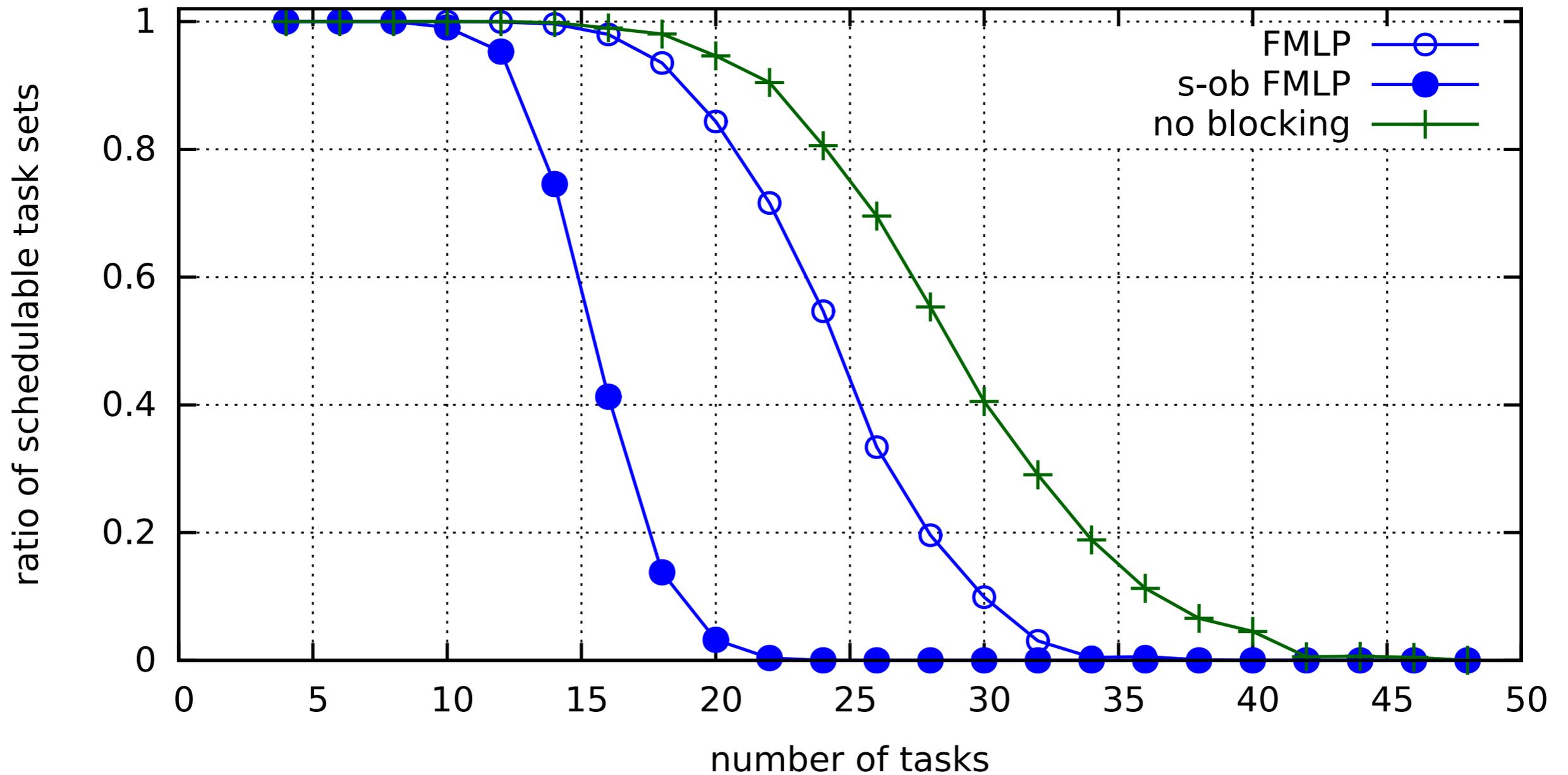
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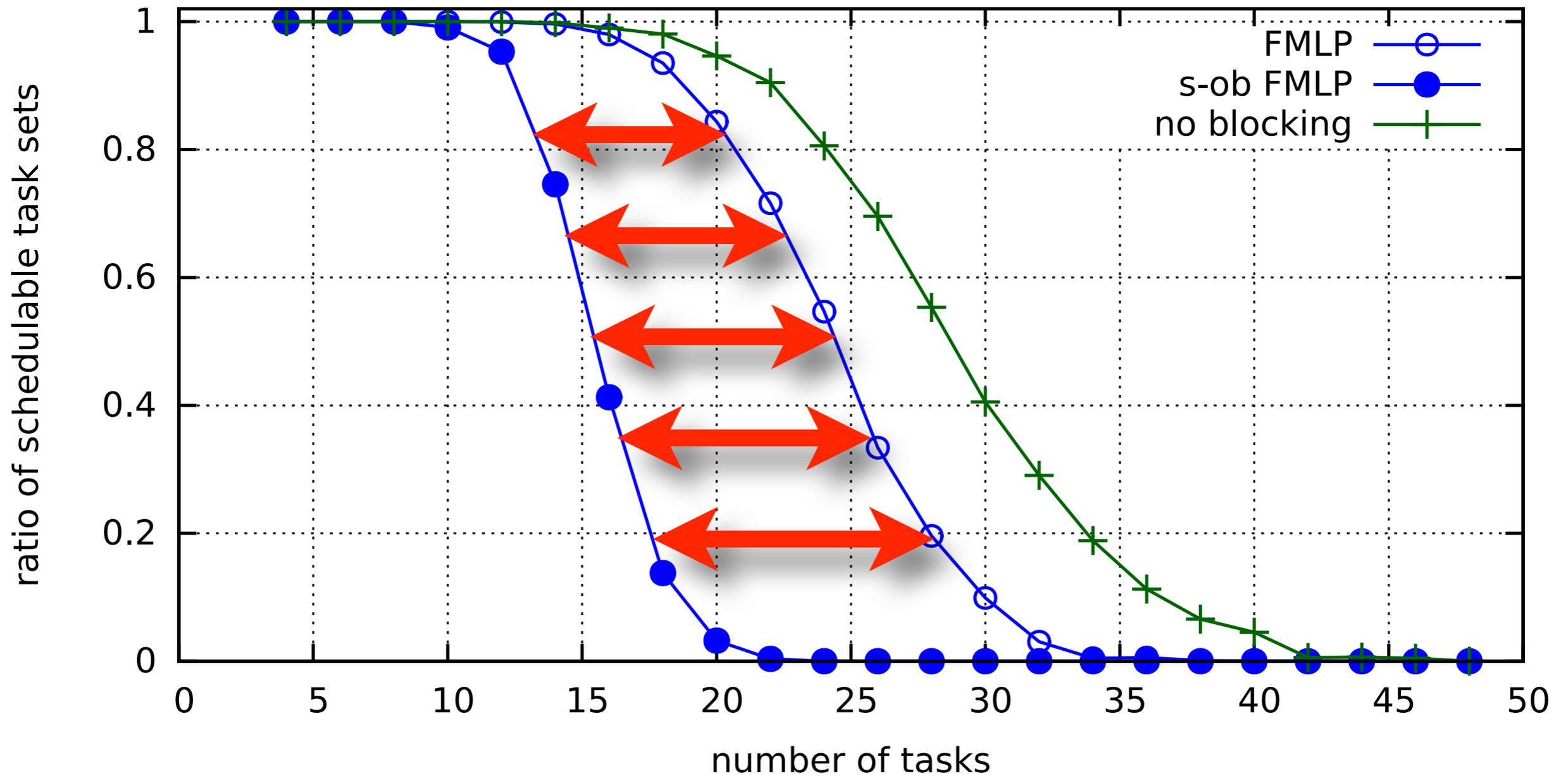
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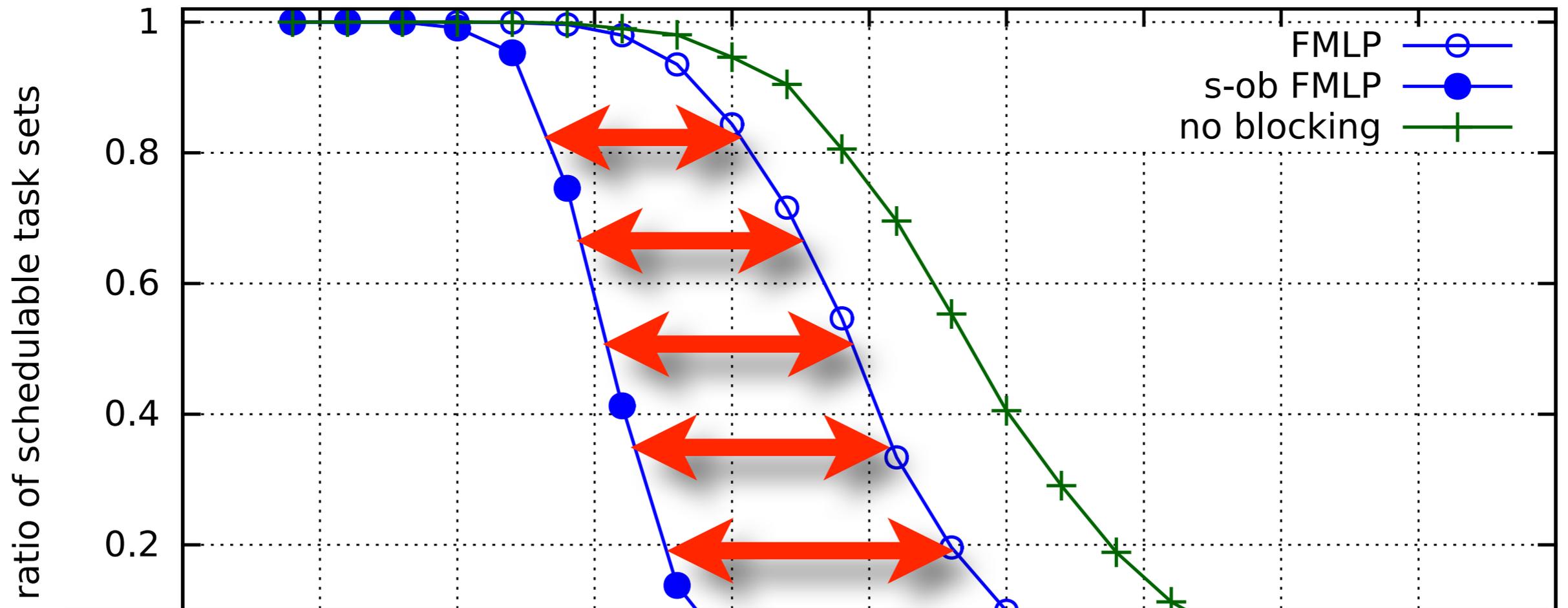
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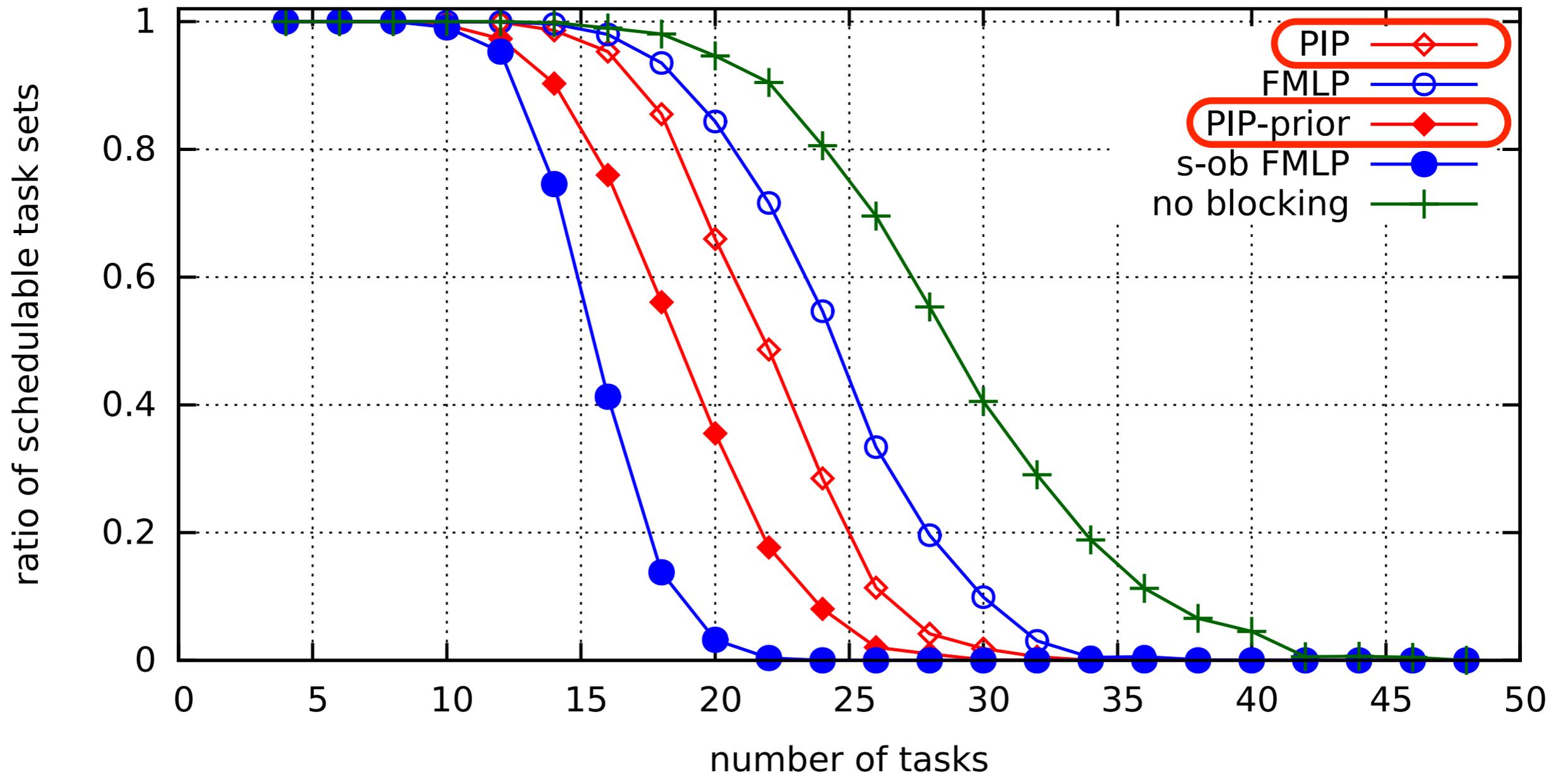
Higher schedulability under new analysis.

