Fast on Average, Predictable in the Worst Case

Exploring Real-Time Futexes in LITMUS^{RT}

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Max
Planck
Institute
for
Software Systems

Real-Time Locking API

Mutex API

```
kernel_do_lock();
// critical section
kernel_do_unlock();
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```

No other task is currently holding the lock

No other task is waiting for the lock

Operations are typically ***uncontended*** at runtime

Futexes: Fast Userspace Mutexes

A **mechanism (API) in the Linux** kernel

- For optimizing the uncontended case of locking protocol implementations

- Avoid kernel invocation during uncontended operations

Futexes: Fast Userspace Mutexes

A **mechanism (API) in the Linux** kernel

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- Avoid kernel invocation during uncontended operations

Why optimize the uncontended case?

- Improved throughput for soft real-time workloads
- Increasing available slack time in the system

Real-Time Locking Implementations

	PRIO_INHERIT (Priority Inheritance Protocol)
Futex Implementation	✓

↑

Linux

Real-Time Locking Implementations

	PRIO_INHERIT (Priority Inheritance Protocol)	PRIO_PROTECT (Immediate Priority Ceiling Protocol)
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Linux

Real-Time Locking Implementations

	PRIO_INHERIT (Priority Inheritance Protocol)	PRIO_PROTECT (Immediate Priority Ceiling Protocol)	Classic Priority Ceiling Protocol (PCP)	Multiprocessor PCP (MPCP)	FMLP
Futex Implementation	✓	✗	✗	✗	✗

Linux

LITMUS^{RT}

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Choice between futex implementation and better analytical properties

