TimerShield

Protecting High-Priority Tasks from Low-Priority Timer Interference

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FOR SOFTWARE SYSTEMS
Kaiserslautern, Germany

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Pittsburgh, USA

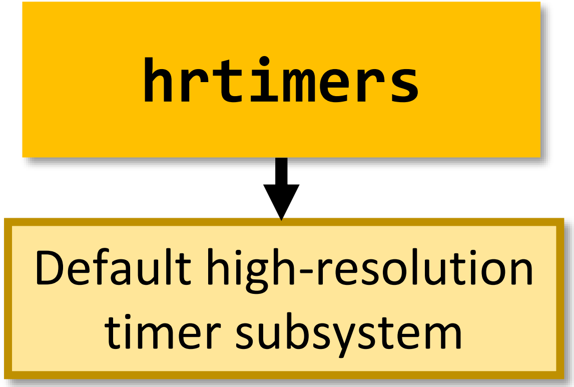
This Paper

This Paper

`hrtimers`

PREEMPT_RT

This Paper



hrtimers

Default high-resolution timer subsystem

PREEMPT_RT

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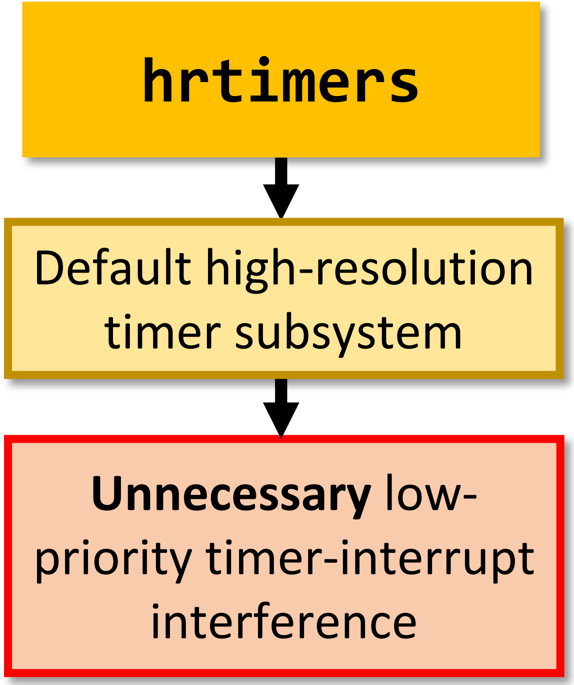

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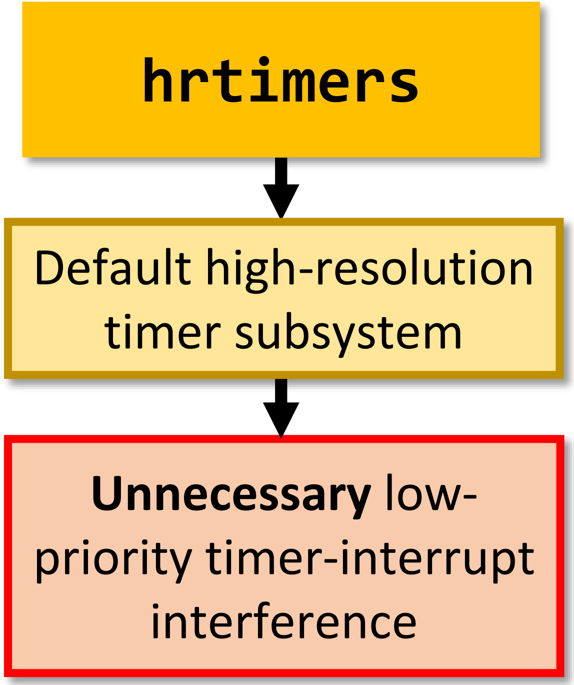