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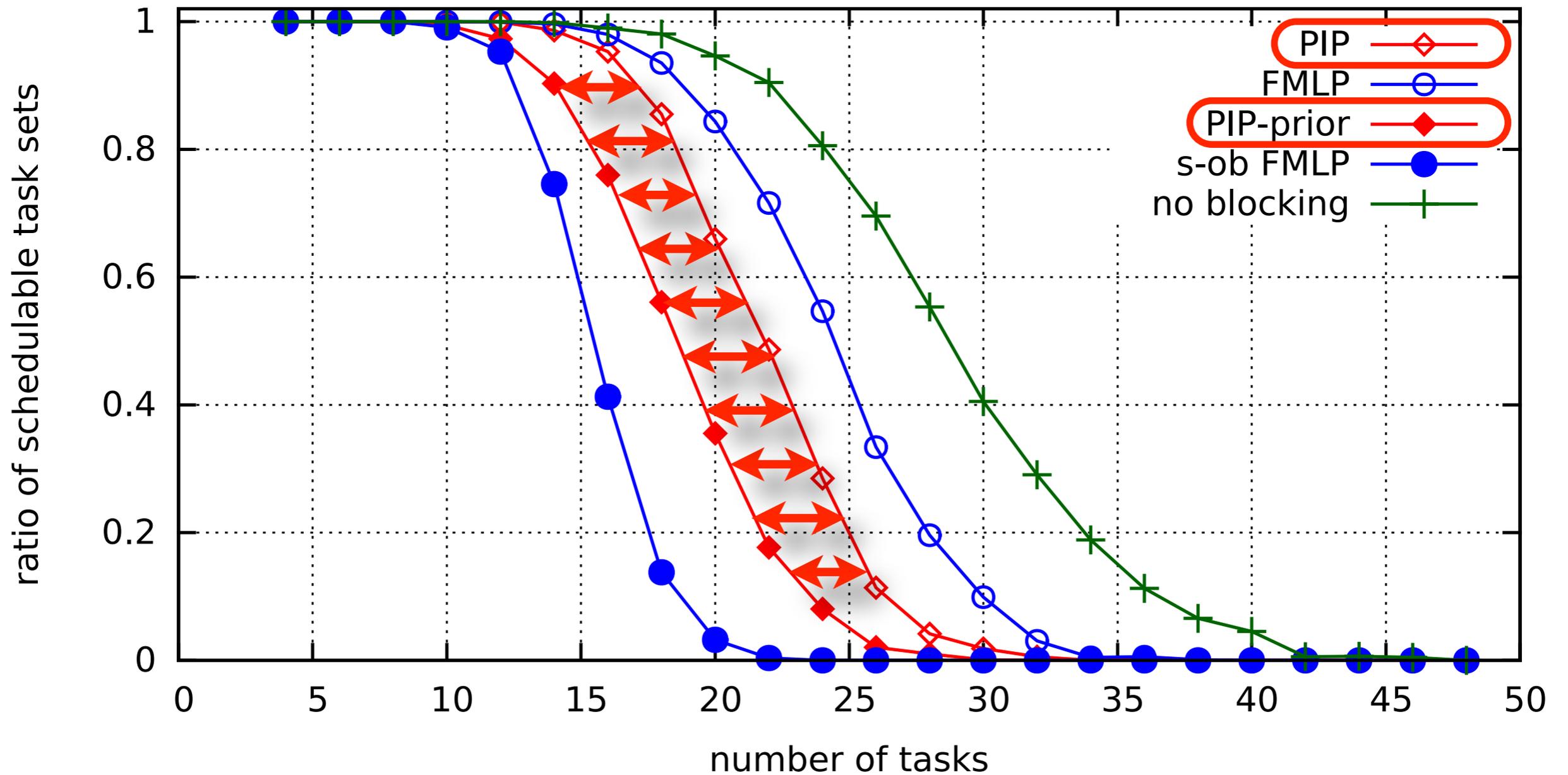
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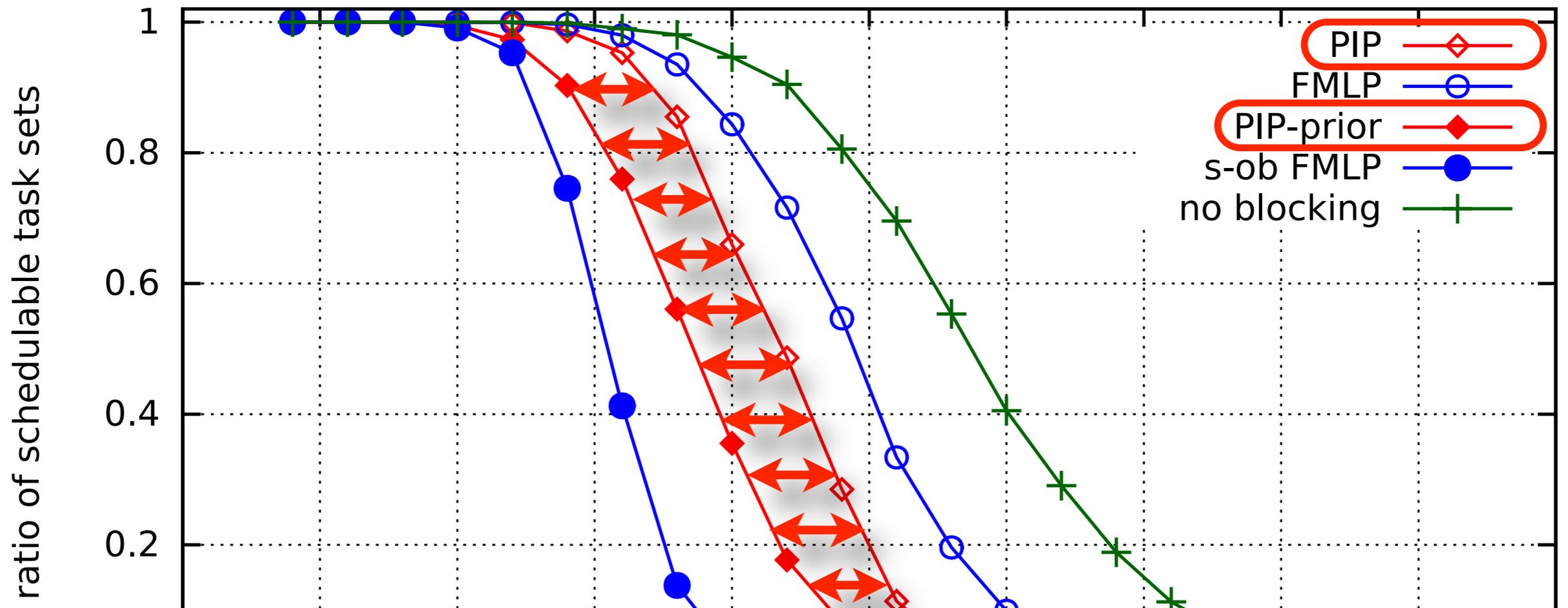
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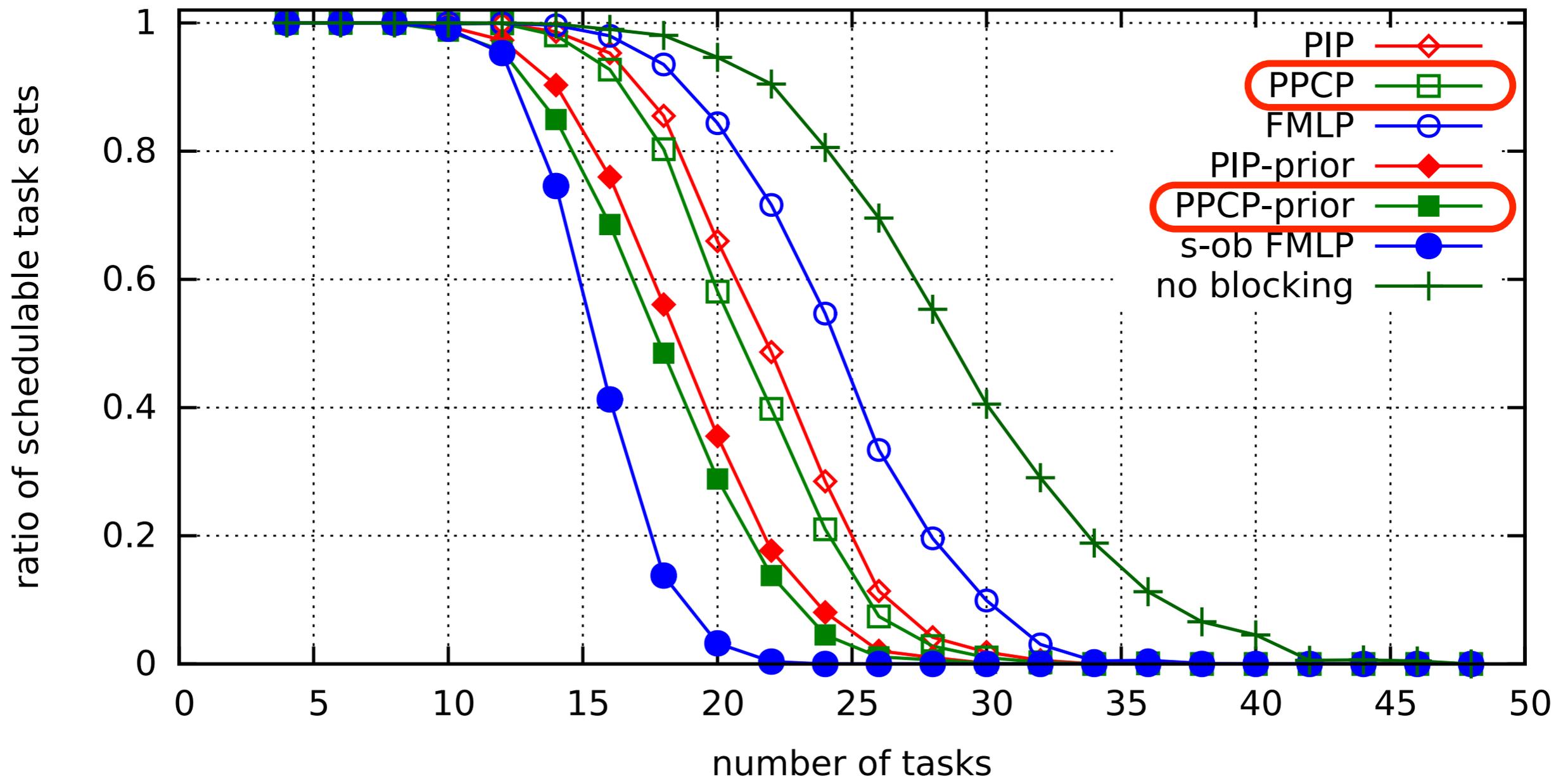