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Linux

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Choice between futex implementation and better analytical properties

Why is it challenging to have both?

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Reactive

Anticipatory

Real-Time Locking Protocol Dichotomy

Reactive Locking Protocols	Anticipatory Locking Protocols
React to contention on a lock **only when it occurs**.	**Anticipate problem scenarios** and take measure to minimize priority-inversion (pi) blocking.

Real-Time Locking Protocol Dichotomy

Reactive Locking Protocols	Anticipatory Locking Protocols
React to contention on a lock **only when it occurs**.	**Anticipate problem scenarios** and take measure to minimize priority-inversion (pi) blocking.
Simple futex implementation	**Tricky** to implement futexes without **violating semantics**

Contributions

	PRIO_INHERIT (Priority Inheritance Protocol)	PRIO_PROTECT (Immediate Priority Ceiling Protocol)	Classic Priority Ceiling Protocol (PCP)	Multiprocessor PCP (MPCP)	FMLP
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Design and implementation of futexes for **three anticipatory real-time locking protocols**

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Observed overhead reduction:			**92%**	**85%**	**84%**

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Design and implementation of futexes for **three anticipatory real-time locking protocols**

Method of **using page faults** to implement futexes

Overview of Talk

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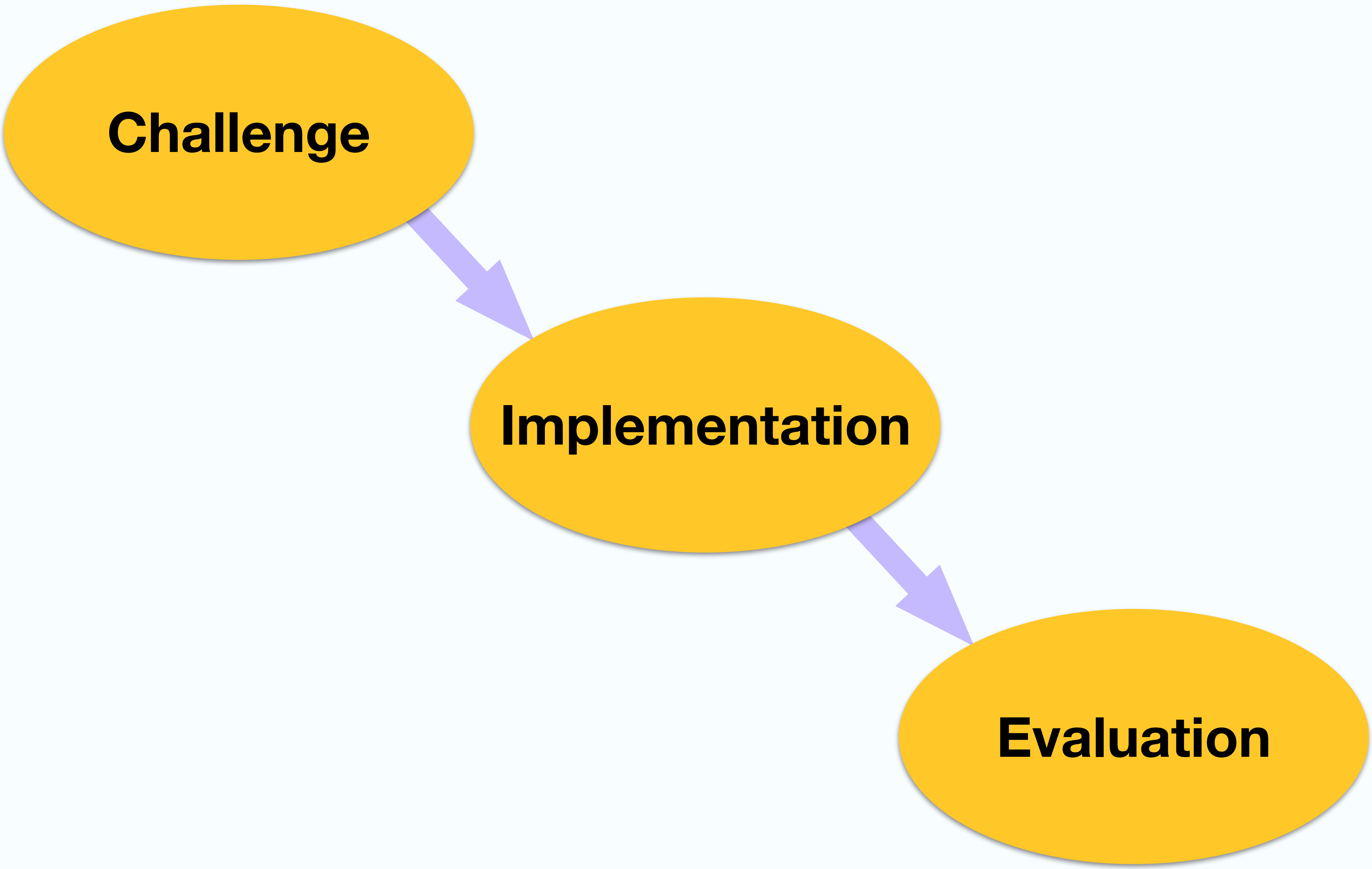

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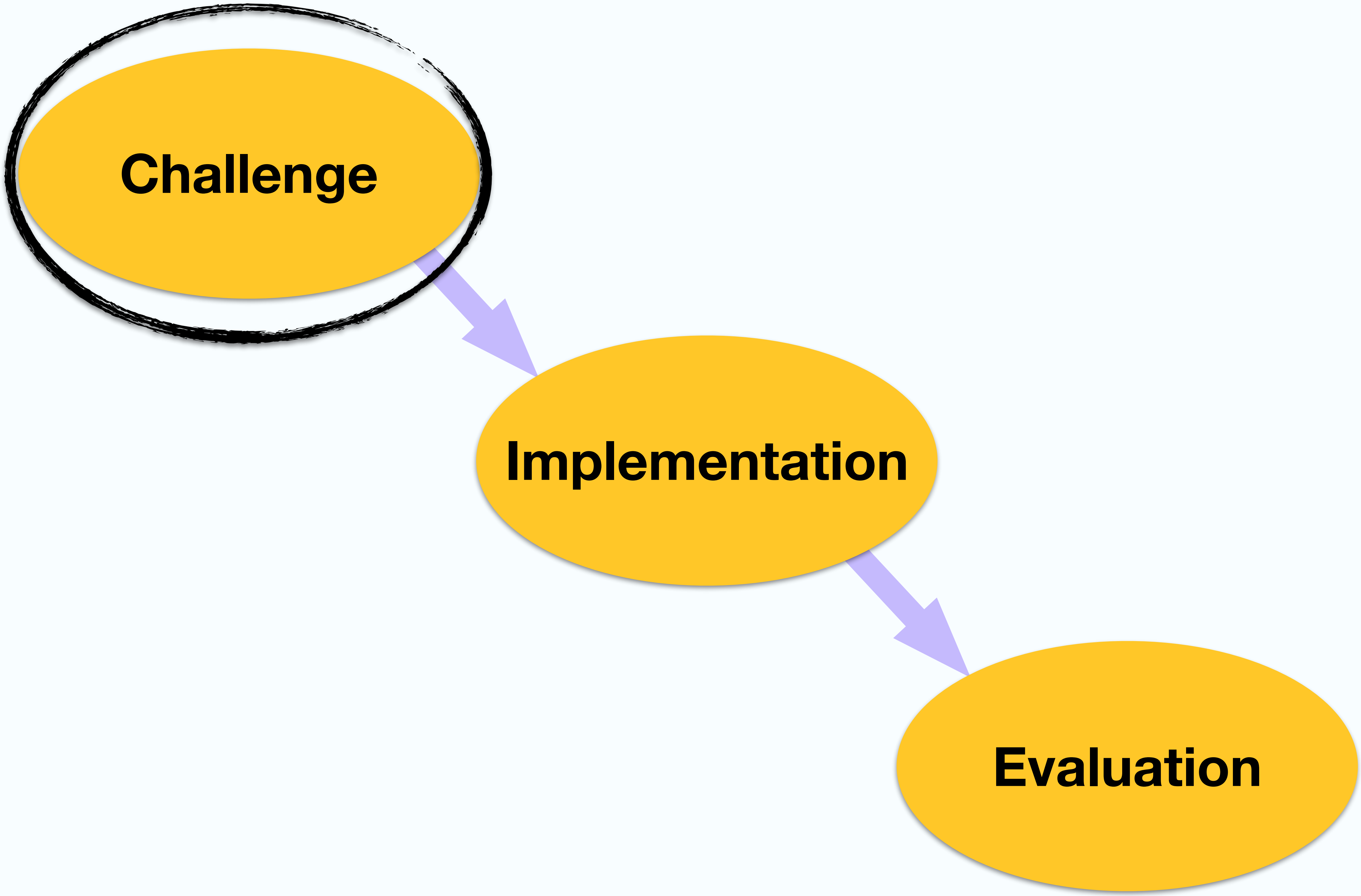