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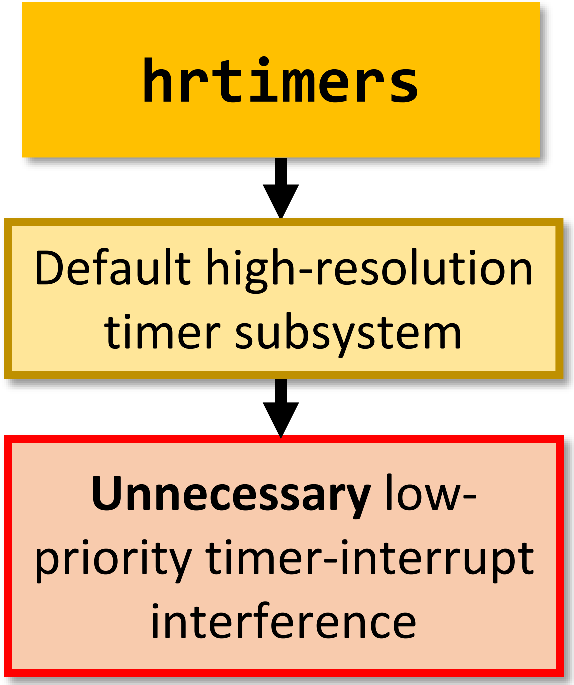

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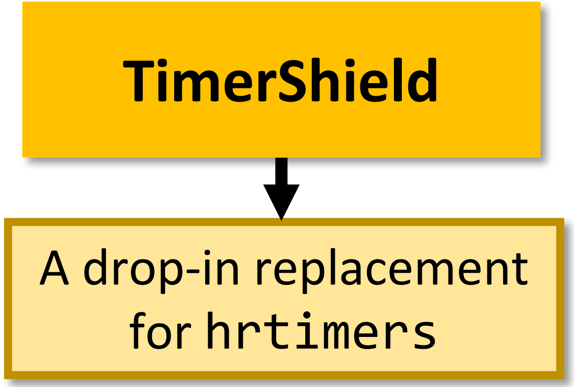

TimerShield

A drop-in replacement for `hrtimers`

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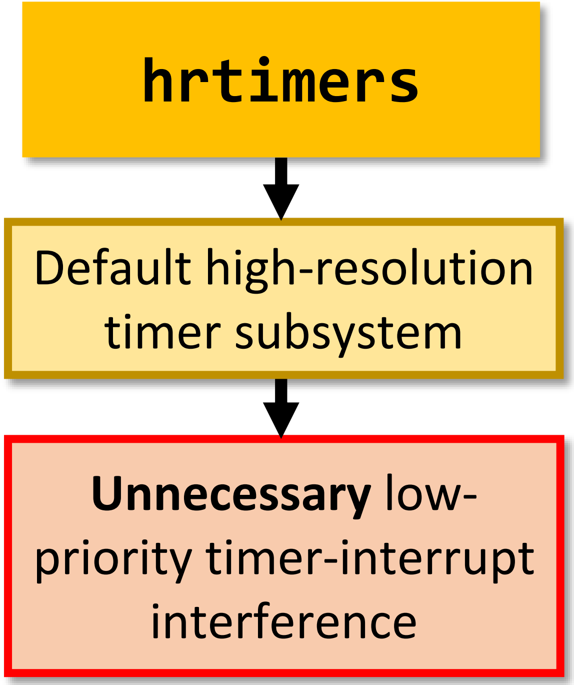

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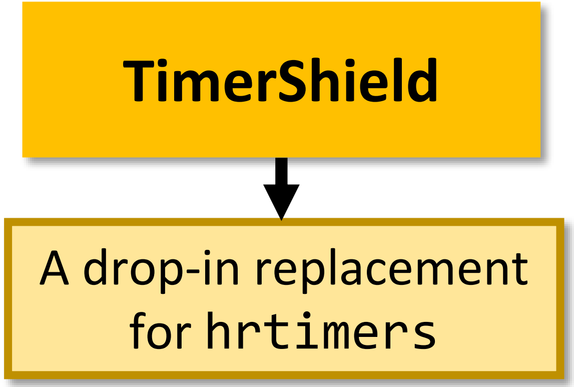
ARM intel