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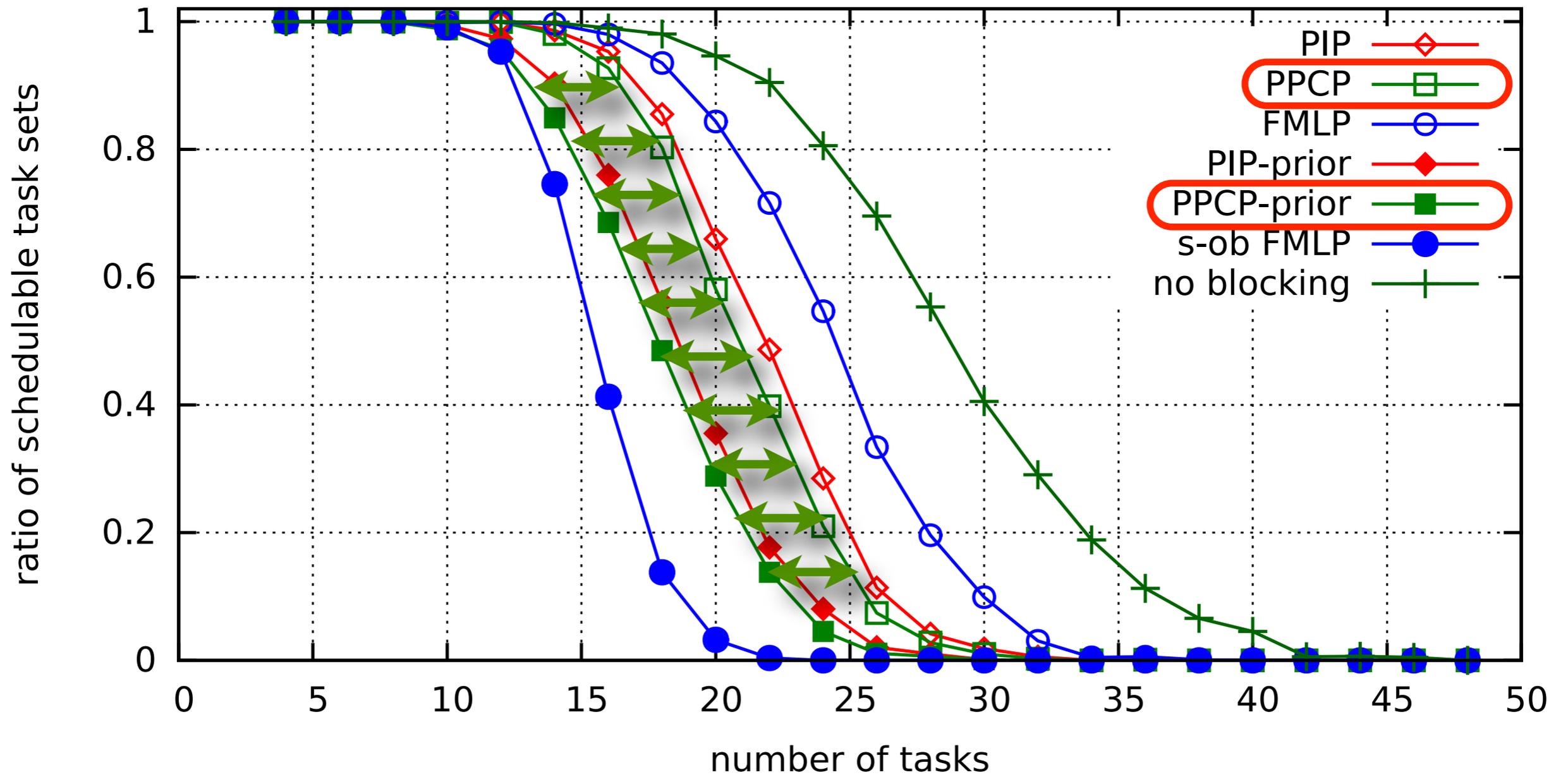
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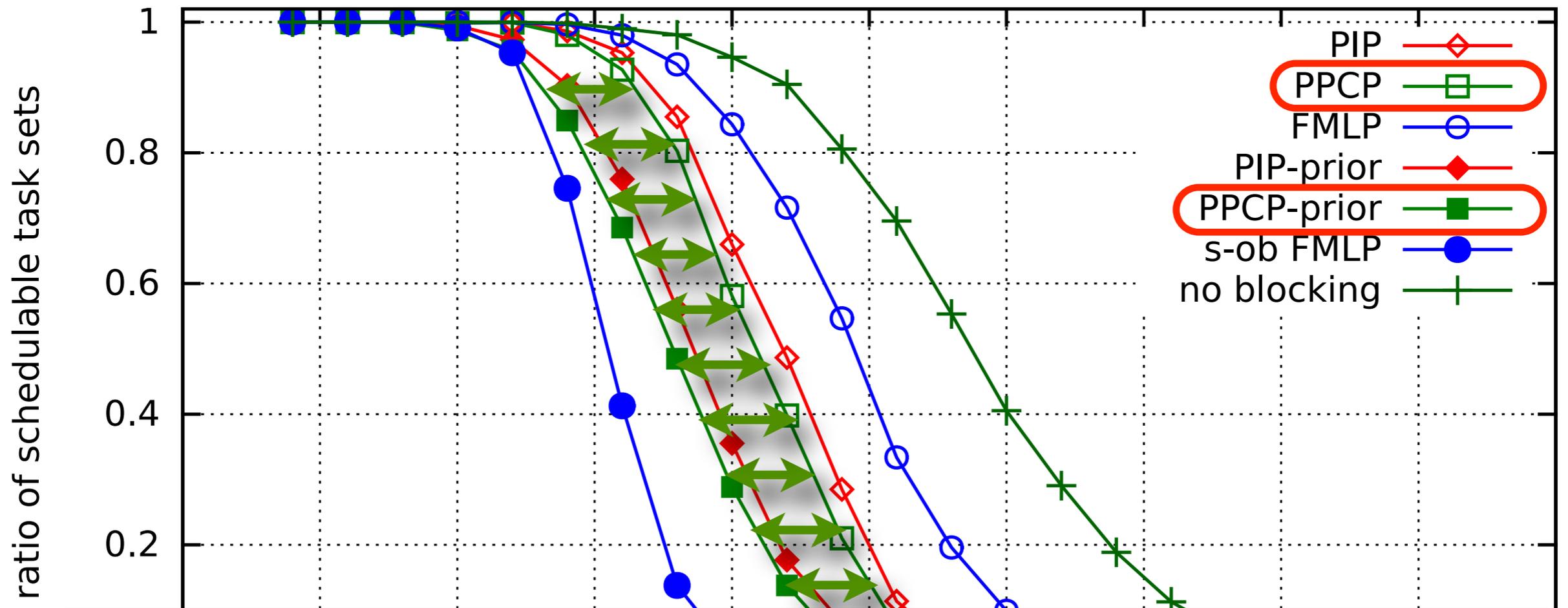
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Locking Protocols for Global Scheduling