Futexes — Overview and Intuition

The problem with the vanilla approach

Mutex API

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The problem with the vanilla approach

Kernel invoked on every lock and unlock operation

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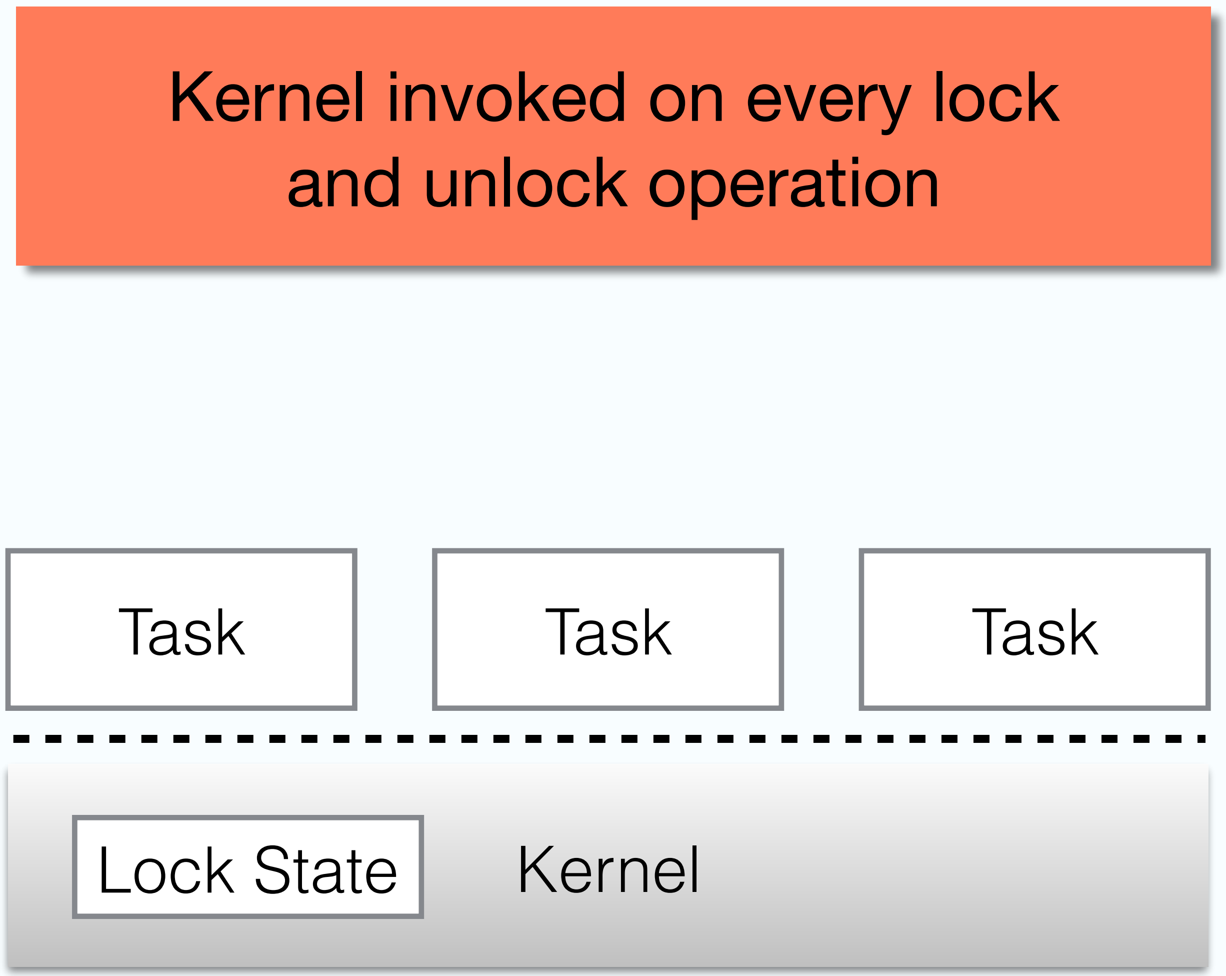

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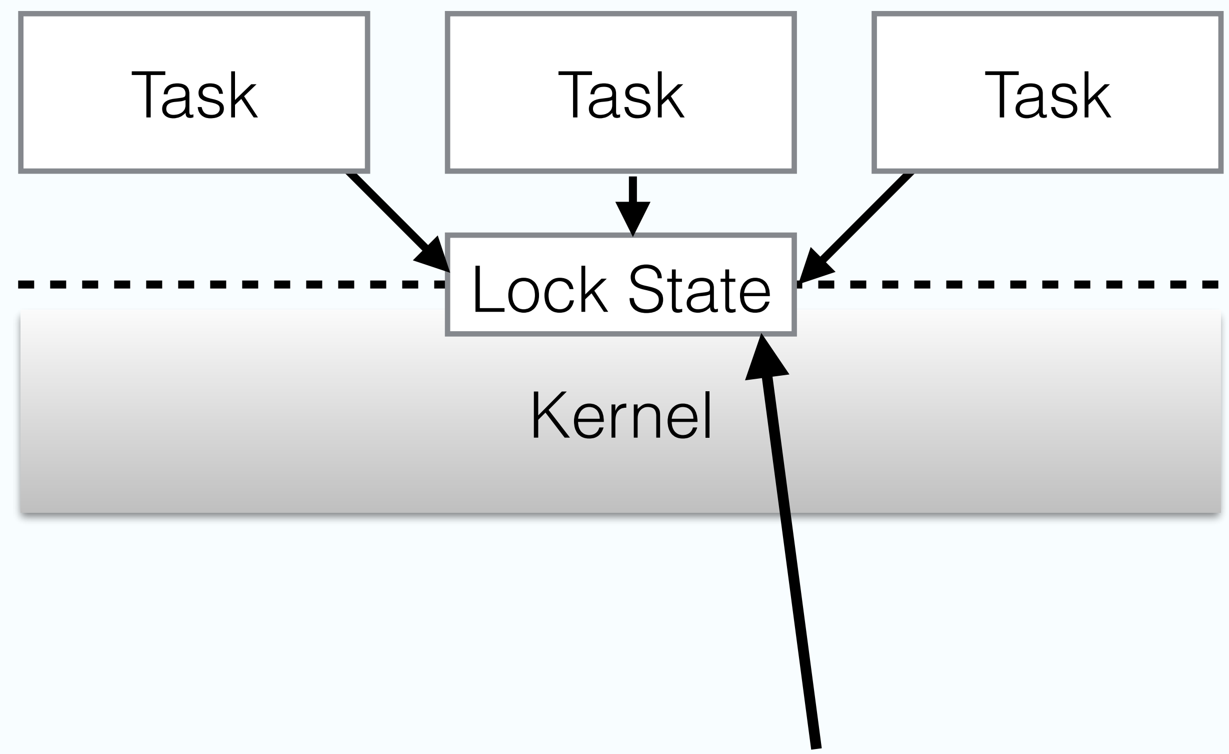
Futexes — Overview and Intuition

Exporting Lock State to Userspace Processes



Shared lock state between userspace and kernel

Futexes — Overview and Intuition

Exporting Lock State to Userspace Processes

Futex Pseudocode

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try_to_acquire_lock(lock);
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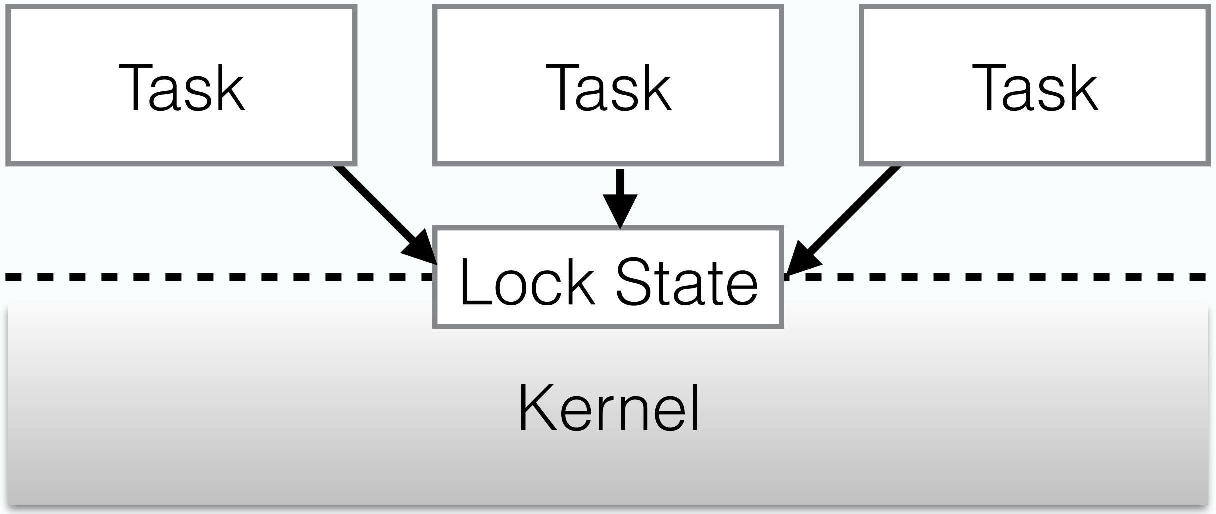

Futexes — Overview and Intuition

Fast-Path for Uncontended Operations

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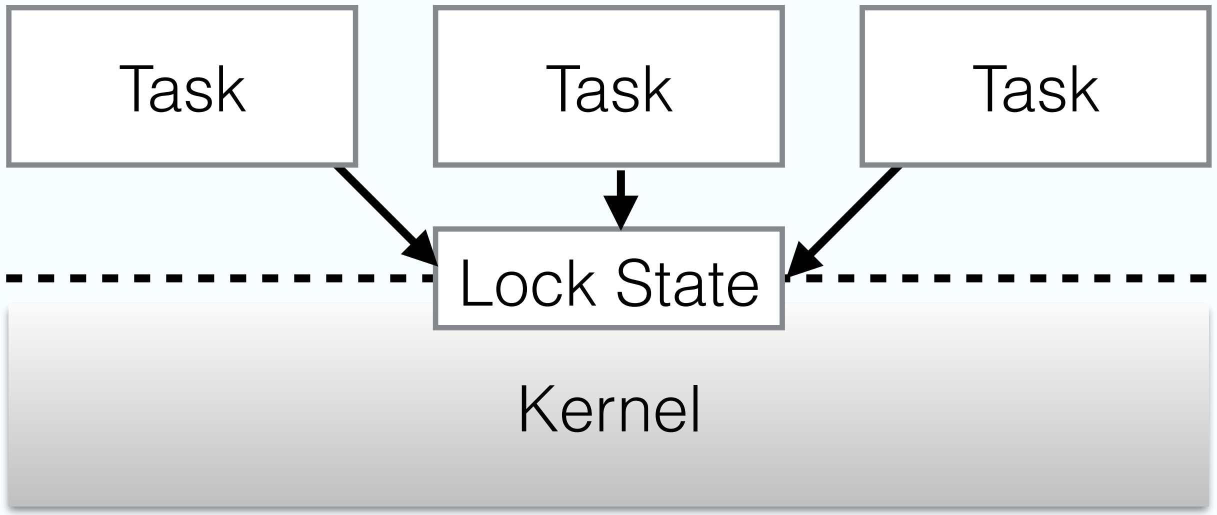

Fast-path when operation is uncontended (kernel not invoked)

Futexes — Overview and Intuition

Slow-Path for Contended Operations

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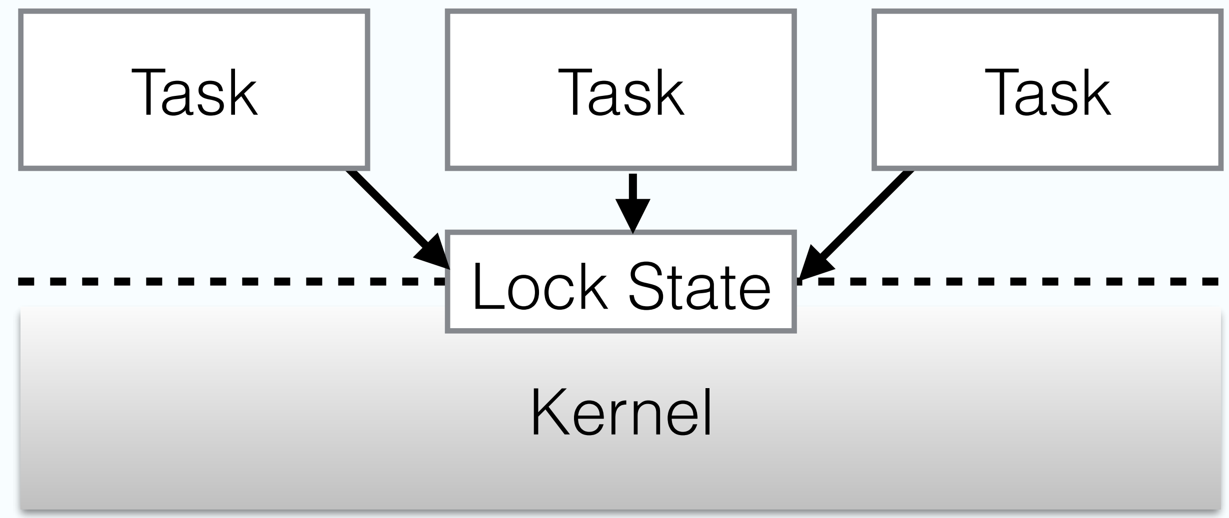
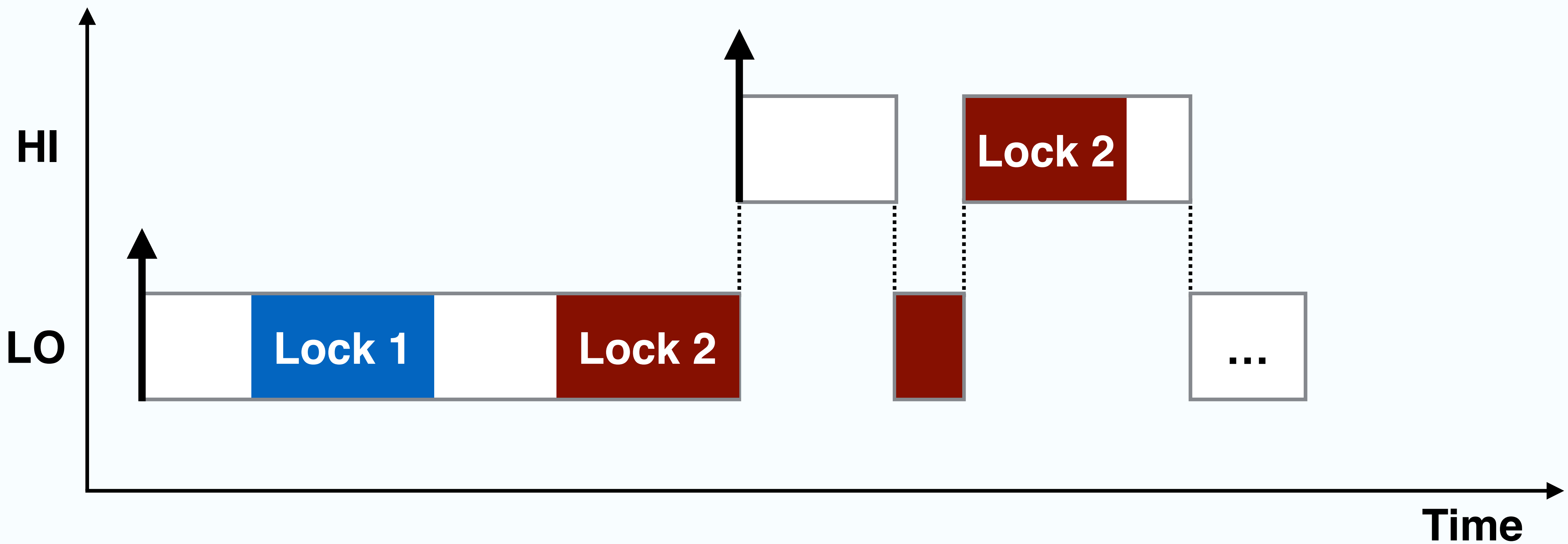


Kernel invoked **only when lock or unlock operation is contended**

Priority Inheritance Protocol

Futexes for reactive locking protocols



Fixed-Priority Scheduling

Priority Inheritance Protocol

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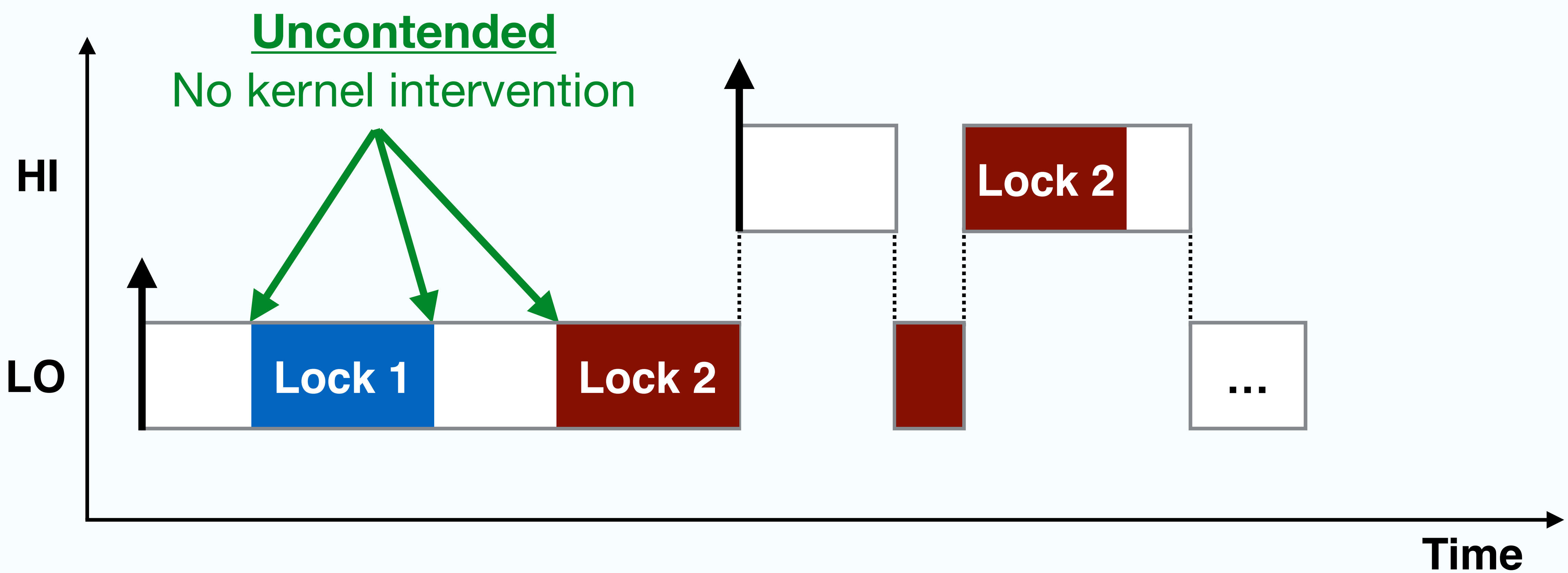

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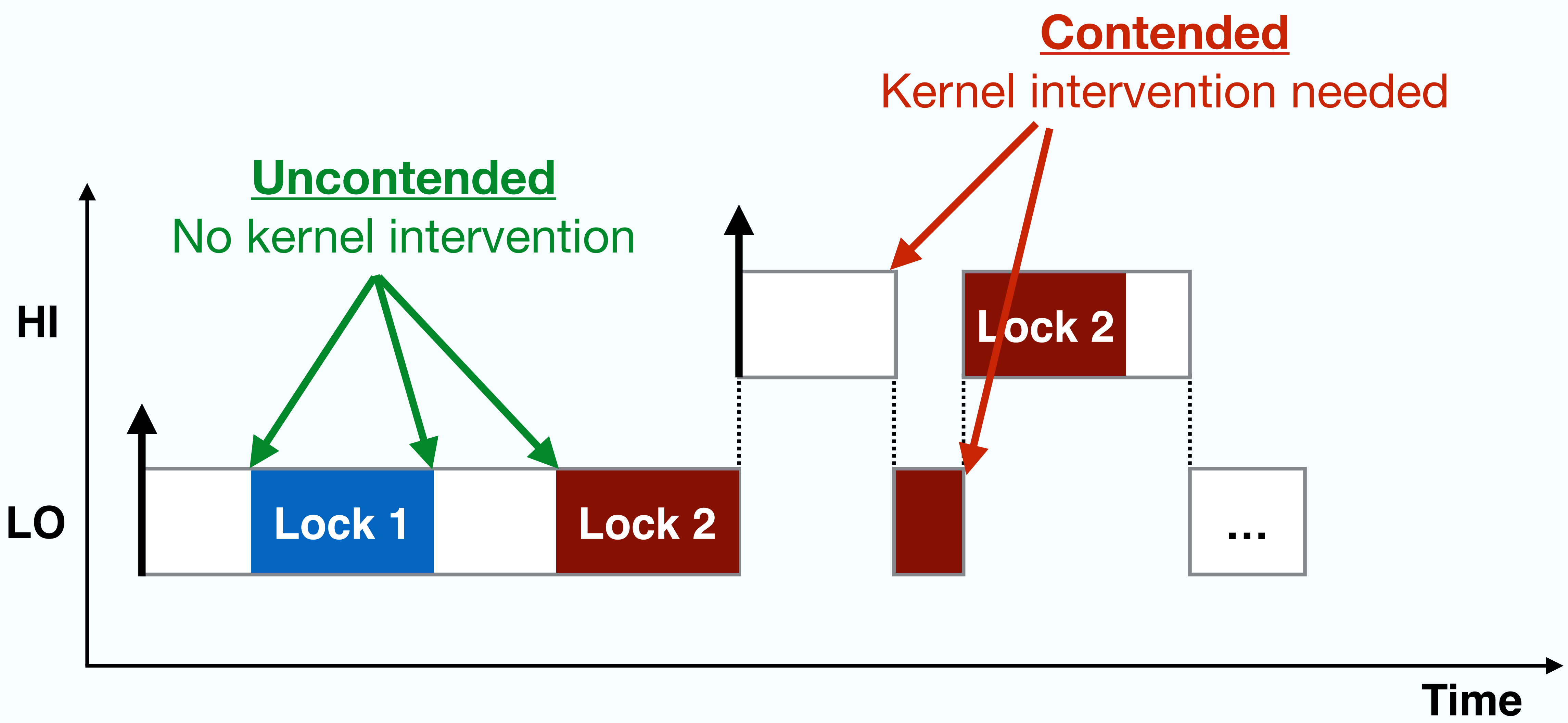

Fixed-Priority Scheduling

Priority Ceiling Protocol (PCP)