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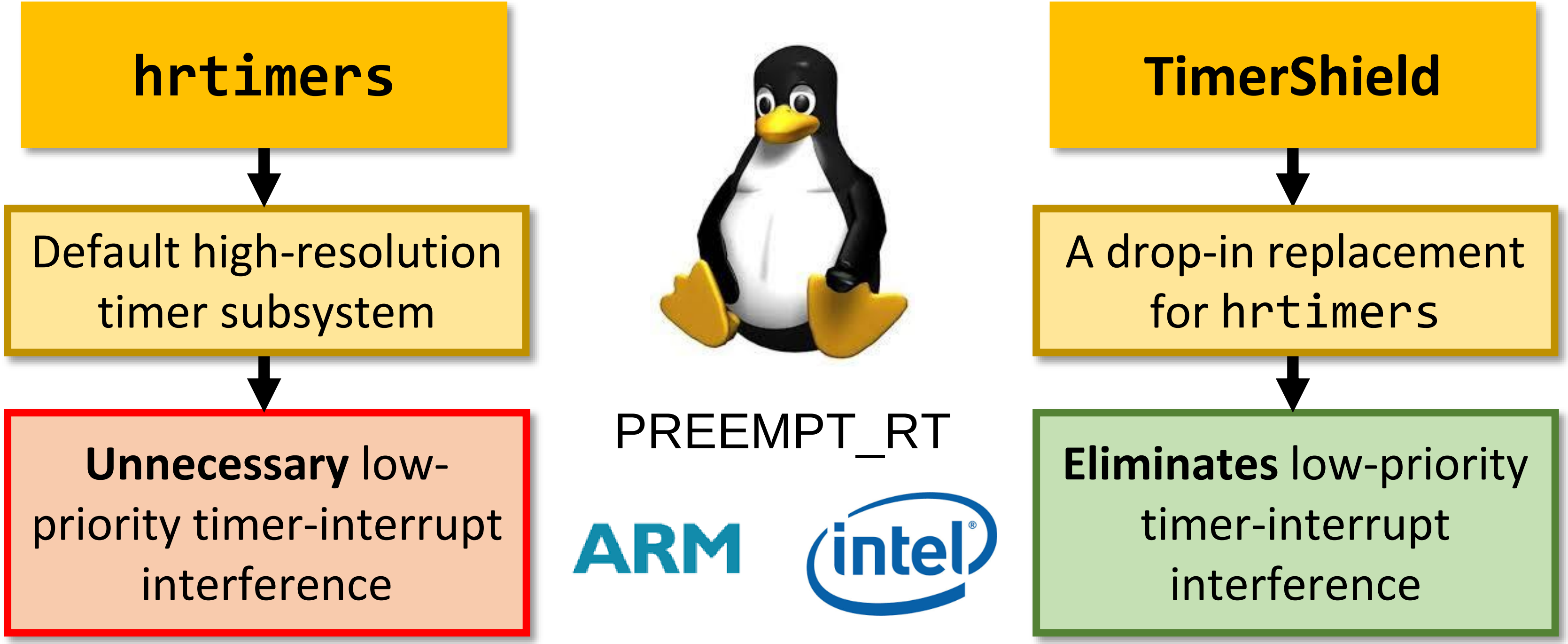

`hrtimers`

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TimerShield

A drop-in replacement for `hrtimers`

Eliminates low-priority timer-interrupt interference

Talk Overview

Timers and the Interference Problem

TimerShield Design

Evaluation

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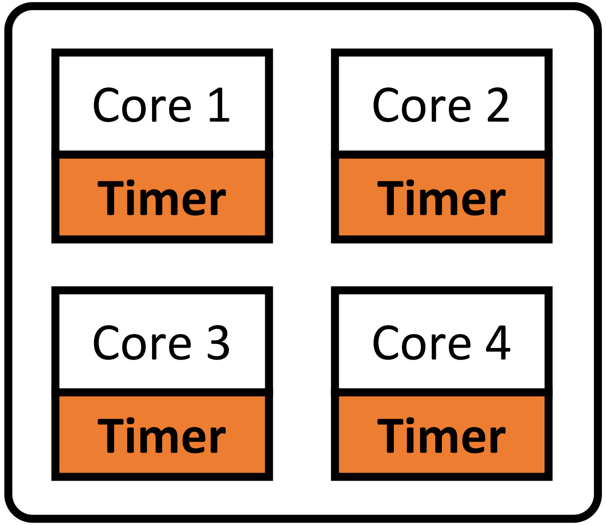
High-Resolution Timers