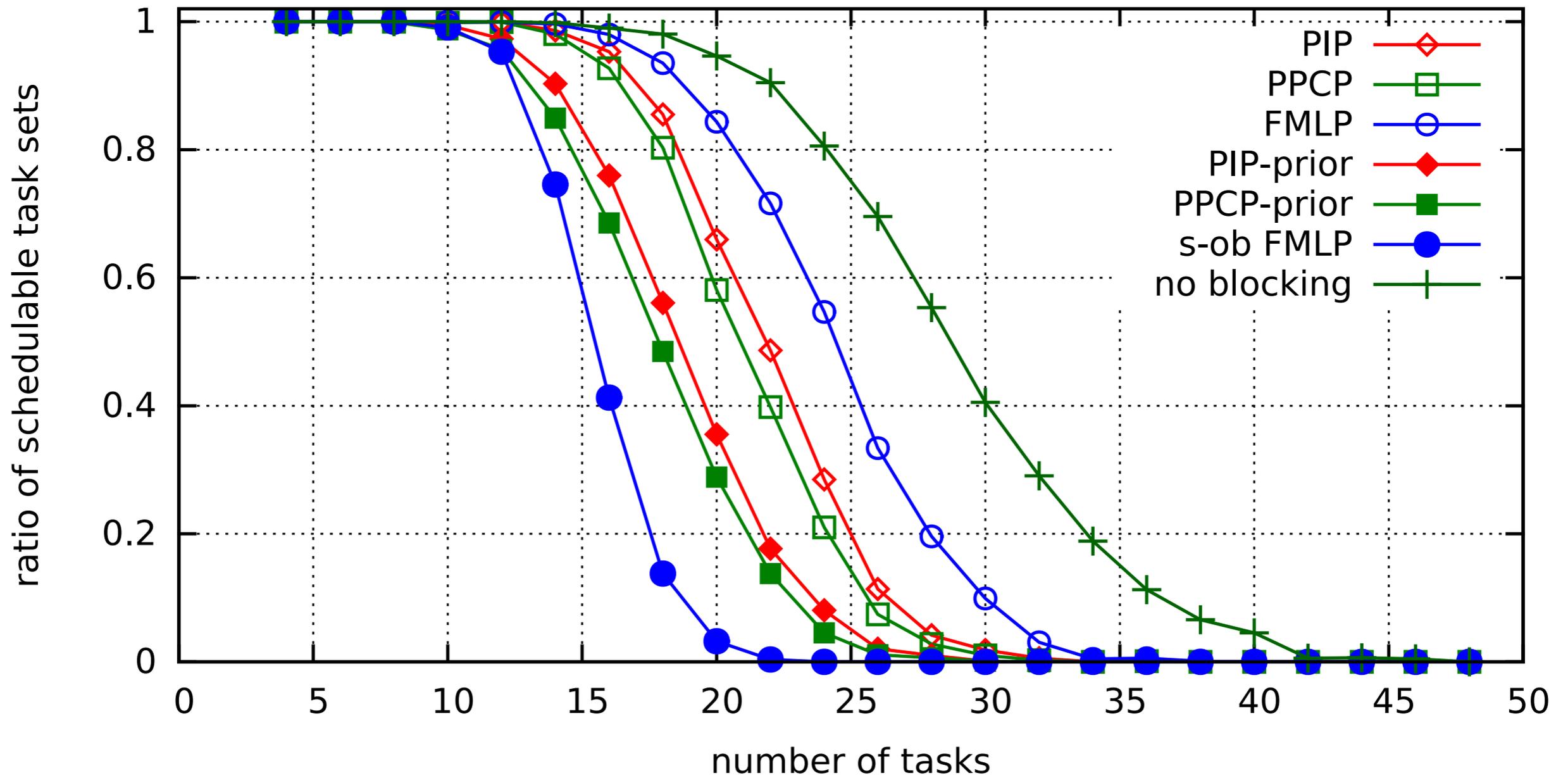
| Protocol | Progress Mechanism | Queue Type | Is LP-based analysis the best available? | Empirical Results |
|-------------|--------------------|------------|--|-------------------|
| NP-FIFO | - | FIFO | ✓ | ? |
| NP-Priority | - | Priority | ✓ | ? |
| FMLP | PI | FIFO | ✓ | ? |
| PIP | PI | Priority | ✓ | ? |
| PPCP | PI | Priority | ✓ | ? |
| FMLP+ | RSB | FIFO | ✓ | ? |
| PRSB | RSB | Priority | ✓ | ? |