- Each lock has a **priority ceiling** — the highest priority of all tasks that can acquire that lock.

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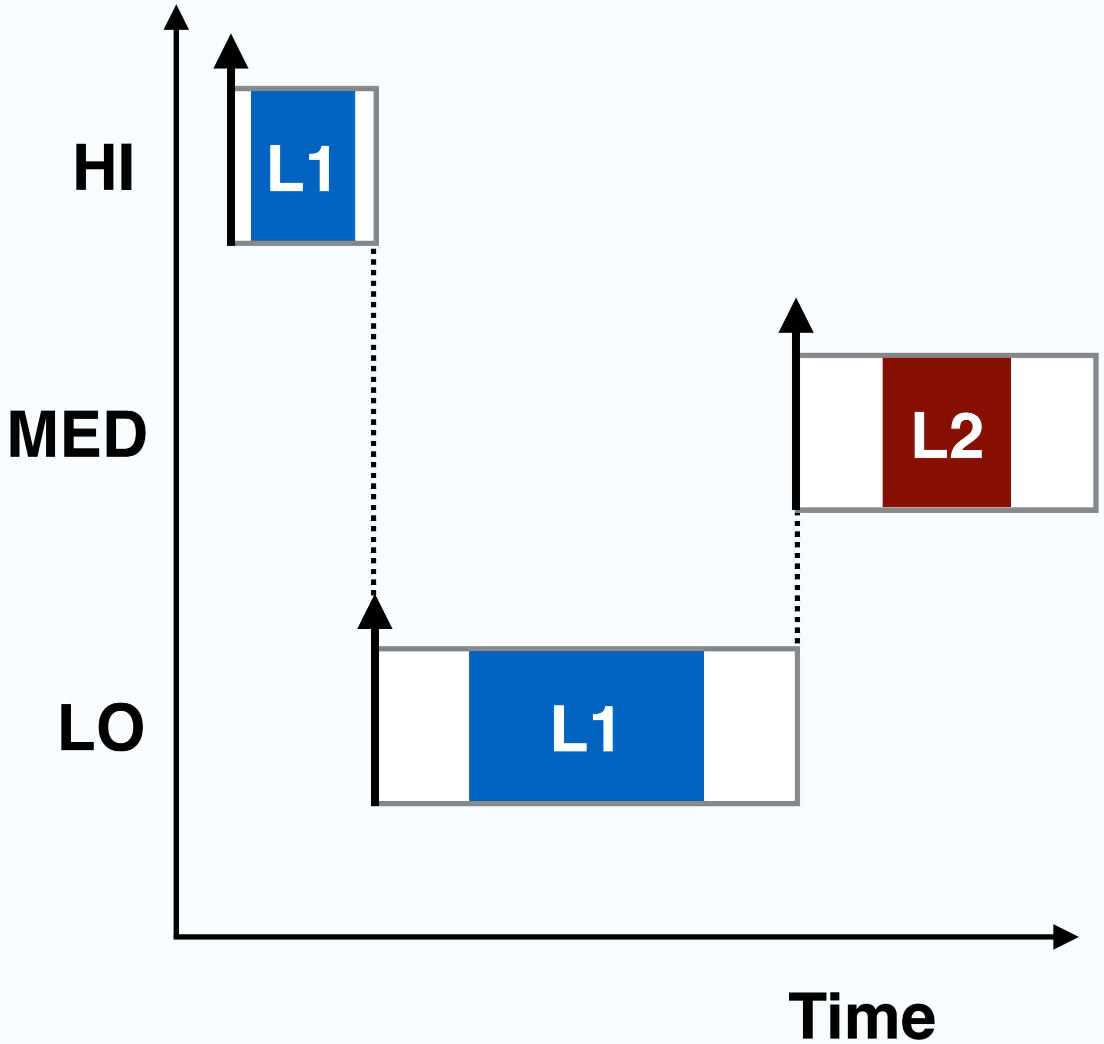
- **System ceiling** — Currently held lock with highest ceiling
- A lock may be acquired by a task only if:
    - **Task priority > System Ceiling Priority**
    - Or the task is **holding the system ceiling**
- When **under contention, priority inheritance** (raises priority of lower priority task to that of higher priority task).

PCP Futexes — Challenge



Fixed-Priority Scheduling

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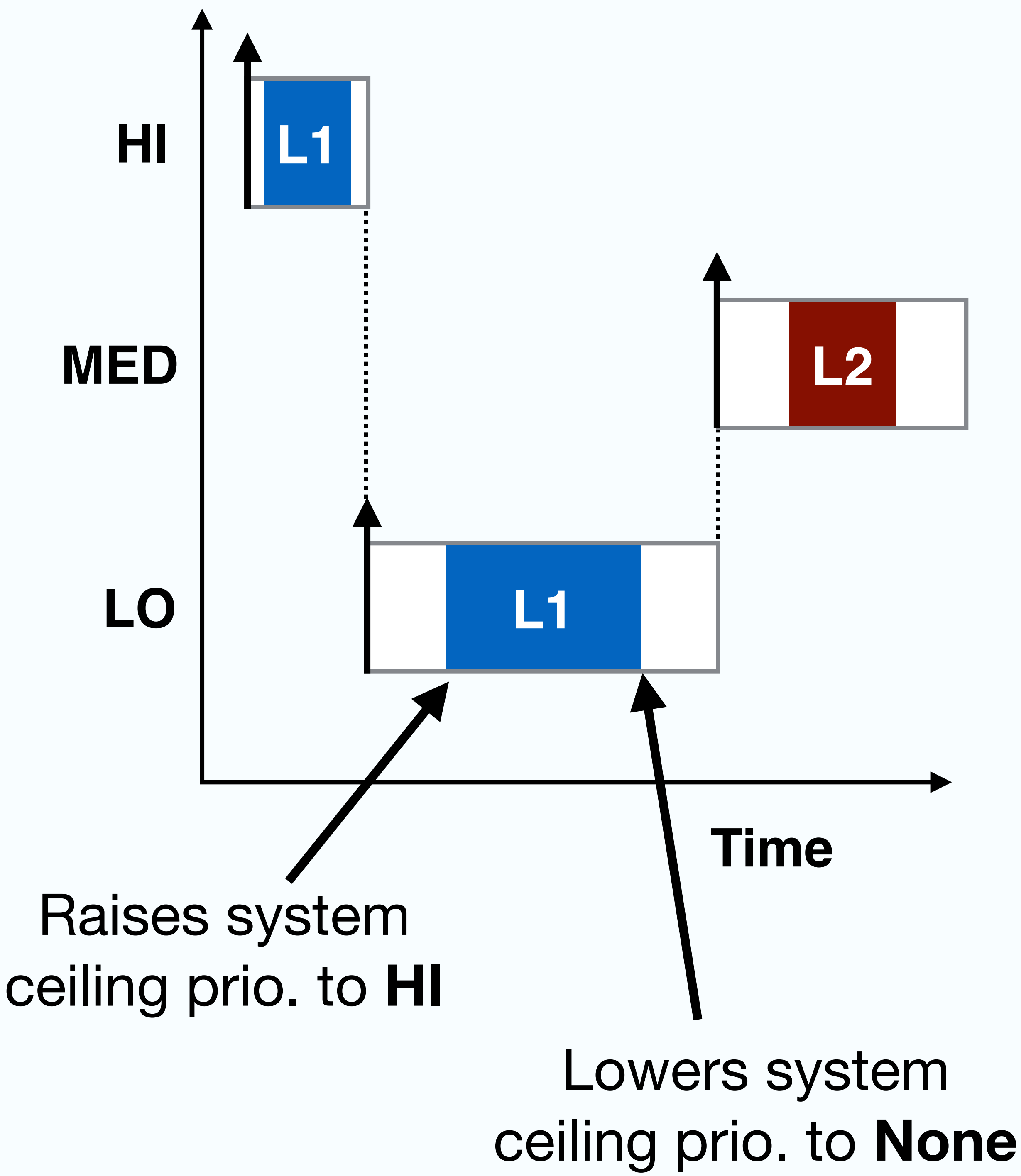

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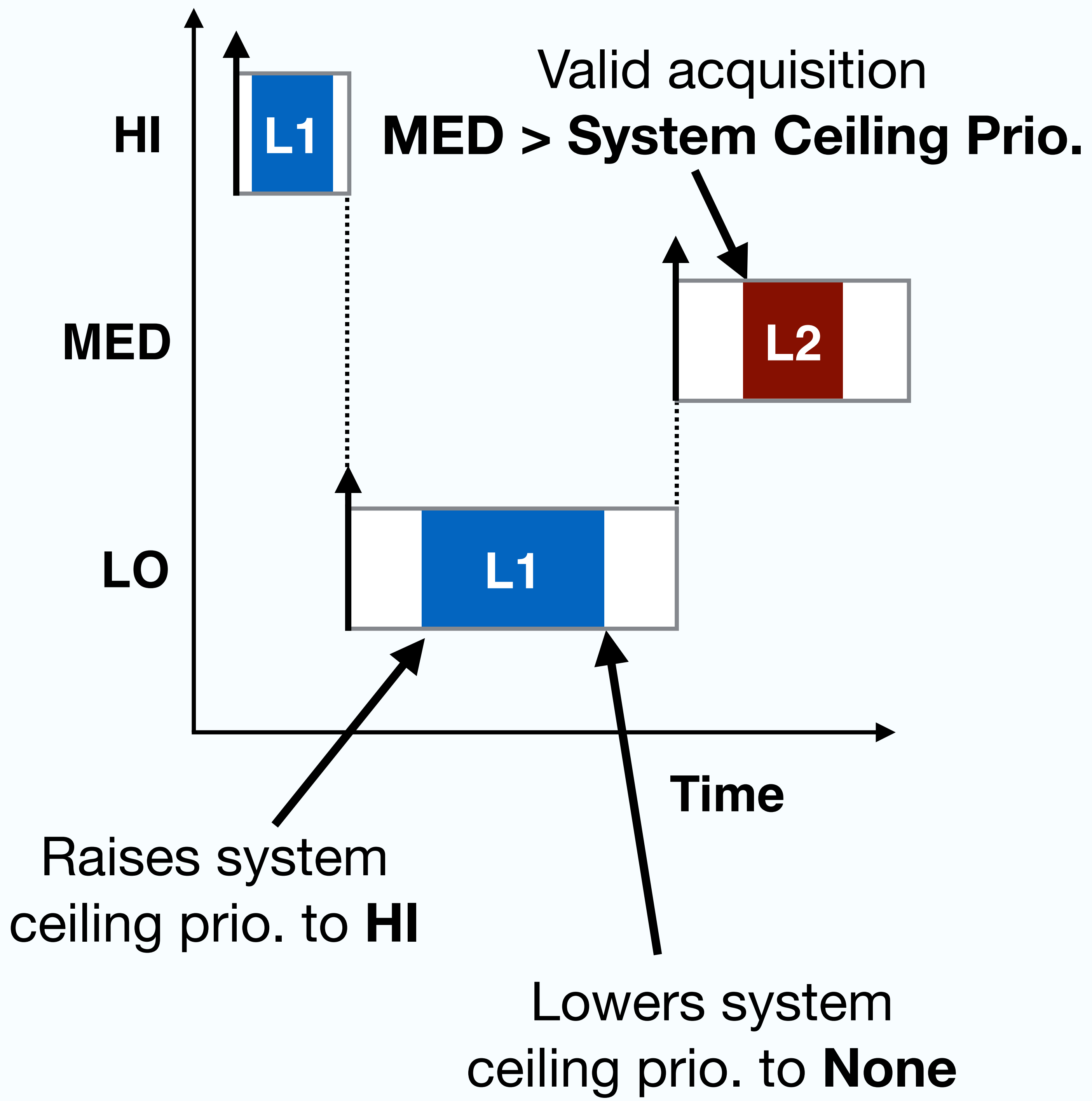

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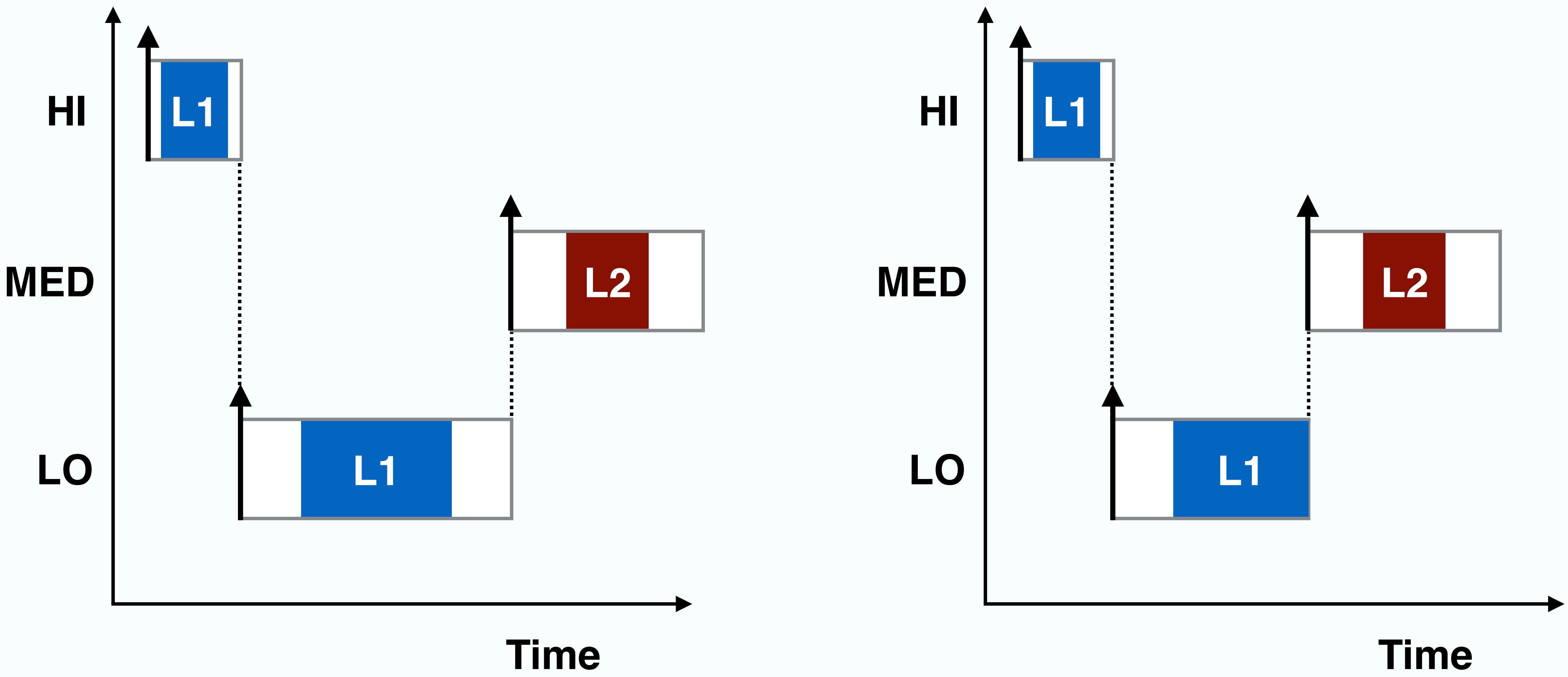

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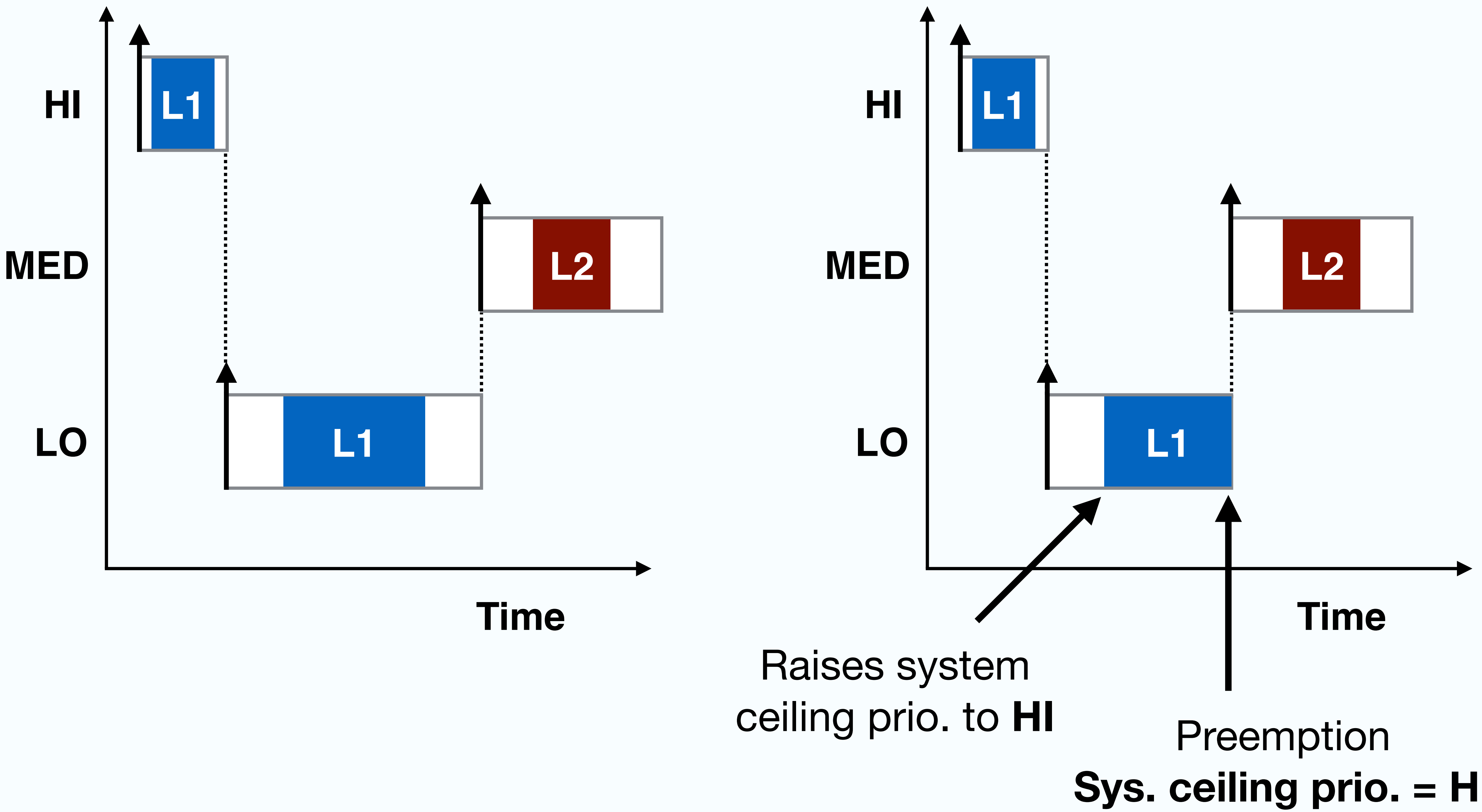

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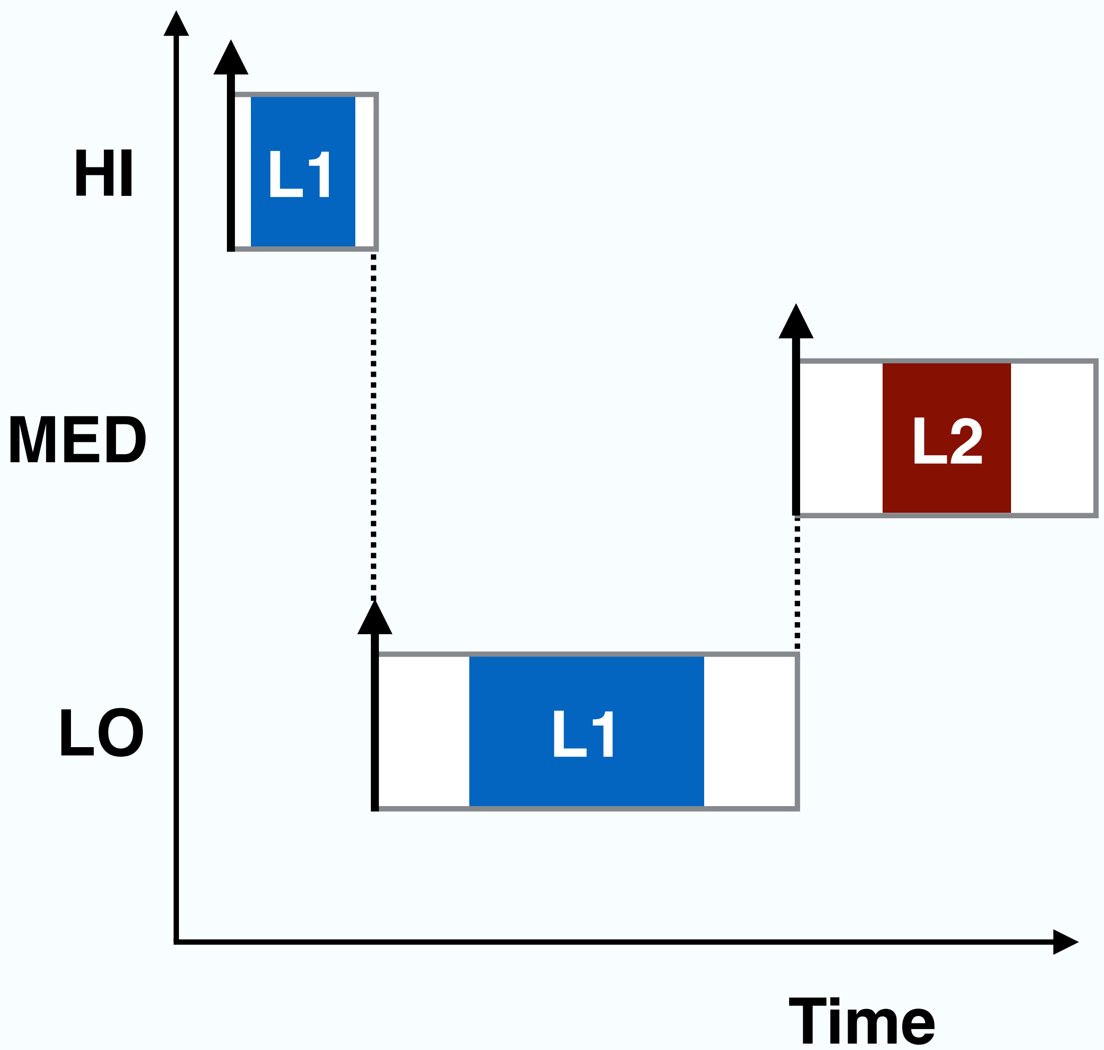

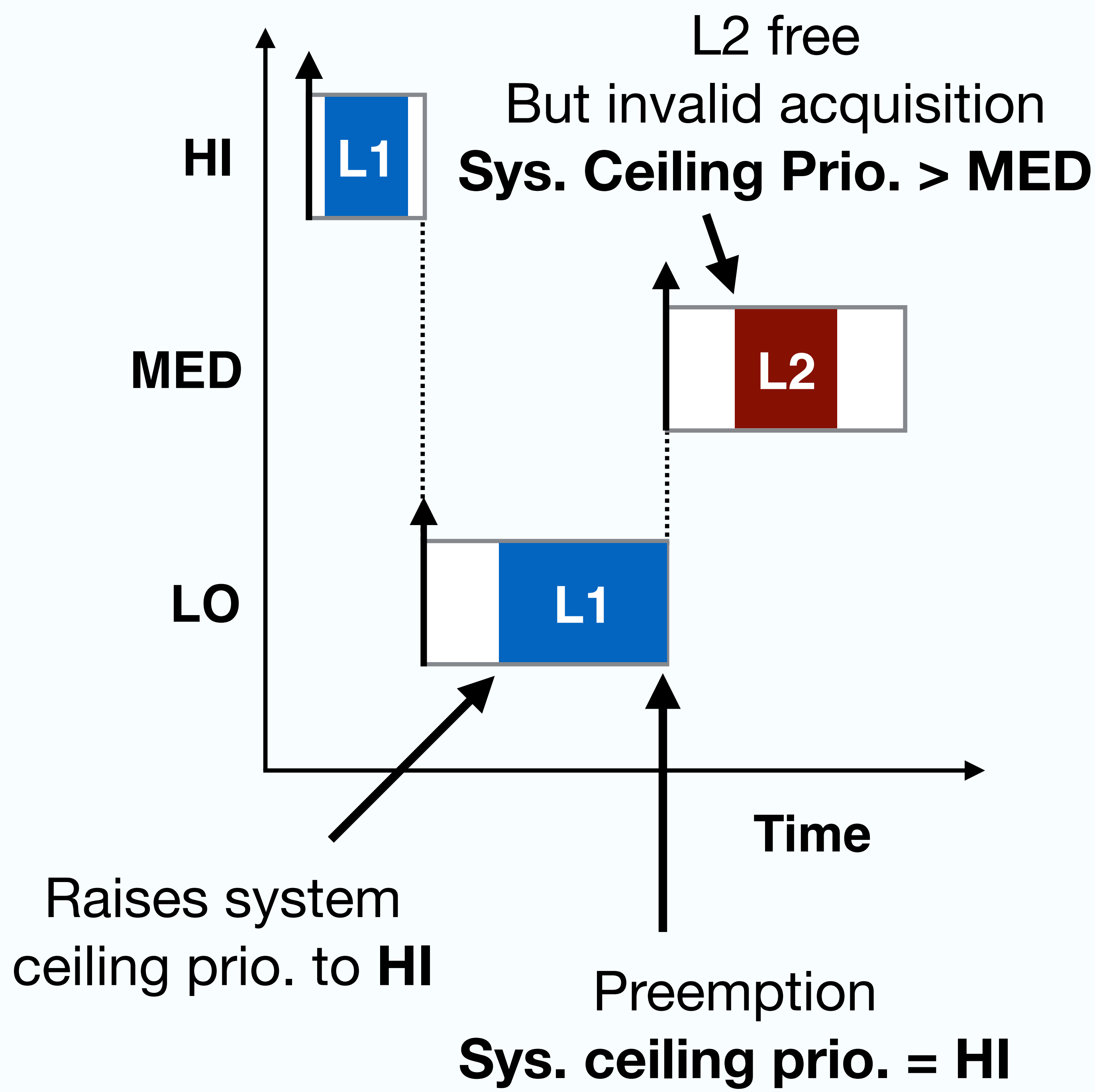

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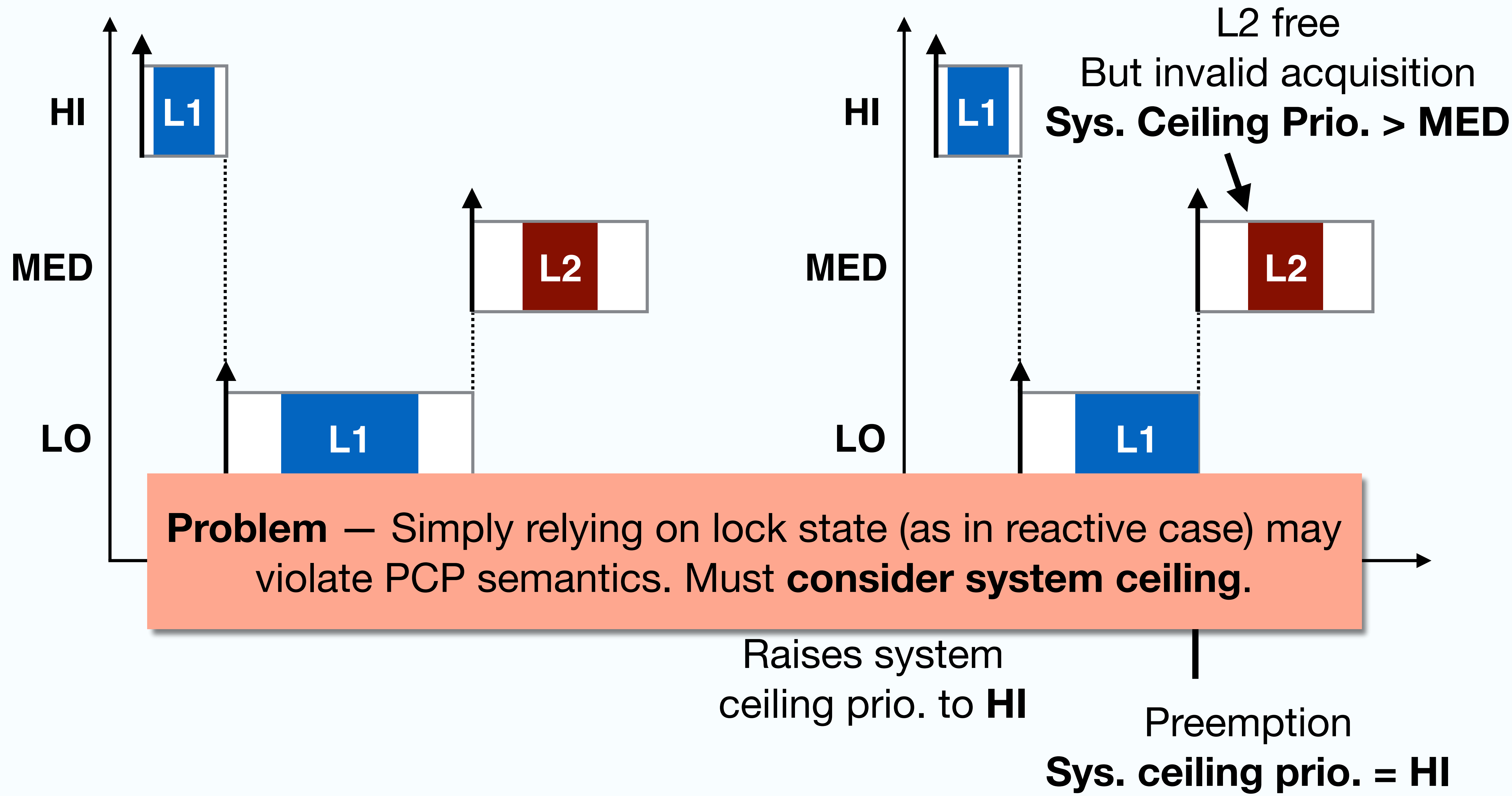

Problem — Simply relying on lock state (as in reactive case) may violate PCP semantics. Must **consider system ceiling.**

Fixed-Priority Scheduling

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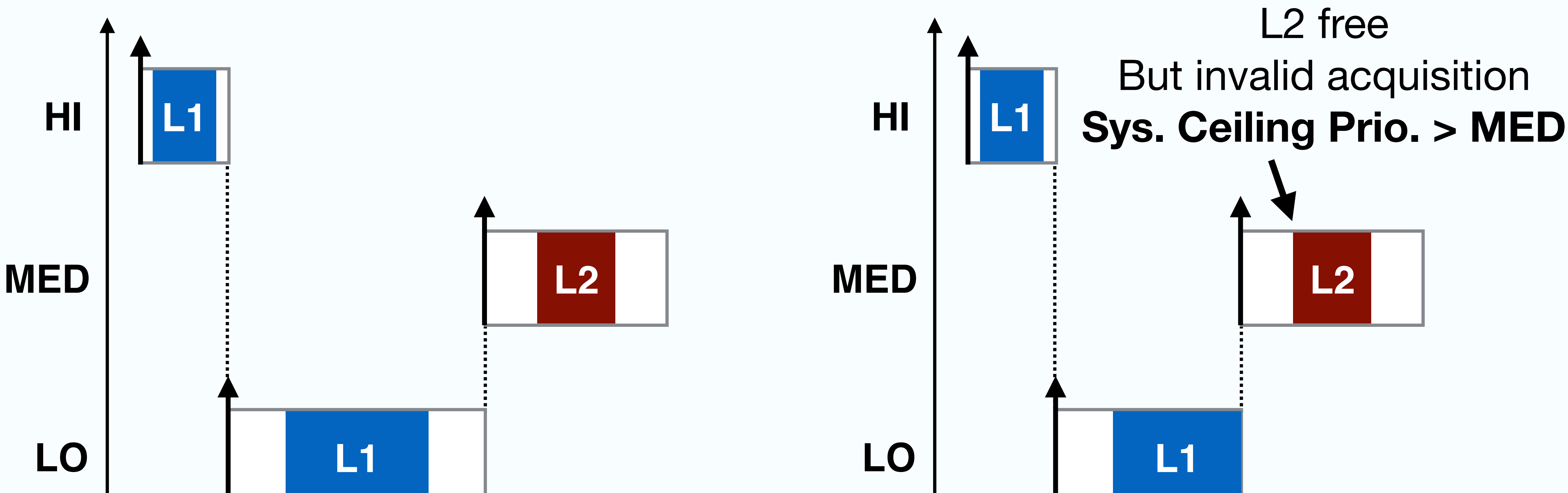

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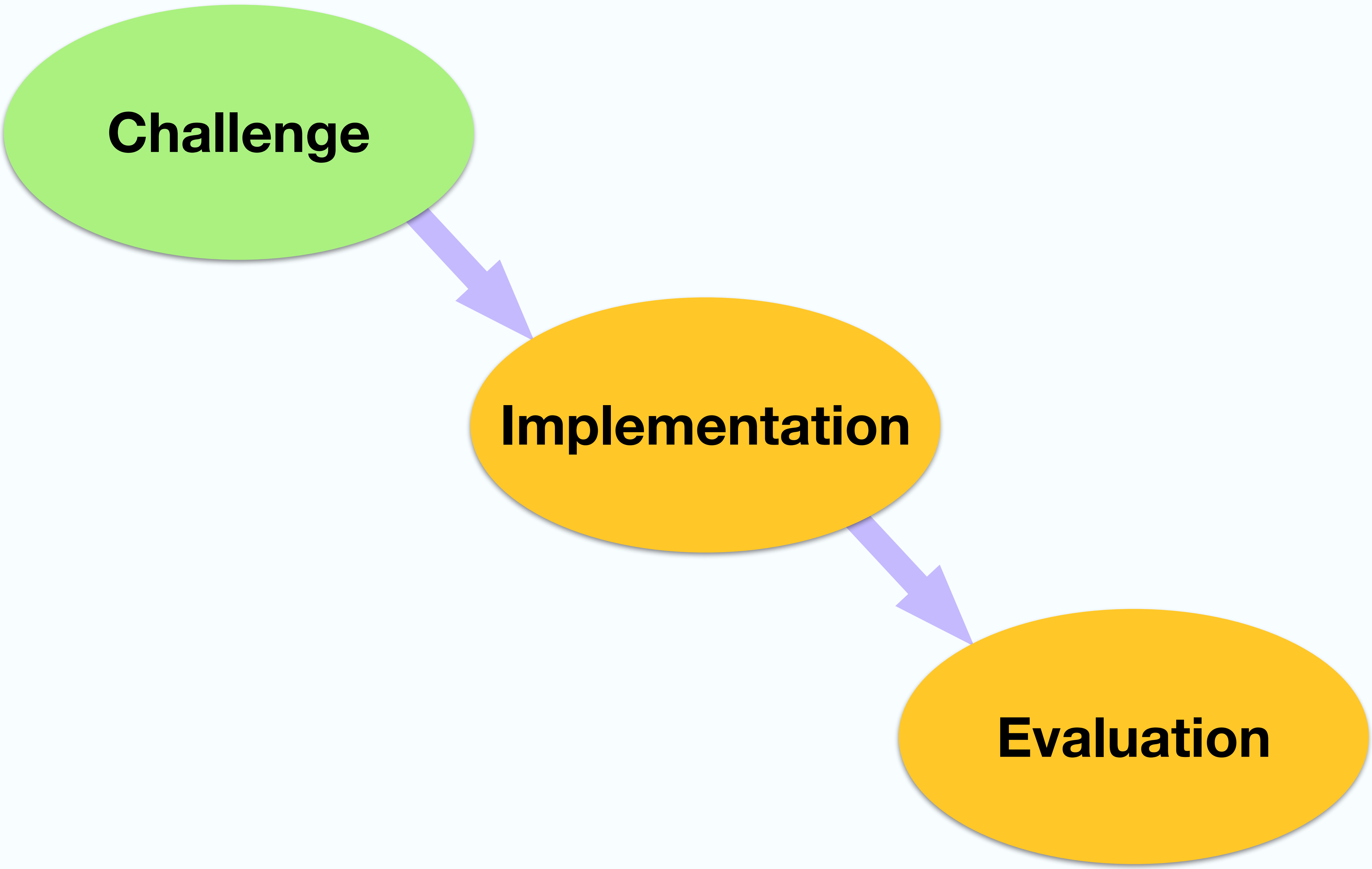
Raises system

Problem — system ceiling potentially updated at every lock acquisition and release — must **always invoke kernel** to avoid protocol violations

= **HI**

Fixed-Priority Scheduling