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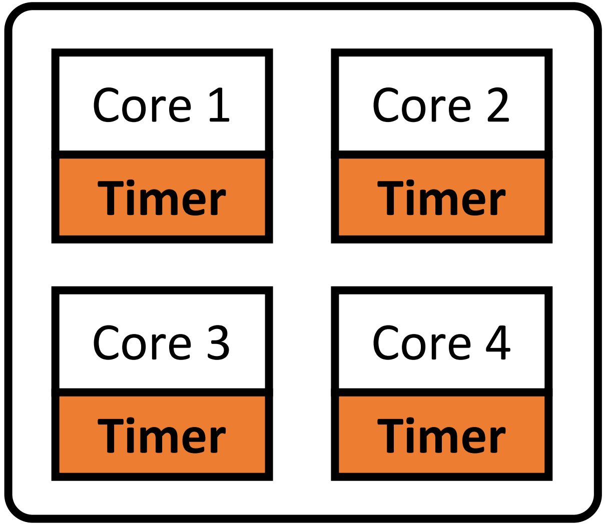
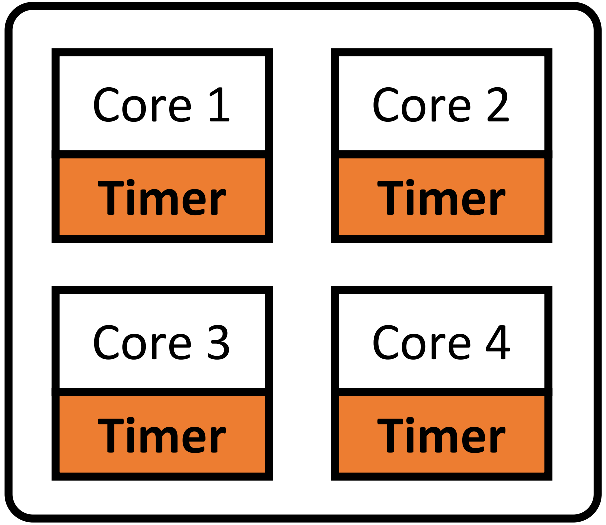


Core-local timers with **cycle precision**

High-Resolution Timers



Core-local timers with **cycle precision**

Can be **programmed** to raise an interrupt at a desired time

Timers in Real-Time OSes

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Job Releases

Tasks can be woken up periodically using timers

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Budget Enforcement

Schedulers use timers to prevent budget overruns

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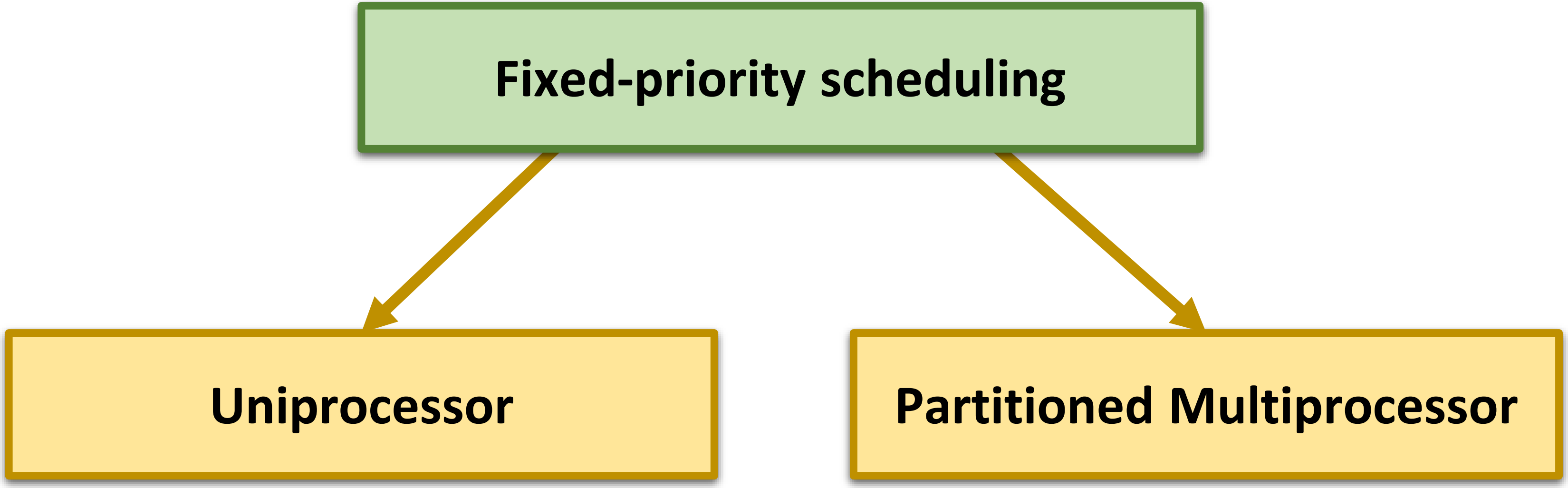
Self-Suspensions