Evaluation

PIP and FMLP dominate.

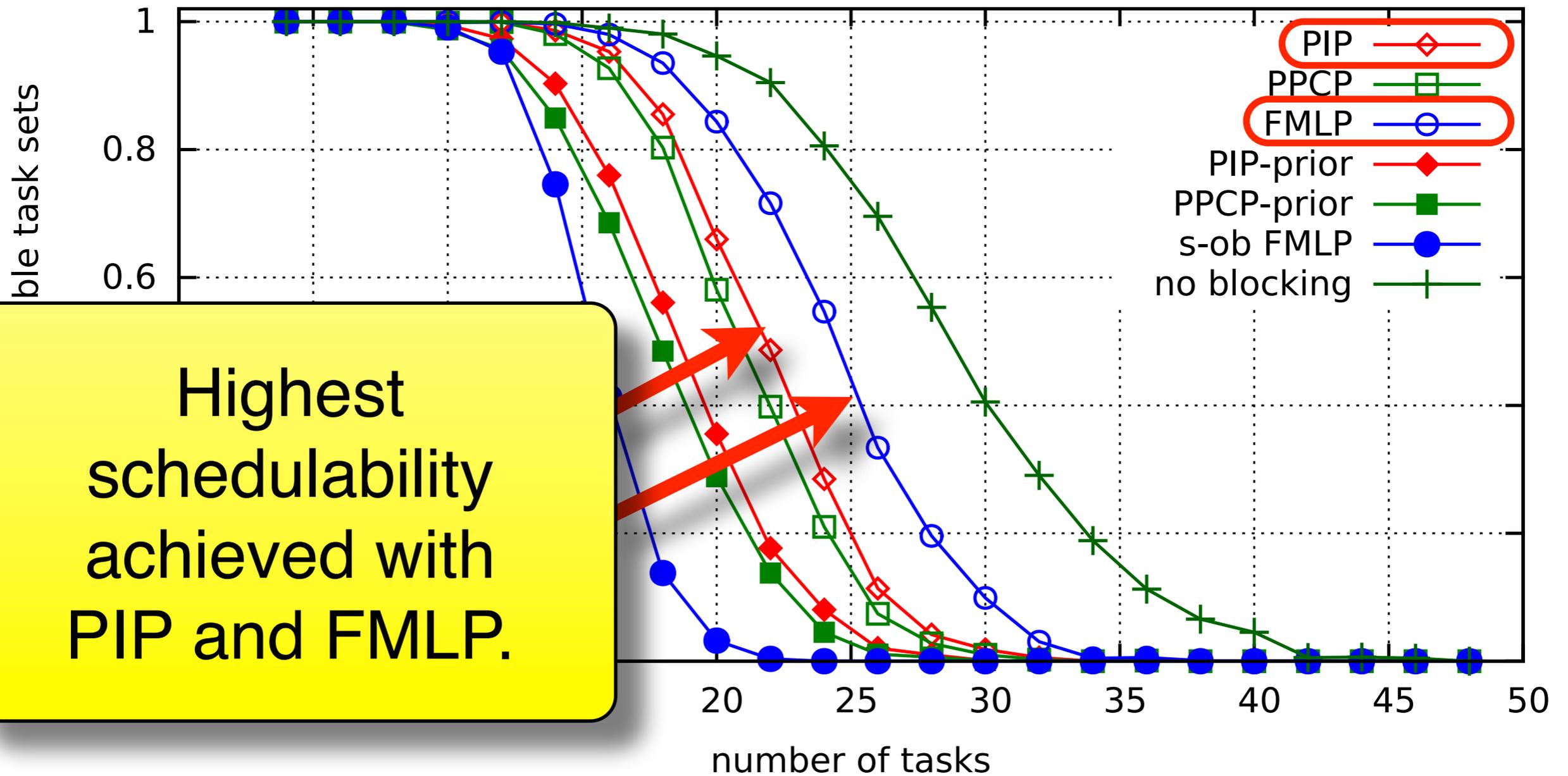
Evaluation

PIP and FMLP dominate.