Overview of Talk



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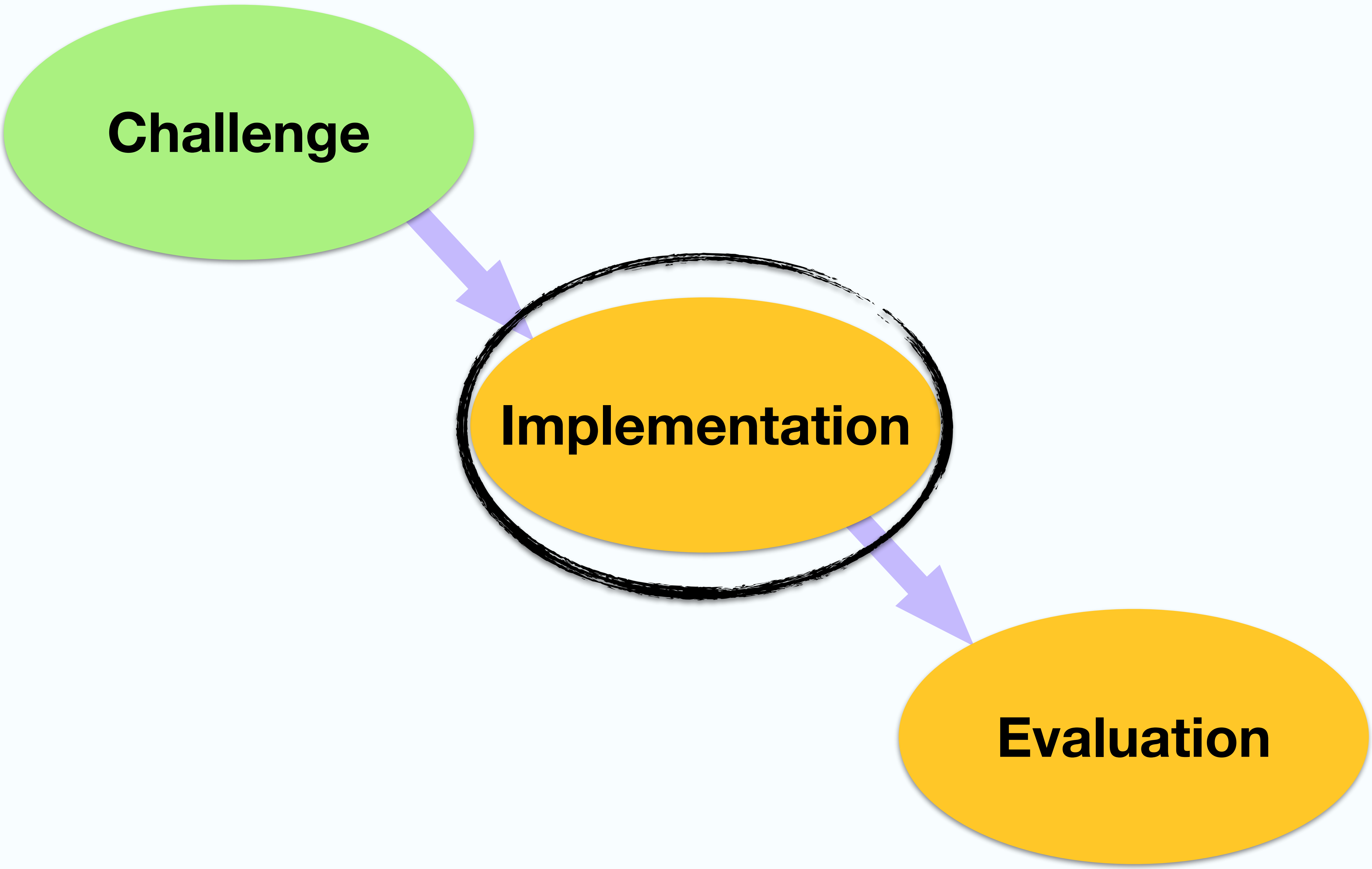

PCP Futexes — Our Approach

PCP Futex Pseudocode

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if (lock is contended)
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Whether lock acquisition is contended is determined in PCP by the **current system ceiling**

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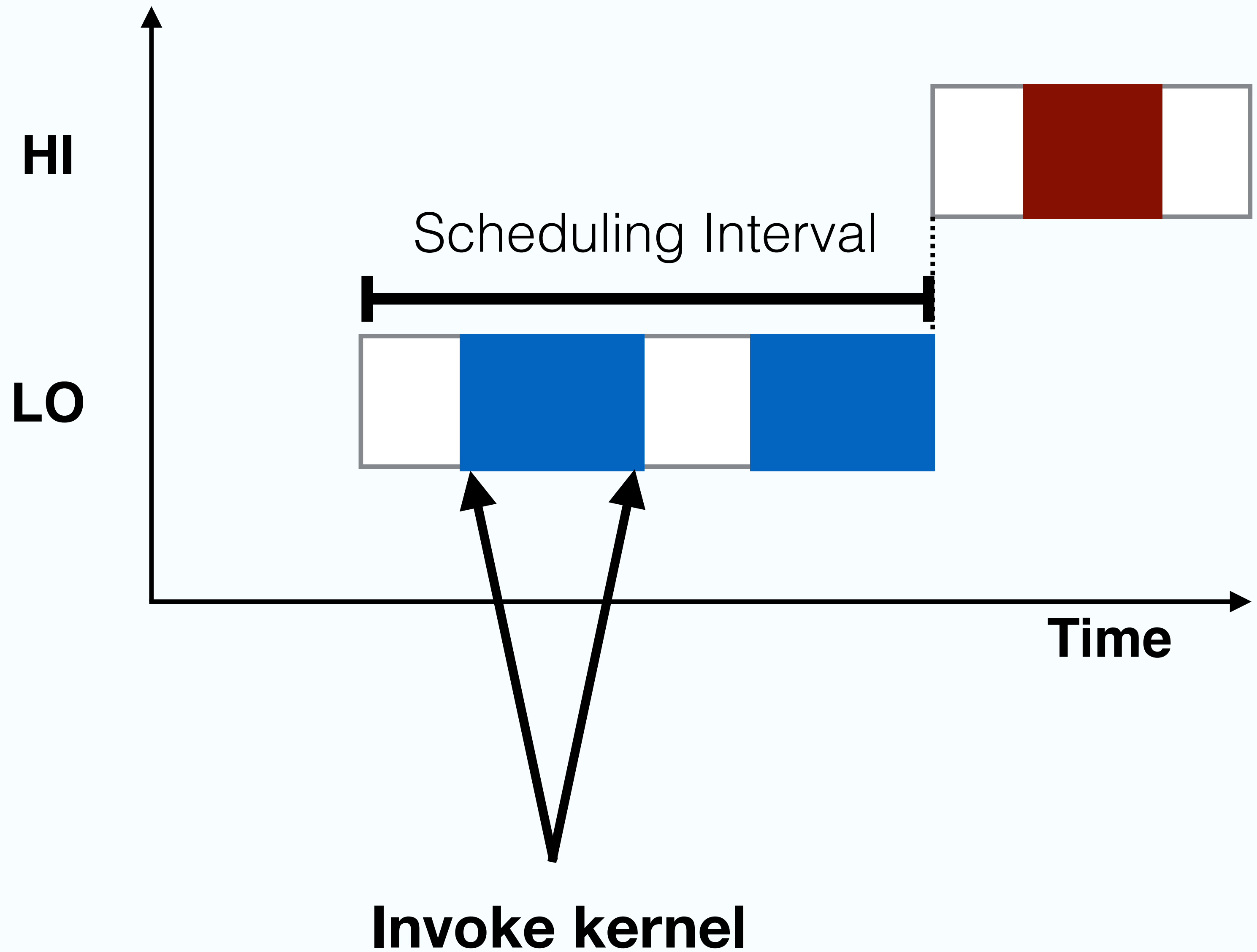
Cannot change **while a task is scheduled** on a uniprocessor!

PCP Futexes — Deferred Updates



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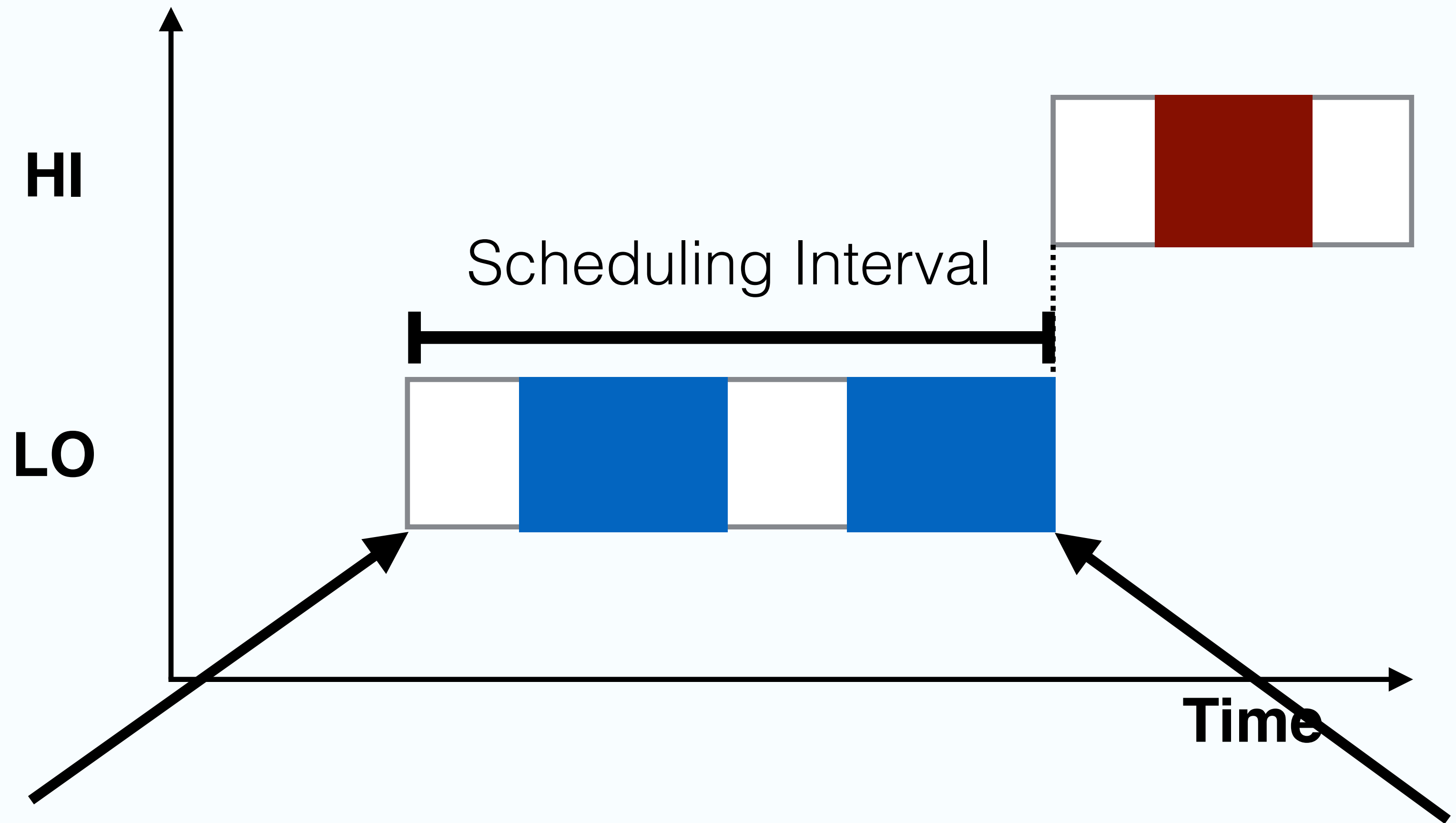
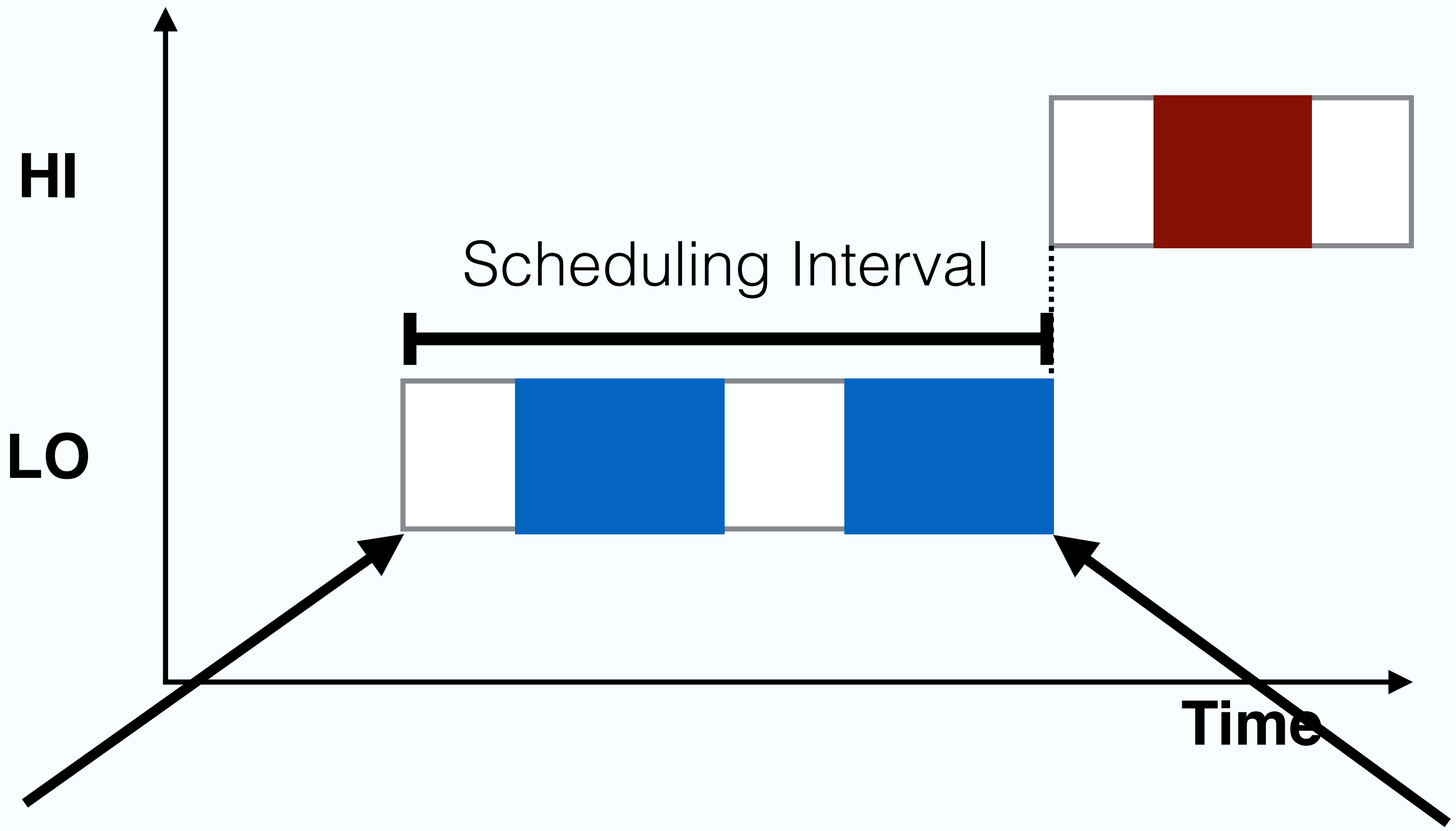


Predetermine contention conditions and communicate them to task

Make changes to **local copy of lock states** (if uncontended)

Update kernel state based on copy **at context switch**

PCP Futexes — Deferred Updates



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Update kernel state based on copy **at context switch**

Requires a **bidirectional communication channel** between tasks and the kernel

Bidirectional Communication — Lock Page

bitmap: lock_states
bool: tasks_blocked

Lock Page

Per-process **page of memory** writable by both the process and kernel.

Bidirectional Communication — Lock Page

Lock-state bitmap used to communicate acquisitions and releases of locks to kernel

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Lock Page

Per-process **page of memory** writable by both the process and kernel.

A “permission bit” set by the kernel to indicate **whether lock acquisition is allowed** (system ceiling check)

Communicating the Permission Bit

PCP Futex Pseudocode