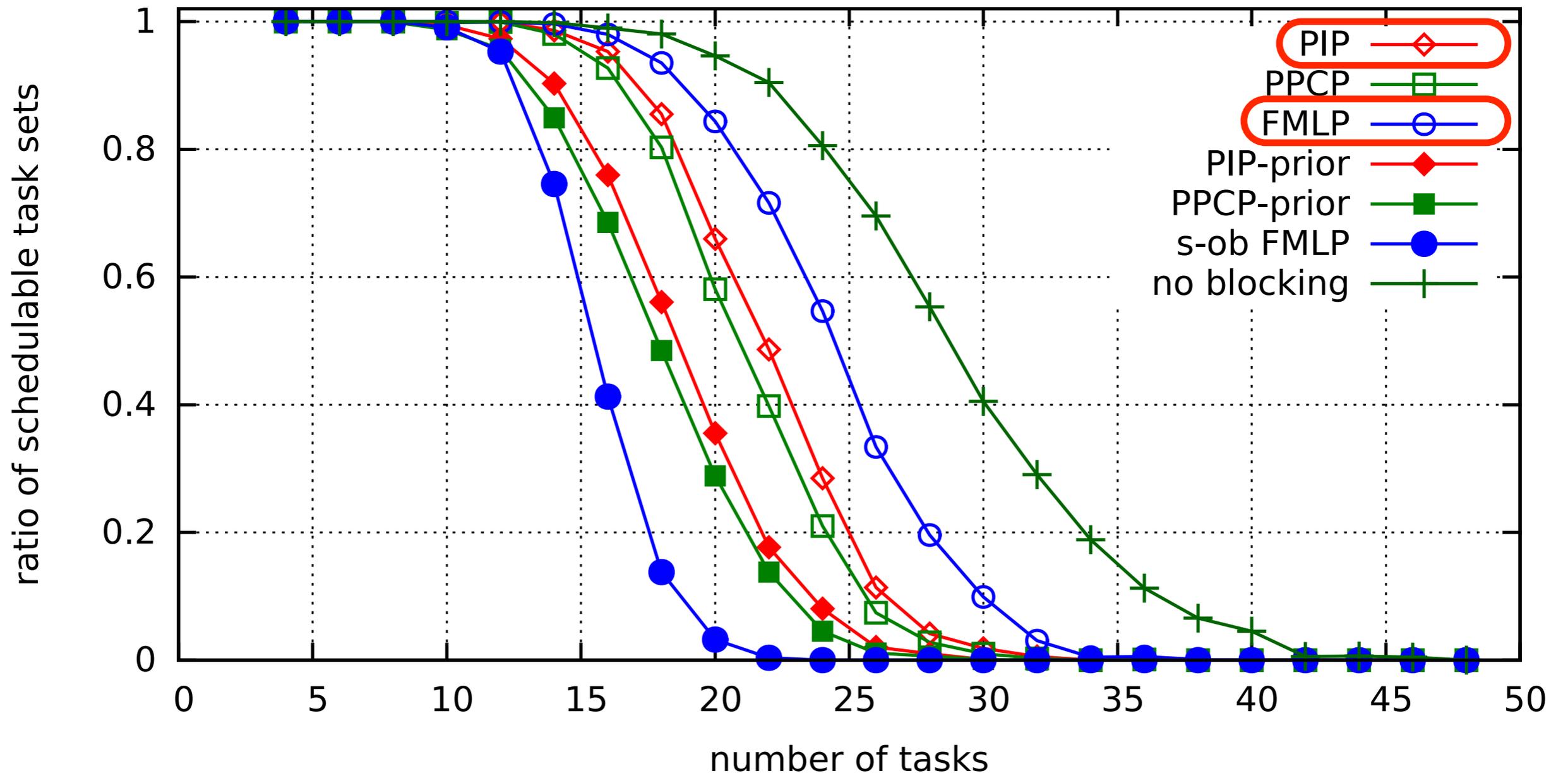
Evaluation

PIP and FMLP dominate.



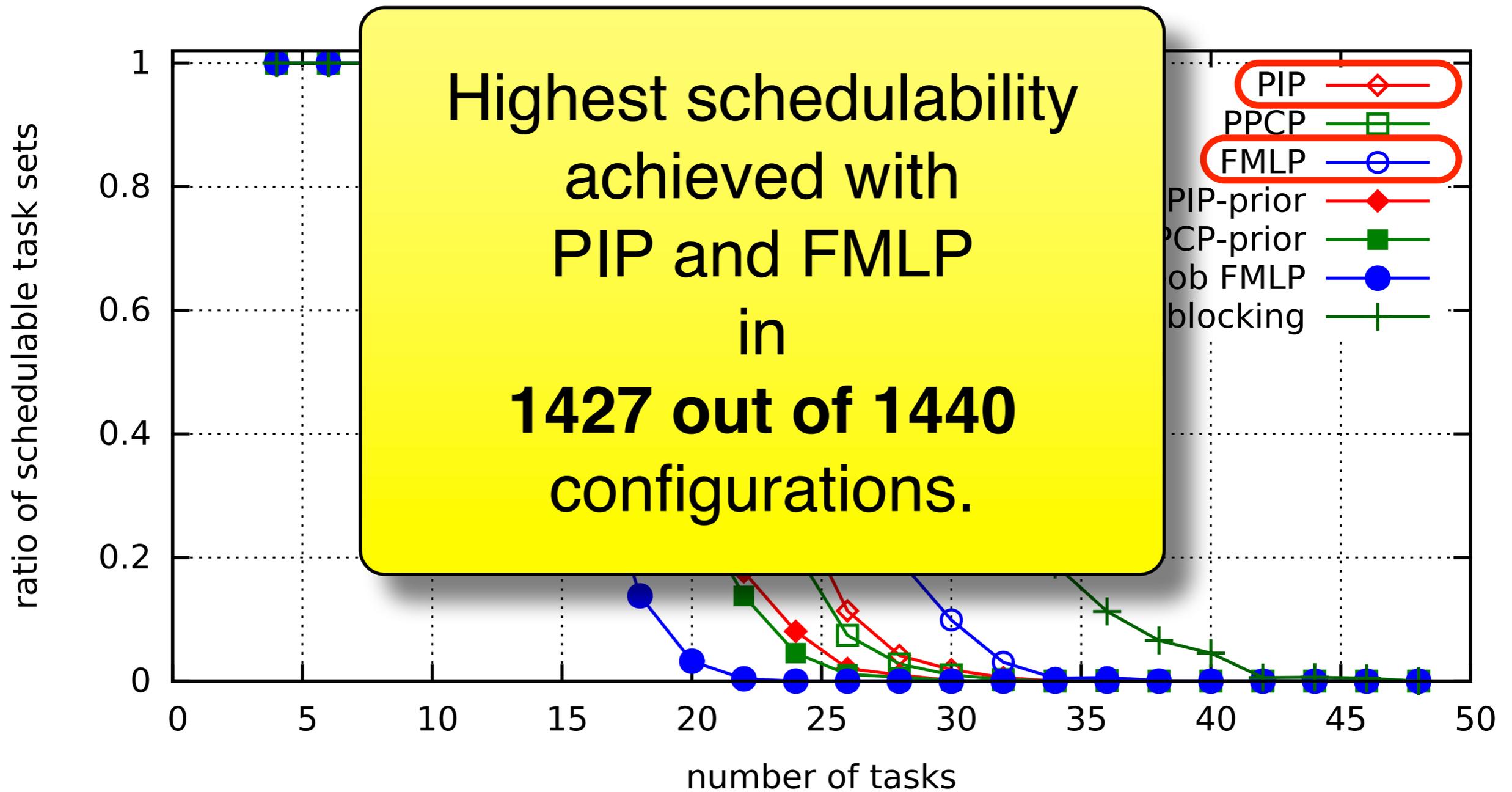
Evaluation

PIP and FMLP dominate.

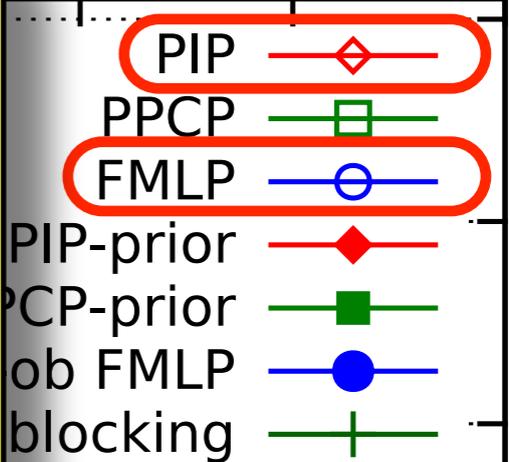


Evaluation

PIP and FMLP dominate.