```
if (permission bit is set)
    set_bit_in_bitmap(lock)
else
    kernel_do_lock(lock);
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release_lock(lock);
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Challenge:

Checking for permission and setting lock bit **must be atomic.**

Why? Preemption between them may change the permission.

Communicating the Permission Bit

We proposed two approaches for the Classic PCP

Page Faults (PCP-DU-PF)

Uses **page faults** to invoke kernel when locking is prohibited

CMPXCHG (PCP-DU-BOOL)

Boolean for permission bit.

Compare-and-exchange operation to check and acquire locks atomically

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See paper for details!

Boolean

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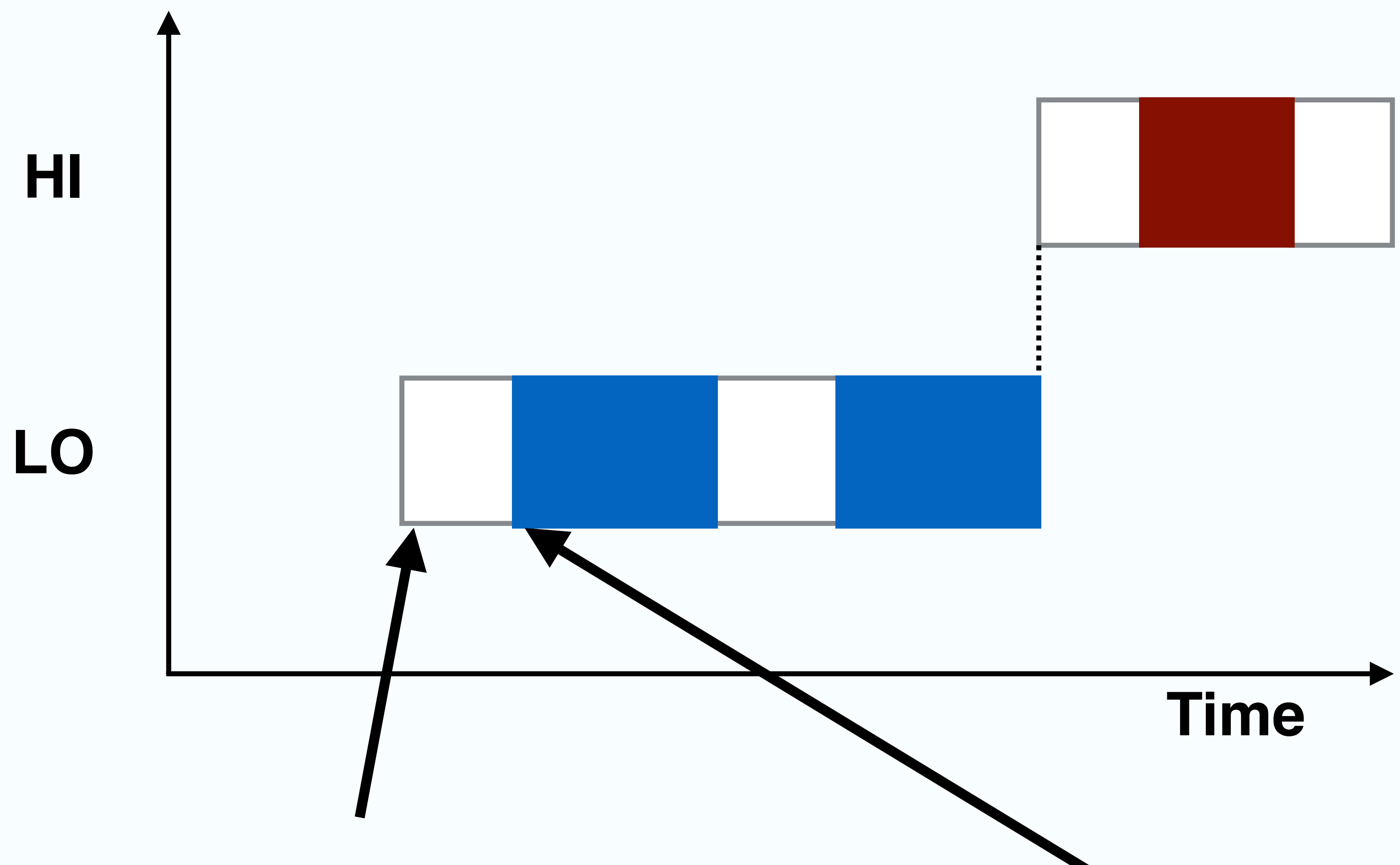


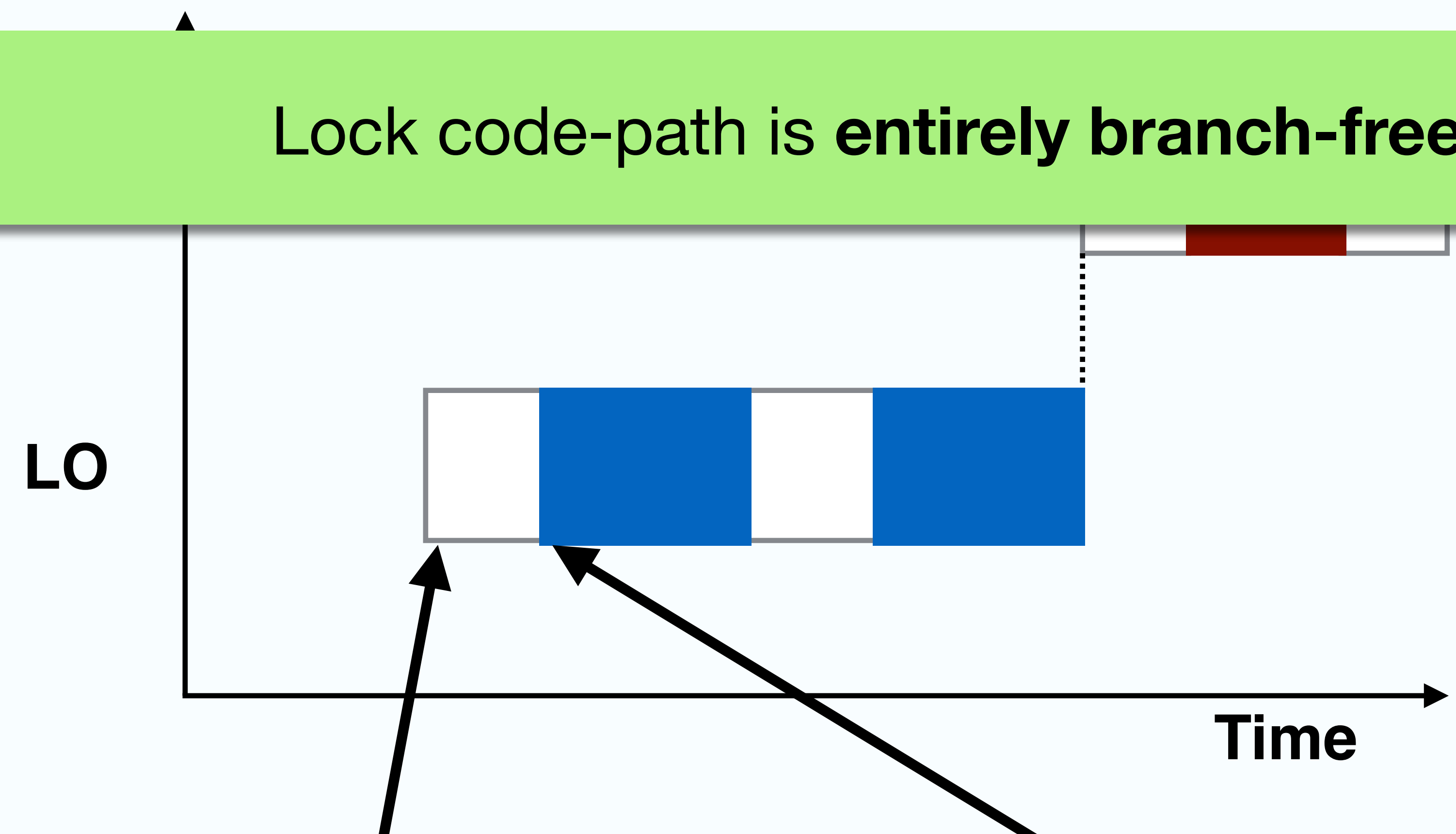
If (locking is allowed)
    set lock page writable
else
    set lock page unwritable

Attempting to write lock bit **will invoke kernel automatically** if locking is not permitted

PCP Futexes — Page Fault Approach

Can be implemented using **segmentation faults** as well

Lock code-path is **entirely branch-free**



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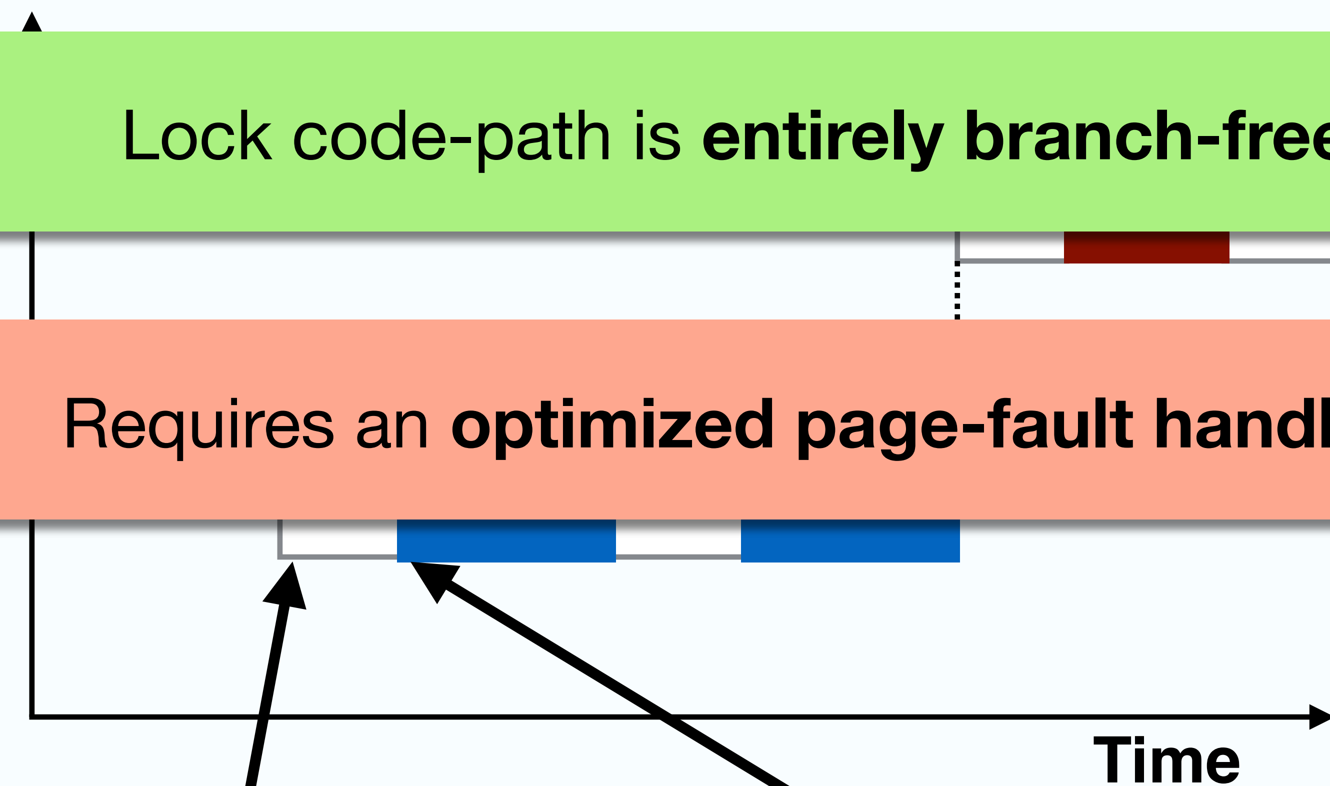
Requires an **optimized page-fault handler**



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Compare-and-exchange operation to check and acquire locks atomically

Avoid page faults at cost of atomic op + branch

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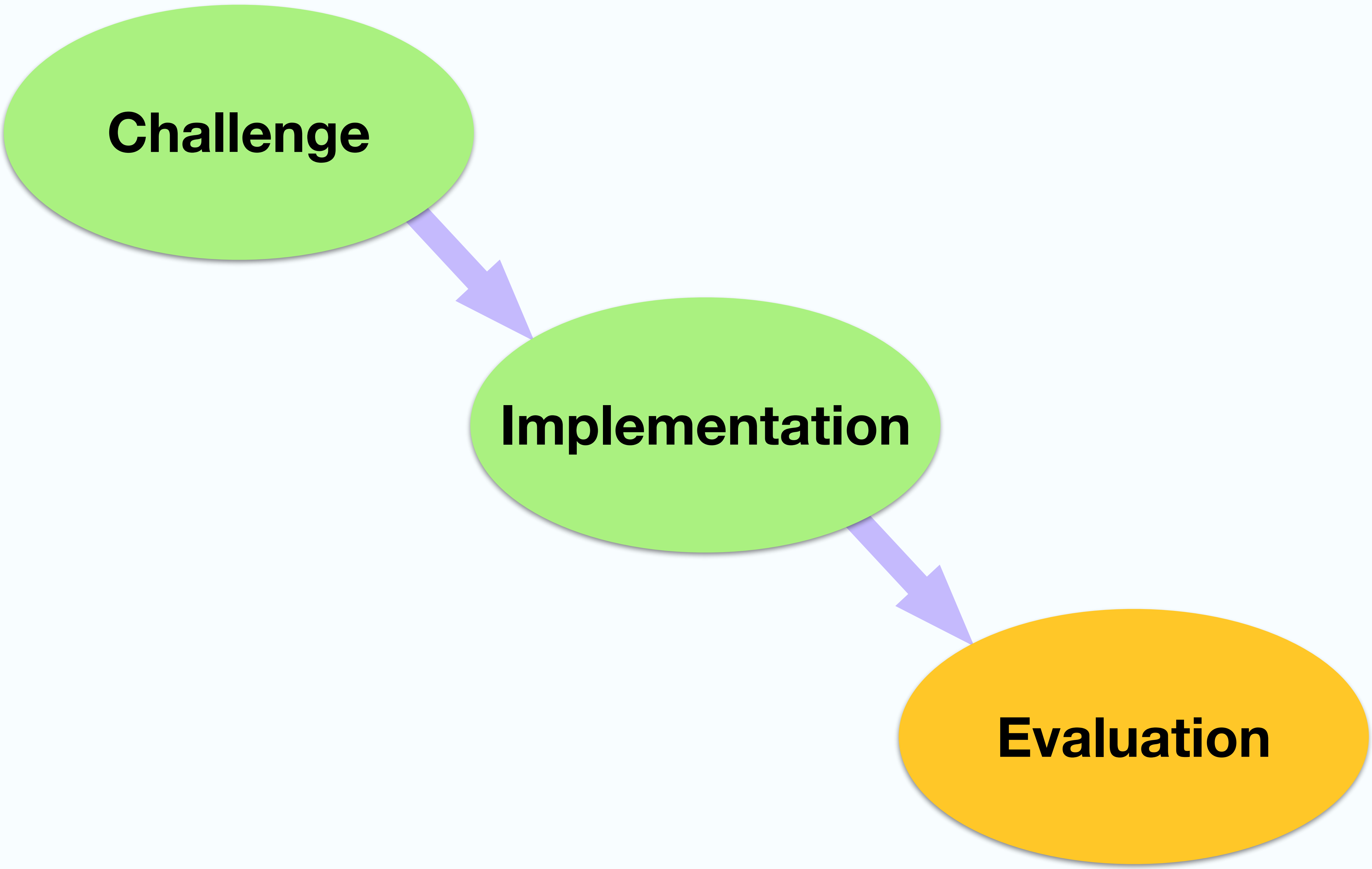

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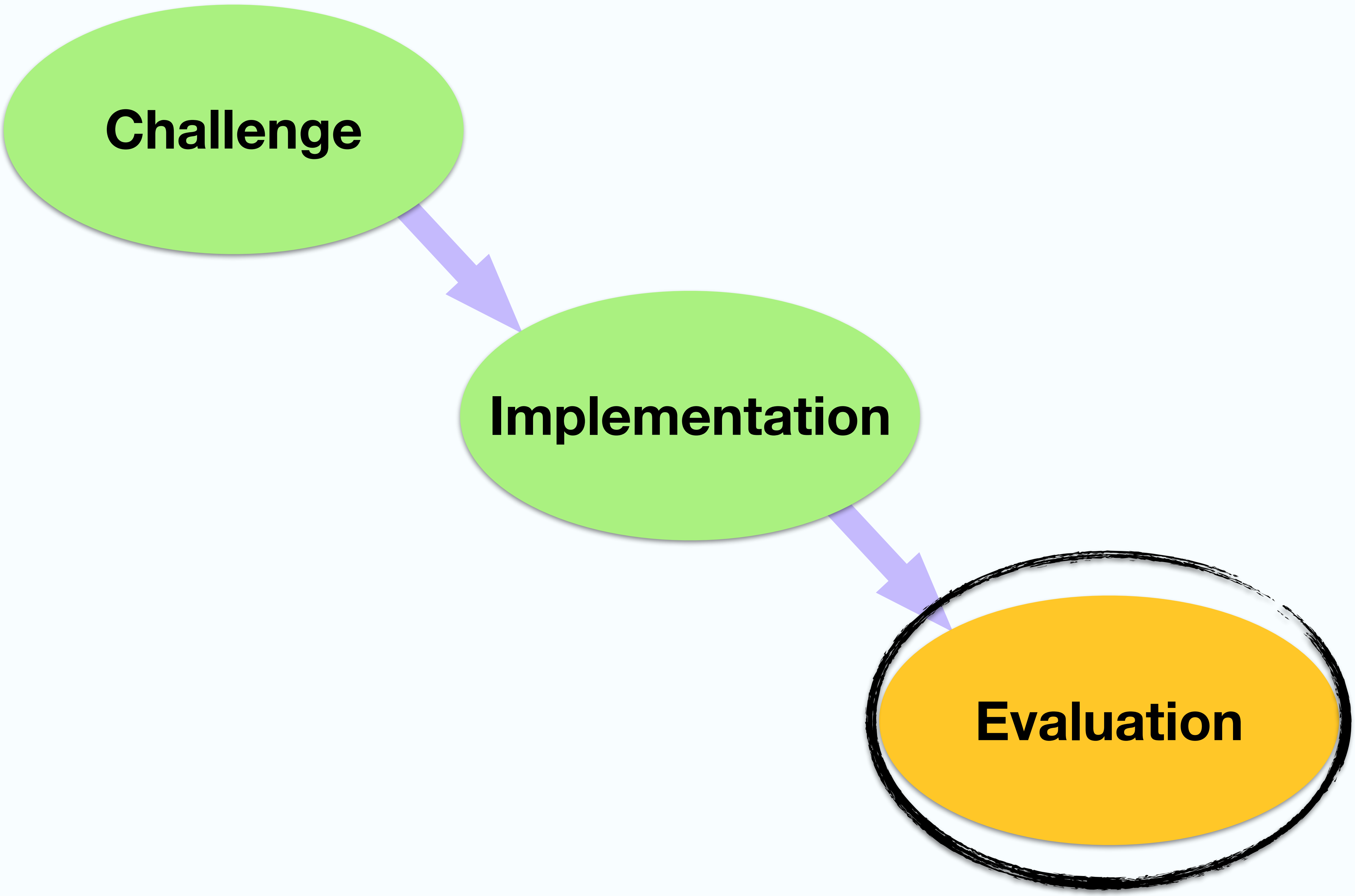

Evaluation — Platform

- Boundary Devices Sabre Lite Board
  - Freescale I.MX6Q Quad Core SoC
  - ARM Cortex A9 (1 GHz)
- Implemented in LITMUS^{RT} 2013.1 (based on Linux 3.10.5)

Evaluation — Benchmarking Methodology

- Test program **locks and unlocks once every period**
    - Uniprocessor tests: 5 threads
- **Randomly assigned parameters** for threads
    - *Critical section length — 25-45μs*
    - *Execution time — 25-65μs*
    - *Period — 600-800μs*
- Measured using processor **timestamp counters**

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Demanding workload — thousands of operations per second

- Measured using processor **timestamp counters**

PCP Futex Evaluation — Baseline

We compare all futex implementations against the ***non-futex PCP implementation*** *in LITMUS^{RT}*

	PRIO_INHERIT (Priority Inheritance Protocol)	PRIO_PROTECT (Immediate Priority Ceiling Protocol)	Classic Priority Ceiling Protocol (PCP)	Multiprocessor PCP (MPCP)	FMLP
Futex Implementation	✓	✗	✗	✗	✗

Linux

LITMUS^{RT}

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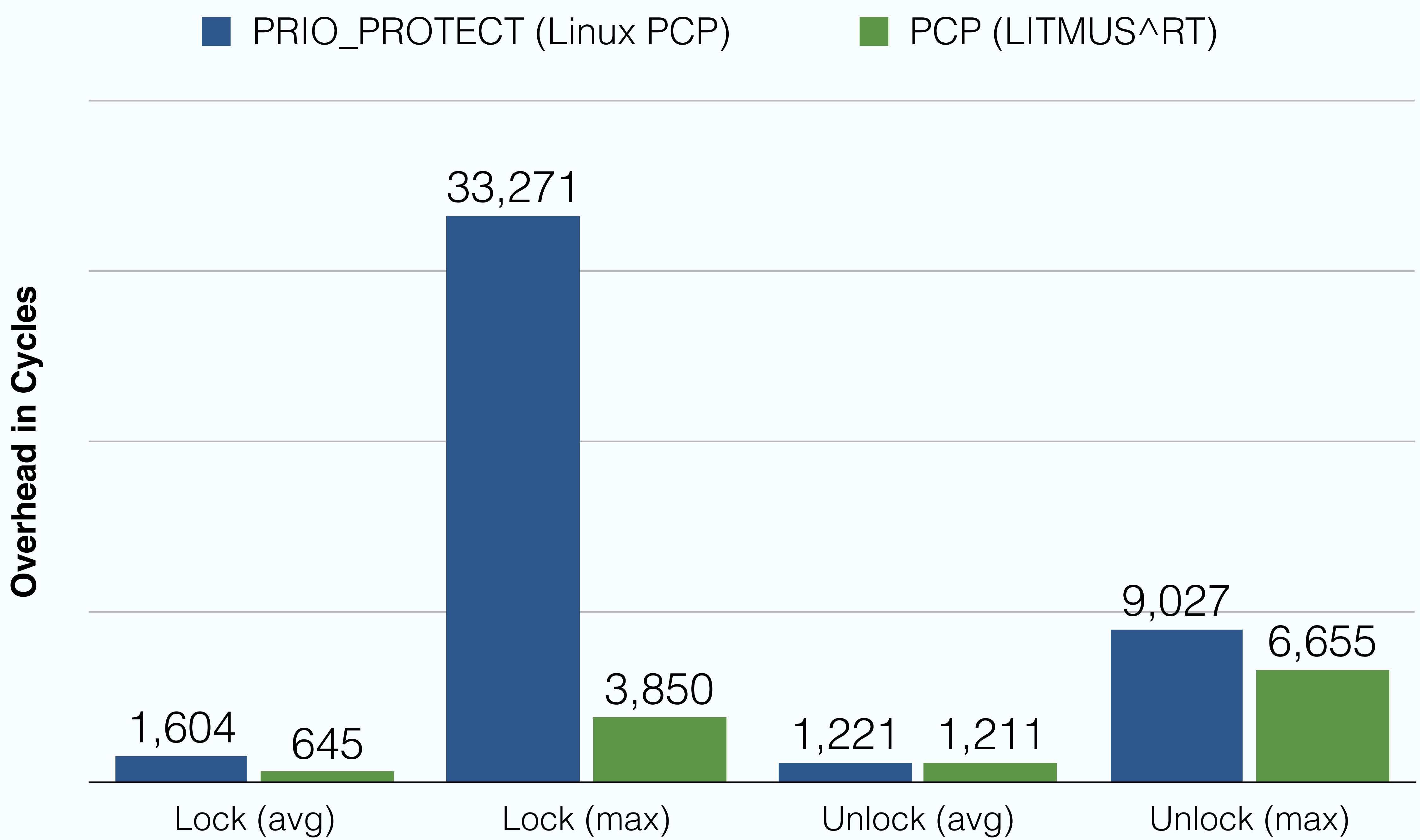

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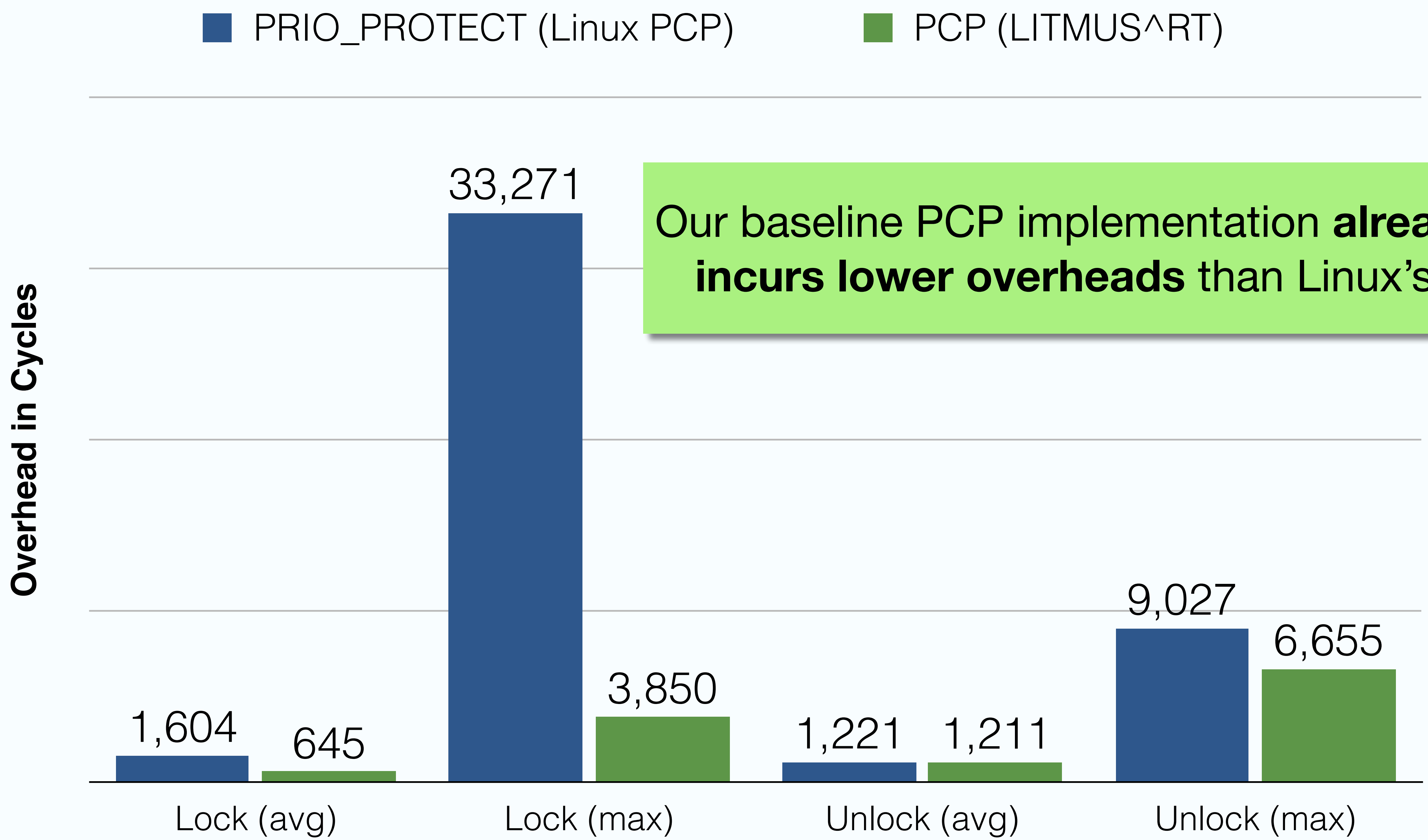
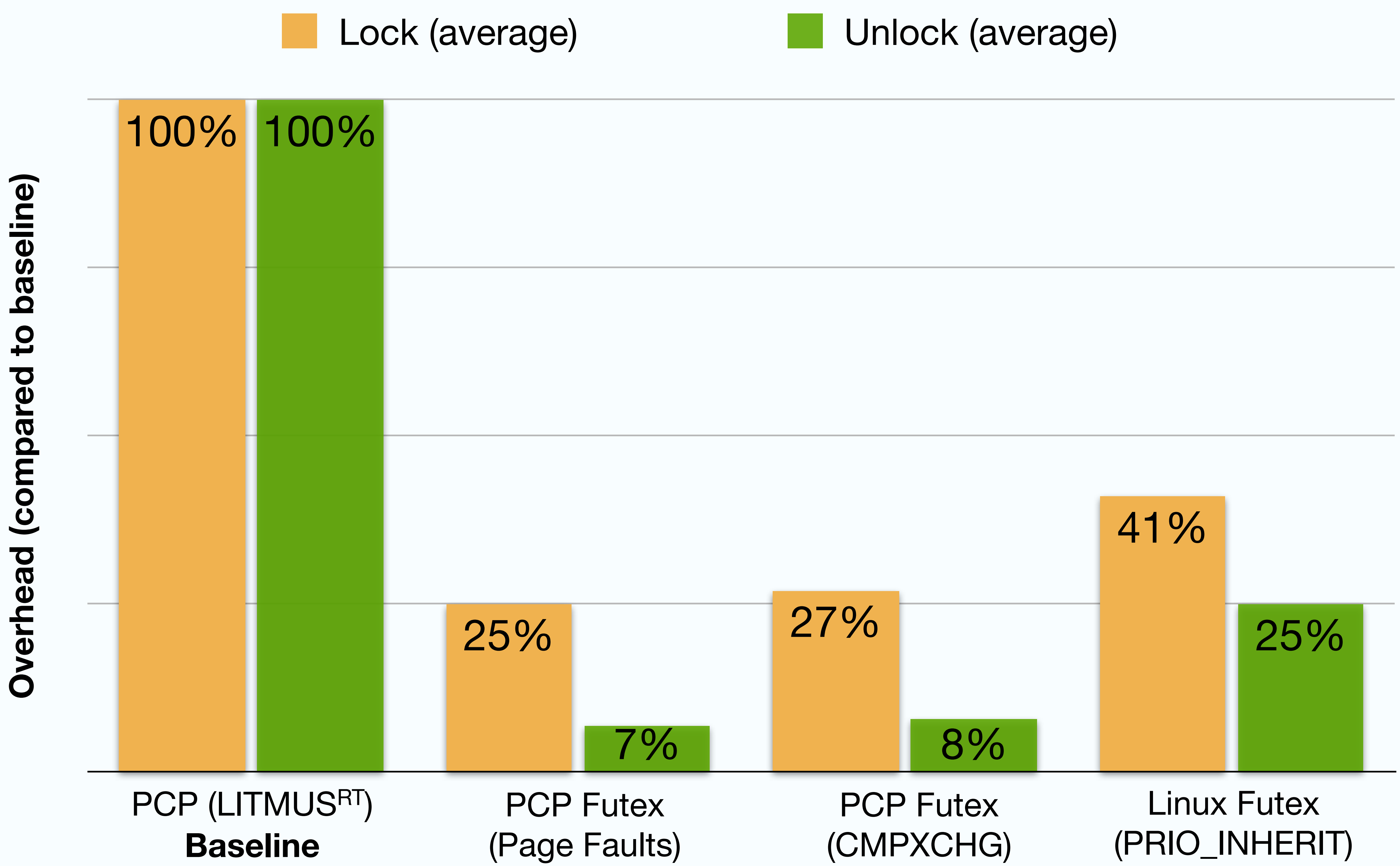


Our baseline PCP implementation **already incurs lower overheads** than Linux's.

PCP Futex Evaluation — Uncontended Case

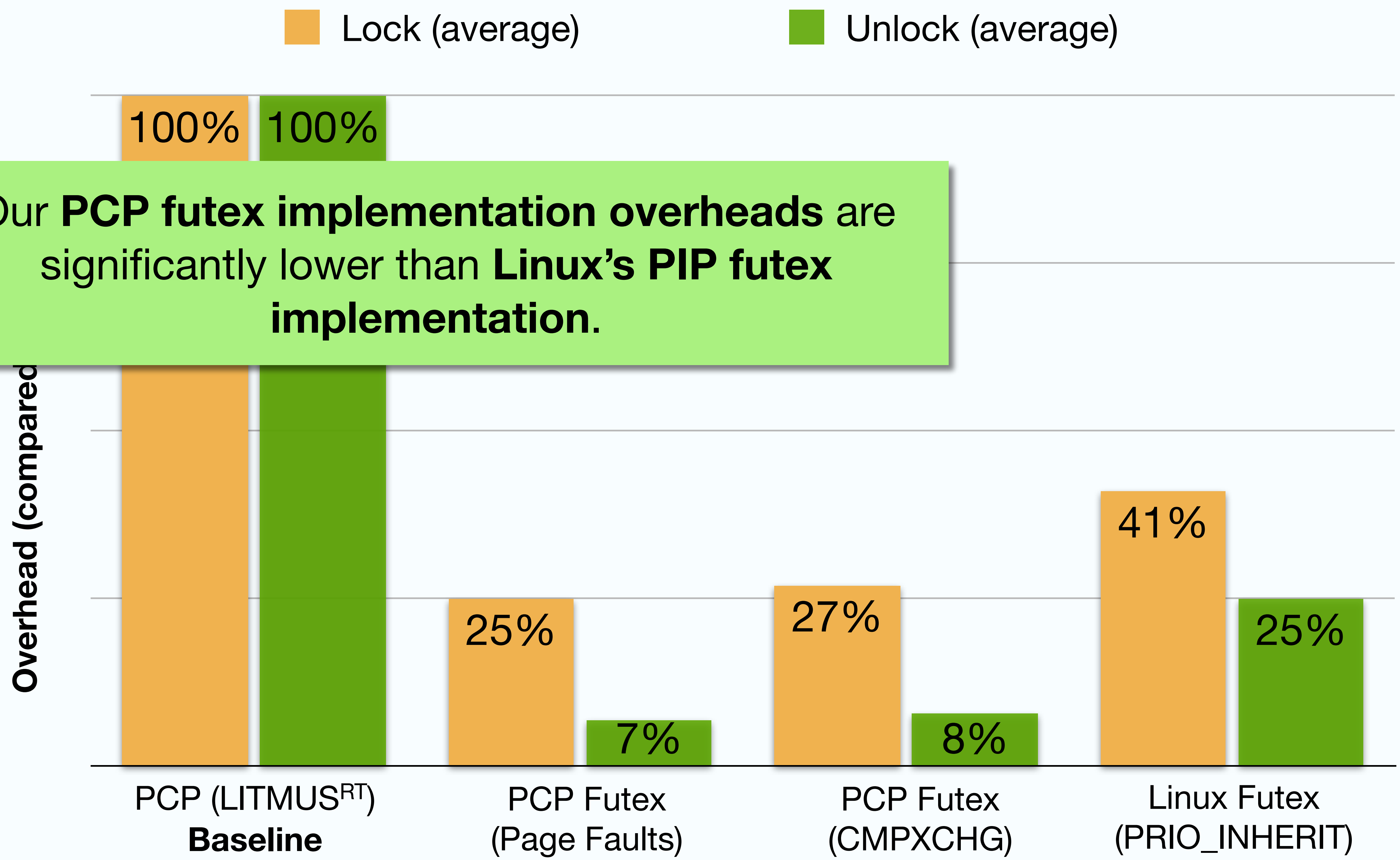
How much reduction do we see in average uncontended-case overheads?

PCP Futex Evaluation — Uncontended Case



Based on 6.6 million samples per protocol

PCP Futex Evaluation — Uncontended Case



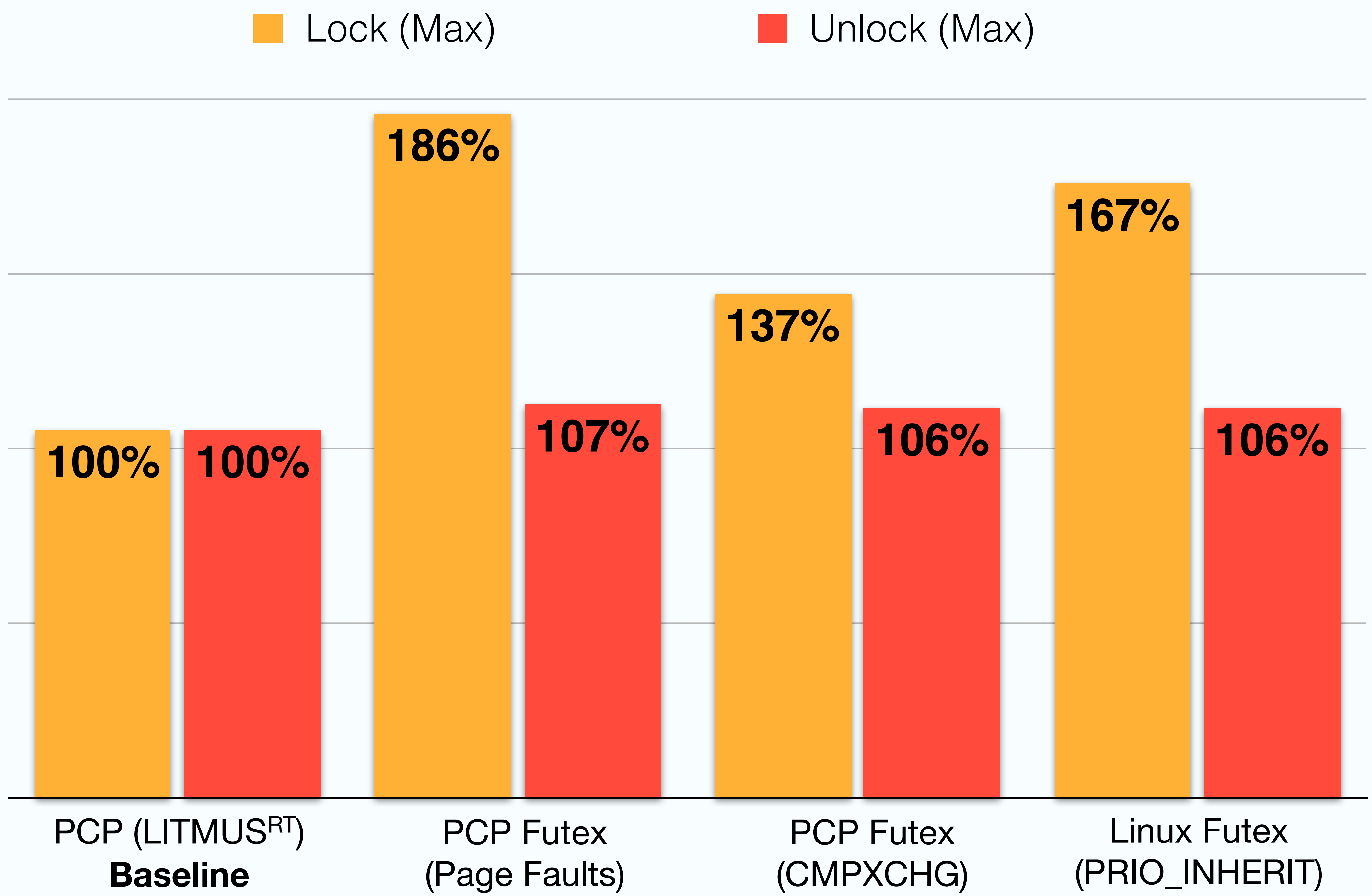
Our **PCP futex implementation overheads** are significantly lower than **Linux's PIP futex implementation.**