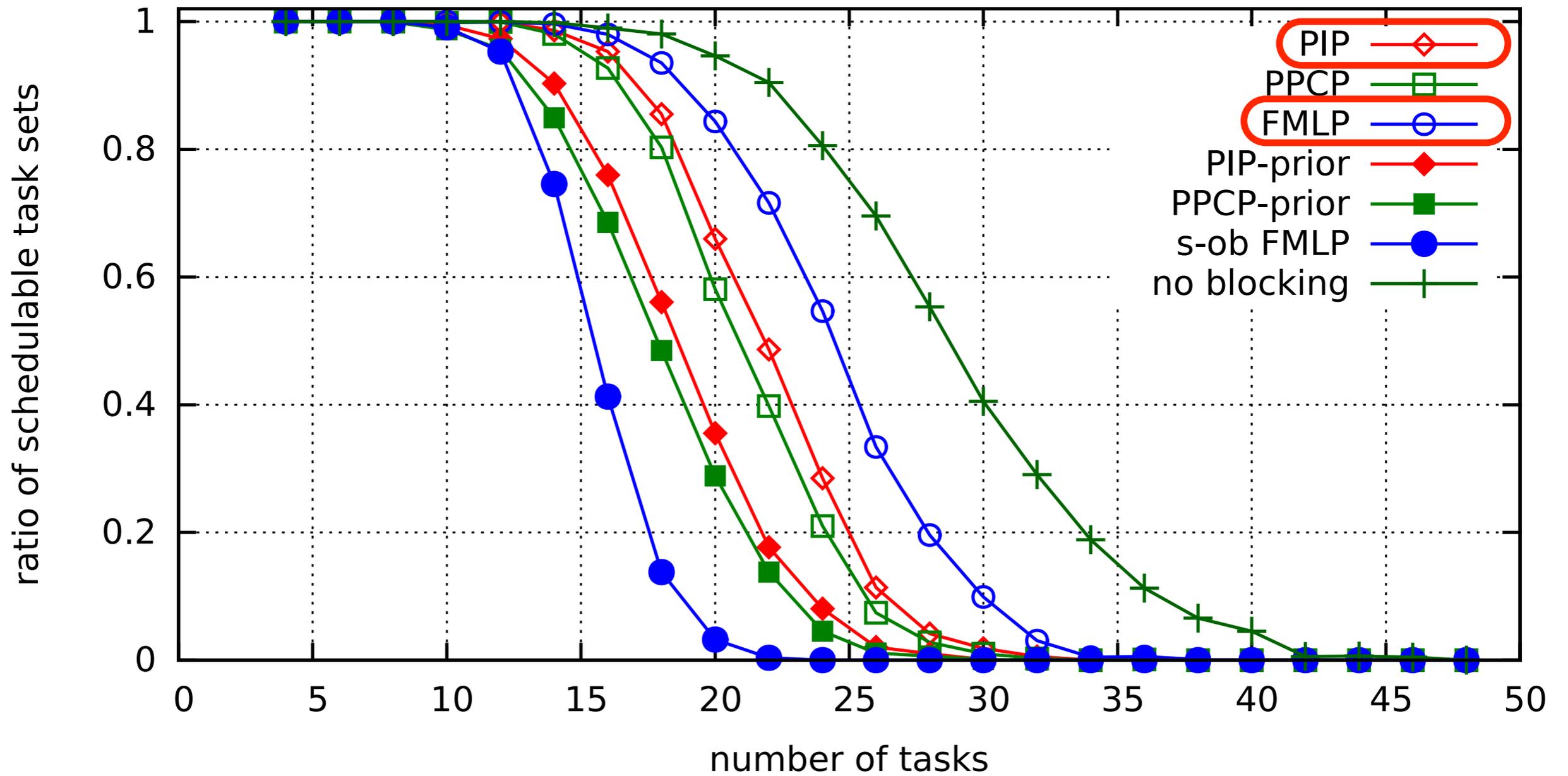


Highest schedulability achieved with PIP and FMLP in 1427 out of 1440 configurations.



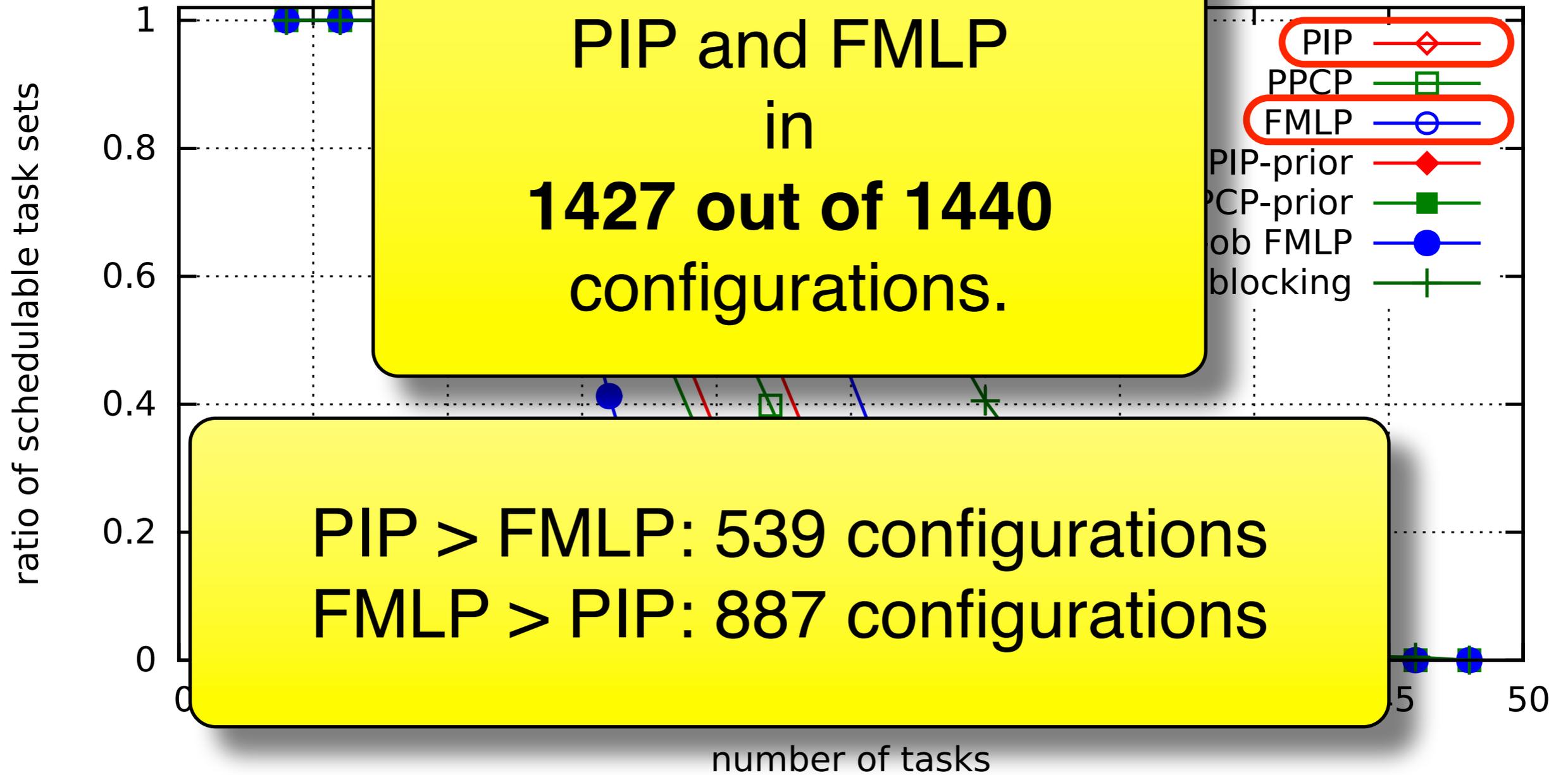
Evaluation

PIP and FMLP dominate.



Evaluation

Highest schedulability achieved with PIP and FMLP in **1427 out of 1440** configurations.



PIP > FMLP: 539 configurations
FMLP > PIP: 887 configurations

Locking Protocols for Global Scheduling

| Protocol | | | LP-based is le? | Empirical Results |
|--------------|-----|----------|-----------------------|--|
| NP-FIFO | | | | ? |
| NP-Priority | | | | ? |
| FMLP | PI | FIFO | ✓ | best in 1427 out of 1440 configurations |
| PIP | PI | Priority | ✓ | |
| PPCP | PI | Priority | ✓ | ? |
| FMLP+ | RSB | FIFO | ✓ | ? |
| PRSB | RSB | Priority | ✓ | ? |

The FMLP and the PIP are the oldest and simplest protocols.