Based on 6.6 million samples per protocol

PCP Futex Evaluation —Contended Case

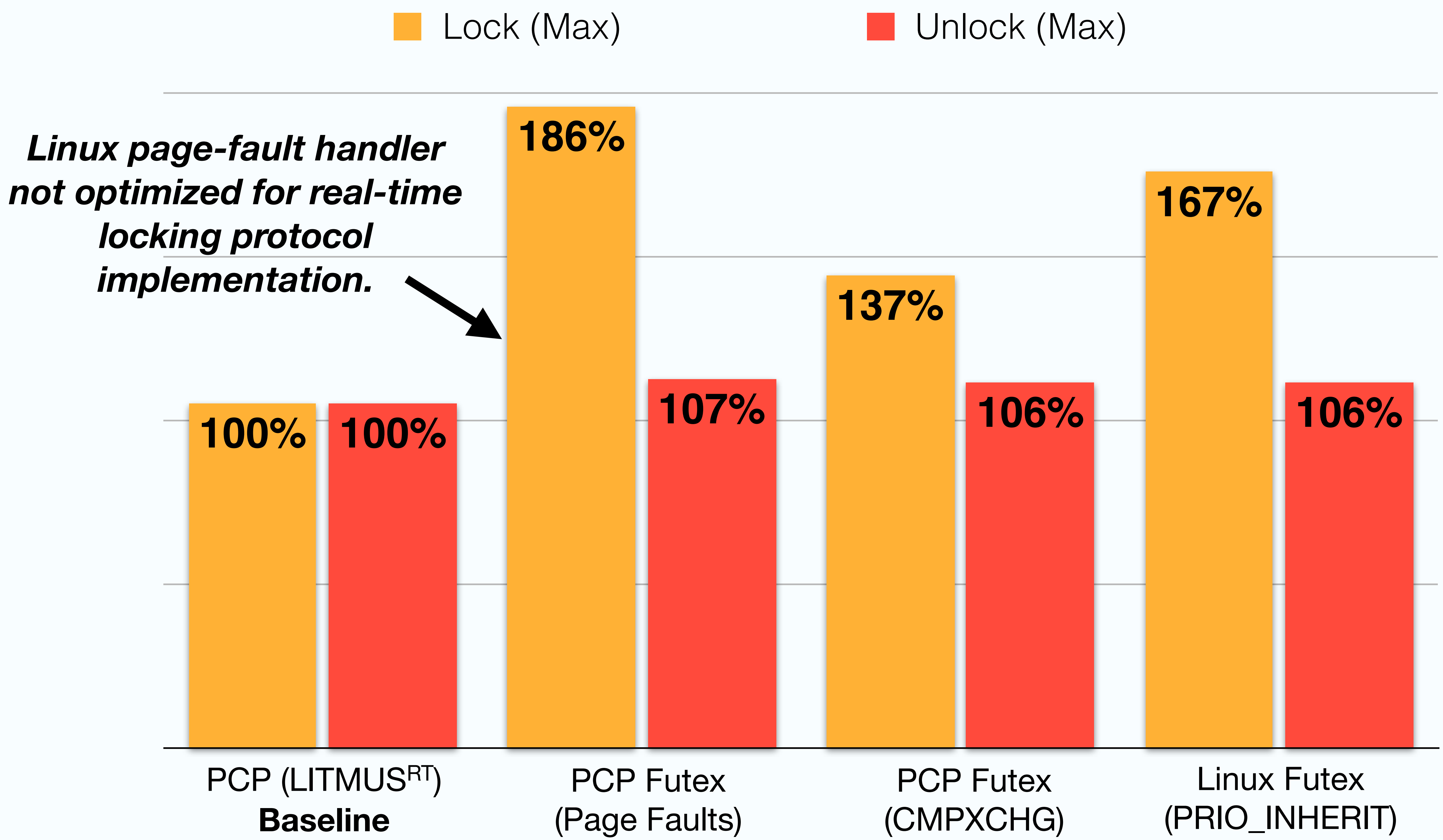
How much additional overhead do we incur in the maximum contended-case overheads?

PCP Futex Evaluation —Contended Case



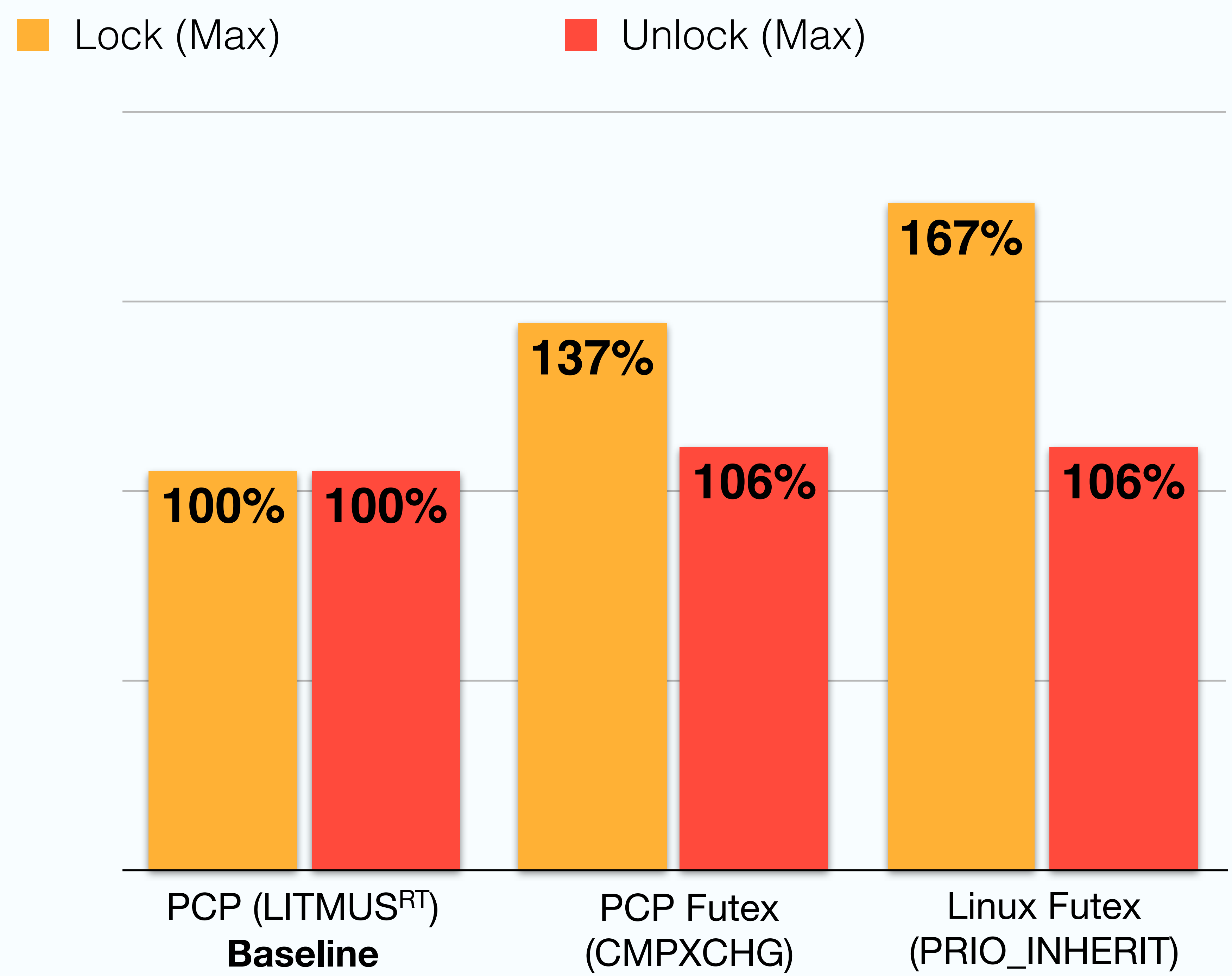
Based on 900K samples per protocol

PCP Futex Evaluation — Contended Case



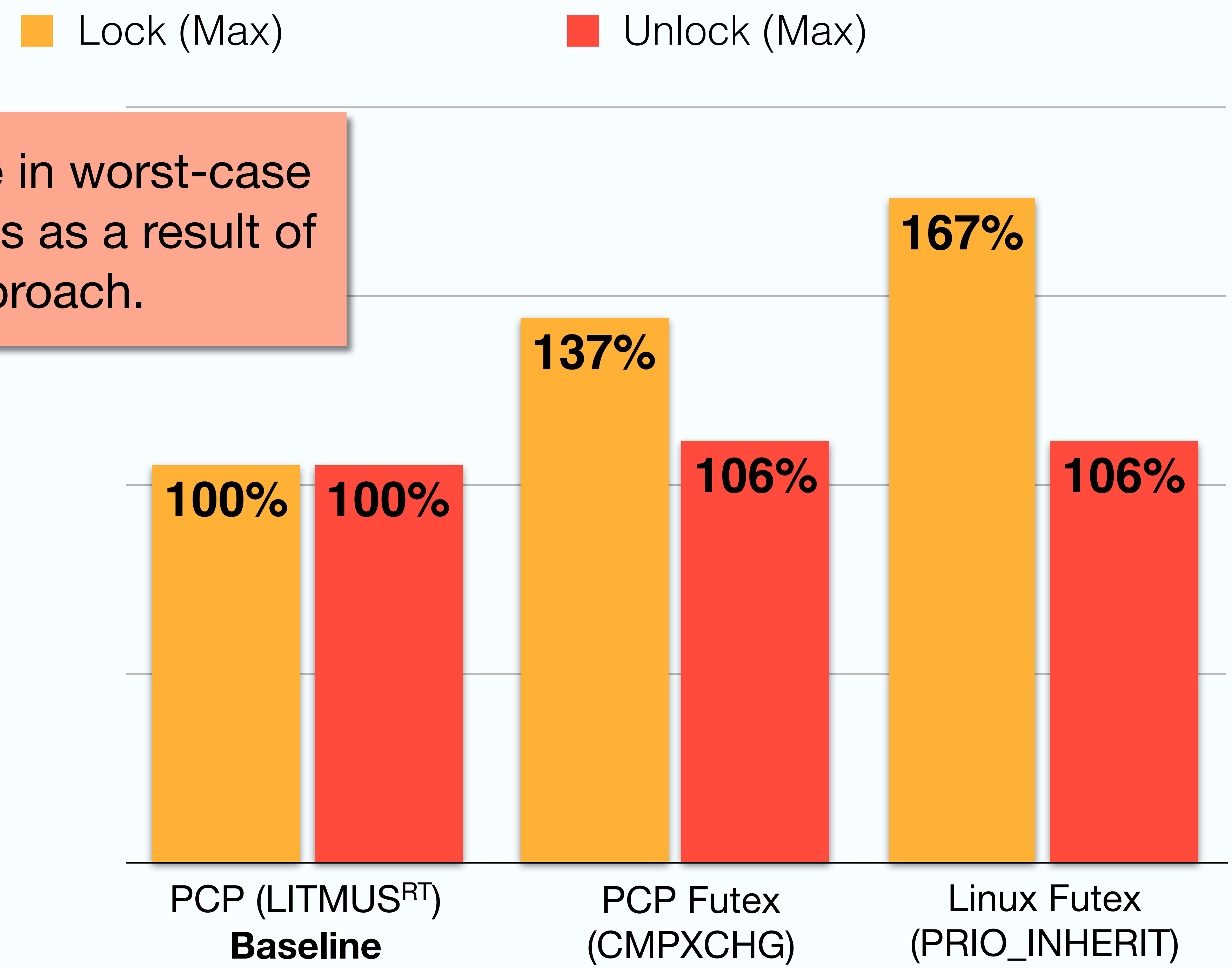
Based on 900K samples per protocol

PCP Futex Evaluation — Contended Case



Based on 900K samples per protocol

PCP Futex Evaluation — Contended Case



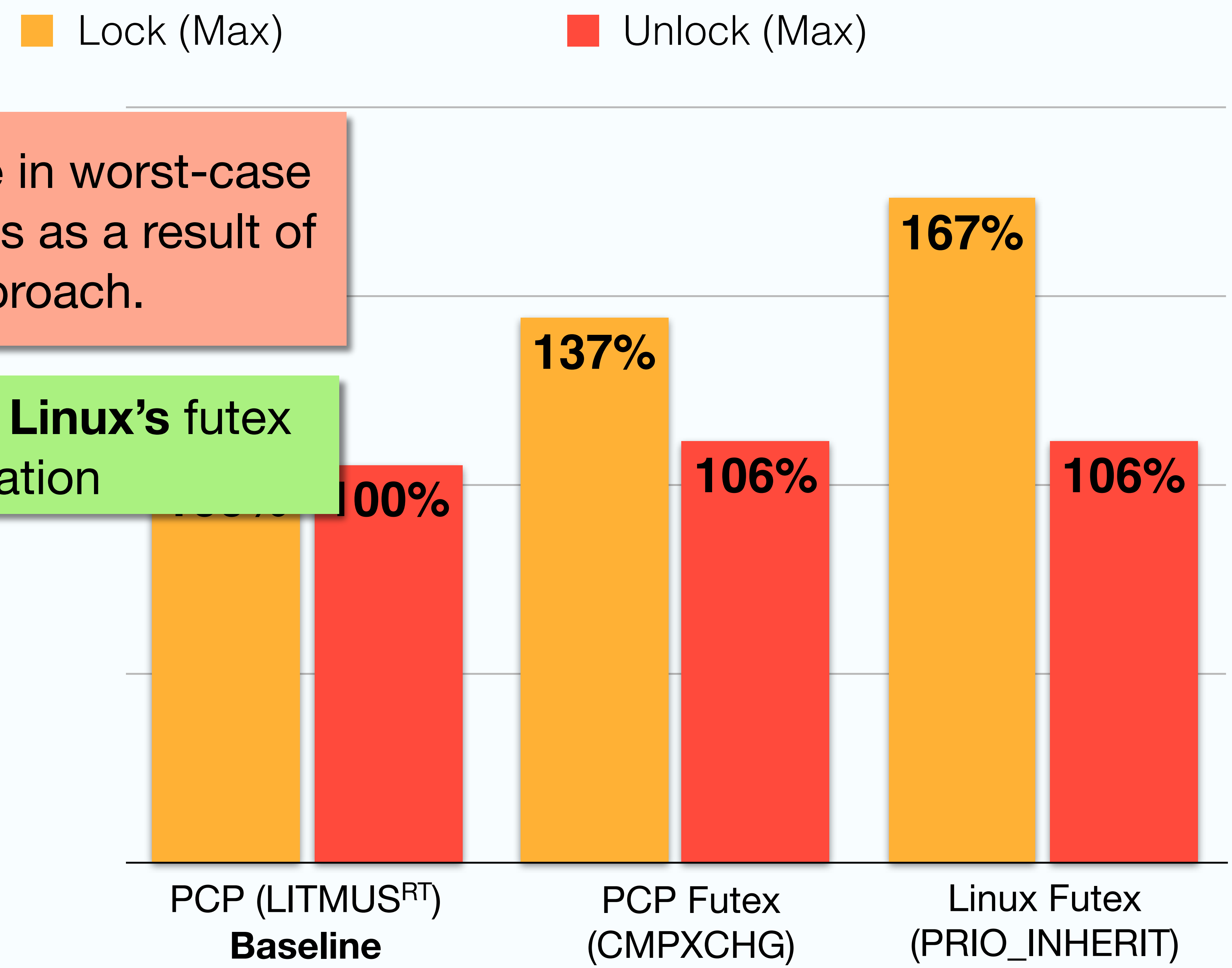
Up to **37% increase** in worst-case contended overheads as a result of the futex approach.

Based on 900K samples per protocol

PCP Futex Evaluation — Contended Case

Up to **37% increase** in worst-case contended overheads as a result of the futex approach.

But **no worse than Linux's** futex implementation



Based on 900K samples per protocol

PCP Futex Evaluation — Summary

Up to **92% reduction in average uncontended overheads** at a cost of 37% increase in maximum contended overheads (**no worse than Linux**).

Page faults can be used to implement futexes for anticipatory real-time locking protocols.

Summary

	PRIO_INHERIT (Priority Inheritance Protocol)	PRIO_PROTECT (Immediate Priority Ceiling Protocol)	Classic Priority Ceiling Protocol (PCP)	Multiprocessor PCP (MPCP)	FMLP
Futex Implementation	✓	✗	✓	✓	✓
Observed overhead reduction:			**92%**	**85%**	**84%**

Design and implementation of futexes for **three anticipatory real-time locking protocols**

Method of **using page faults** to implement futexes

Thanks!

LITMUS RT

Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

All source code available at: http://www.litmus-rt.org/