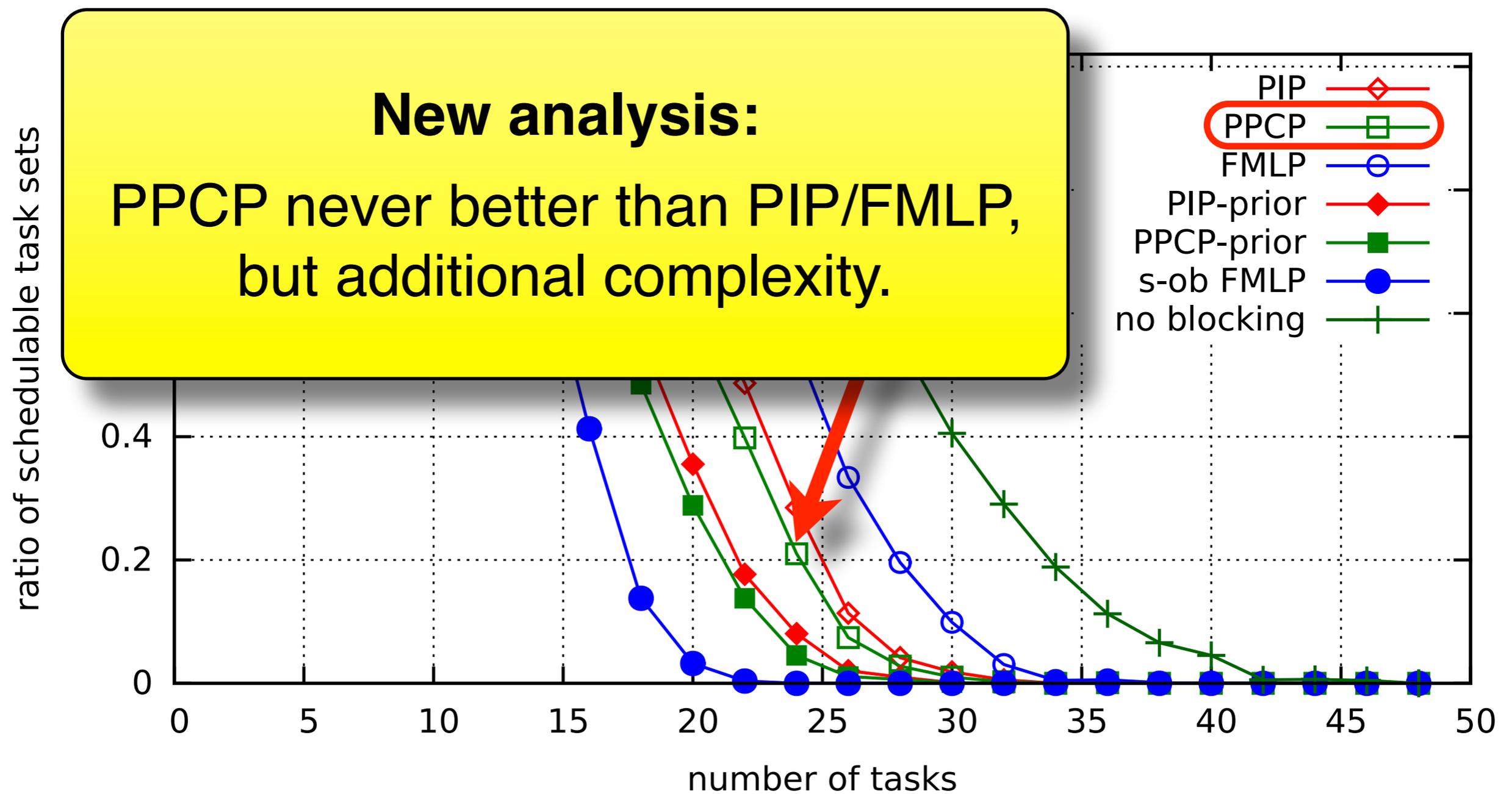
FMLP and PIP are highlighted with a red border.

Evaluation

PPCP results don't justify complexity.

Evaluation

PPCP results don't justify complexity.



Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best | Empirical Results |
|---|--------------------|------------|------------------------|---|
| <p>New analysis: PPCP never better than PIP/FMLP, but additional complexity.</p> | | | | ? |
| | | | | ? |
| | | | | best in 1427 out of 1440 configurations |
| PPCP | PI | Priority | ✓ | never better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | ? |
| PRSB | RSB | Priority | ✓ | ? |

Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best available? | Empirical Results |
|-------------|--------------------|------------|-----------------------------------|---|
| NP-FIFO | - | FIFO | ✓ | ? |
| NP-Priority | - | Priority | ✓ | ? |
| FMLP | PI | FIFO | ✓ | best in 1427 out of 1440 configurations |
| PIP | PI | Priority | ✓ | |
| PPCP | PI | Priority | ✓ | never better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | ? |
| PRSB | RSB | Priority | ✓ | ? |

Evaluation

**RSB/FMLP+ designed to
obtain asymptotically optimal blocking.**

Works well under partitioned scheduling
(Brandenburg, 2013).

Evaluation

PI performs better than RSB
under global scheduling.

Evaluation

PI performs better than RSB.

Highest schedulability
achieved with
PI-based protocols
in
1434 out of 1440
configurations.

Locking Protocols for Global Scheduling

| Protocol | RSB | Priority | PI-based | Empirical results |
|--------------|-----|----------|----------|---|
| NP-FIFO | | | | ? |
| NP-Priority | | | | ? |
| FMLP | | | | Best in 1440 configurations |
| PIP | | | | |
| PPCR | | | | better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | not better than PI-based protocols in 1434 out of 1440 configurations |
| PRSB | RSB | Priority | ✓ | |

RSB under global scheduling:

FMLP+ yields asymptotically optimal blocking (Brandenburg and Anderson, 2010), but

- large constant factors,
- increased parallelism and
- additional sources of blocking.

Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best available? | Empirical Results |
|-------------|--------------------|------------|-----------------------------------|---|
| NP-FIFO | - | FIFO | ✓ | ? |
| NP-Priority | - | Priority | ✓ | ? |
| FMLP | PI | FIFO | ✓ | best in 1427 out of 1440 configurations |
| PIP | PI | Priority | ✓ | |
| PPCP | PI | Priority | ✓ | never better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | not better than PI-based protocols in 1434 out of 1440 configurations |
| PRSB | RSB | Priority | ✓ | |

Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best available? | Empirical Results |
|-------------|--------------------|------------|-----------------------------------|---|
| NP-FIFO | - | FIFO | ✓ | baseline for comparison, not competitive |
| NP-Priority | - | Priority | ✓ | |
| FMLP | PI | FIFO | ✓ | best in 1427 out of 1440 configurations |
| PIP | PI | Priority | ✓ | |
| PPCP | PI | Priority | ✓ | never better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | not better than PI-based protocols in 1434 out of 1440 configurations |
| PRSB | RSB | Priority | ✓ | |

Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best available? | Empirical Results |
|-------------|---|------------|-----------------------------------|--|
| NP-FIFO | - | FIFO | ✓ | baseline for comparison, not competitive |
| NP-Priority | - | Priority | ✓ | |
| F | <p>In extreme scenarios, NP-FIFO/Priority and NP-Priority under LP-based analysis resulted in higher schedulability than any suspension-oblivious analysis!</p> | | | |
| | | | | |
| F | | | | |
| F | | | | |
| P | | | | |

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Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best available? | Empirical Results |
|-------------|--------------------|------------|-----------------------------------|---|
| NP-FIFO | - | FIFO | ✓ | baseline for comparison, not competitive |
| NP-Priority | - | Priority | ✓ | |
| FMLP | PI | FIFO | ✓ | best in 1427 out of 1440 configurations |
| PIP | PI | Priority | ✓ | |
| PPCP | PI | Priority | ✓ | never better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | not better than PI-based protocols in 1434 out of 1440 configurations |
| PRSB | RSB | Priority | ✓ | |

Locking Protocols for Global Scheduling

| Protocol | Progress | Queue Type | LP-based analysis | Empirical |
|----------|----------|------------|-------------------|-----------|
|----------|----------|------------|-------------------|-----------|

Full evaluation results (raw data, plots, stats) available online:

<https://www.mpi-sws.org/~bbb/papers/data/rtss15/index.html>

| | | | | |
|-------|-----|----------|---|---|
| PPCP | PI | Priority | ✓ | never better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | not better than PI-based protocols in 1434 out of 1440 configurations |
| PRSB | RSB | Priority | ✓ | |

Outline

~~Intro~~

~~Unified Analysis Framework~~

~~Evaluation Results~~

Summary and Conclusion

Summary and Conclusion

Unified blocking analysis framework:

- support for a variety of different locks
- enables **comparison based on state-of-the-art analysis**
- **extensible**: easy to incorporate application-specific constraints
- easily **composable constraints**
- implemented in **SchedCAT** open source library:

<http://www.mpi-sws.org/~bbb/projects/schedcat>

Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best available? | Empirical Results |
|-------------|--------------------|------------|-----------------------------------|---|
| NP-FIFO | - | FIFO | ✓ | baseline for comparison, not competitive |
| NP Priority | | Priority | ✓ | |
| FMFPT | RSB | FIFO | ✓ | not better than LP-based protocols in 1434 out of 1440 configurations |
| PRSB | RSB | Priority | ✓ | |

Which locking protocols would be reasonable default choices?

Locking Protocols for Global Scheduling

| Protocol | Progress Mechanism | Queue Type | LP-based analysis best available? | Empirical Results |
|-------------|--------------------|------------|-----------------------------------|---|
| NP-FIFO | - | FIFO | ✓ | baseline for comparison, not competitive |
| NP-Priority | - | Priority | ✓ | |
| FMLP | PI | FIFO | ✓ | best in 1427 out of 1440 configurations |
| PIP | PI | Priority | ✓ | |
| PPCP | PI | Priority | ✓ | never better than PIP/FMLP |
| FMLP+ | RSB | FIFO | ✓ | not better than PI-based protocols in 1434 out of 1440 configurations |
| PRSB | RSB | Priority | ✓ | |

Future Work

Exploit richer task models:

- control flow
- order and separation of critical sections

Exploit restrictions in task models:

- periodic tasks: arrival times known

Exploit application-specific properties

Implementation available as part of
SchedCAT open source library:

<http://www.mpi-sws.org/~bbb/projects/schedcat>

Full evaluation results (raw data, plots, stats)
available online:

<https://www.mpi-sws.org/~bbb/papers/data/rtss15/index.html>