Tasks can use POSIX *clock_nanosleep()* to suspend themselves

Assumptions

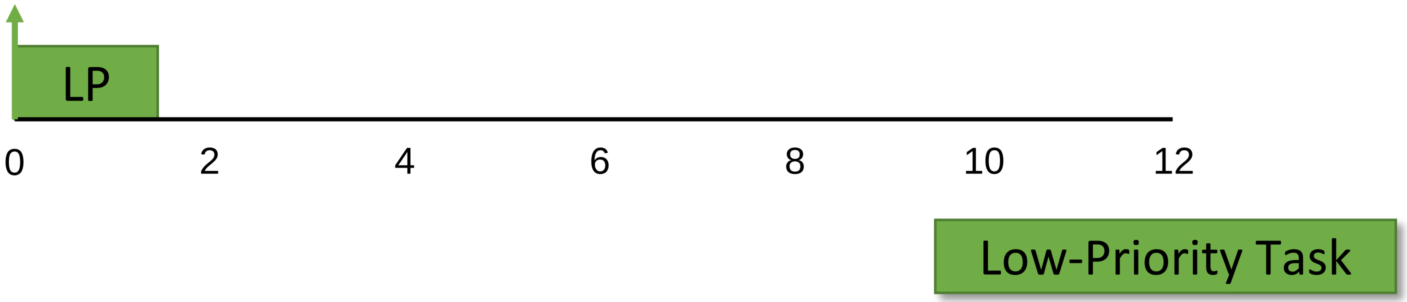


Fixed-priority scheduling

Uniprocessor

Partitioned Multiprocessor

Timer-Interrupt Interference



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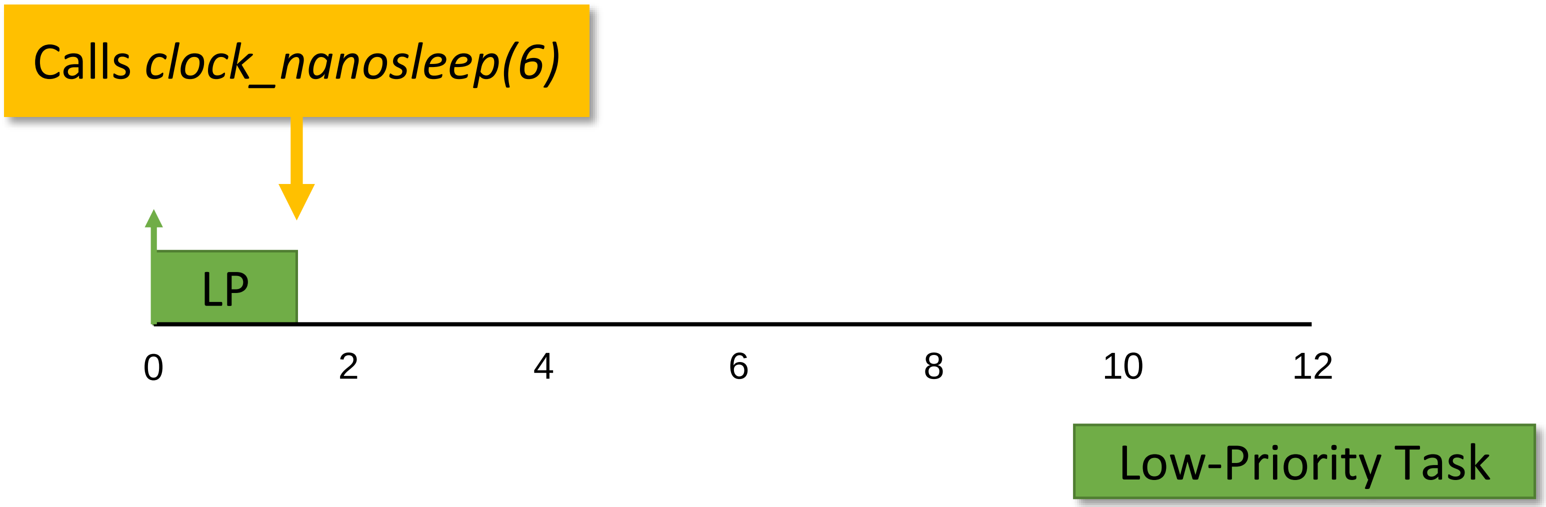
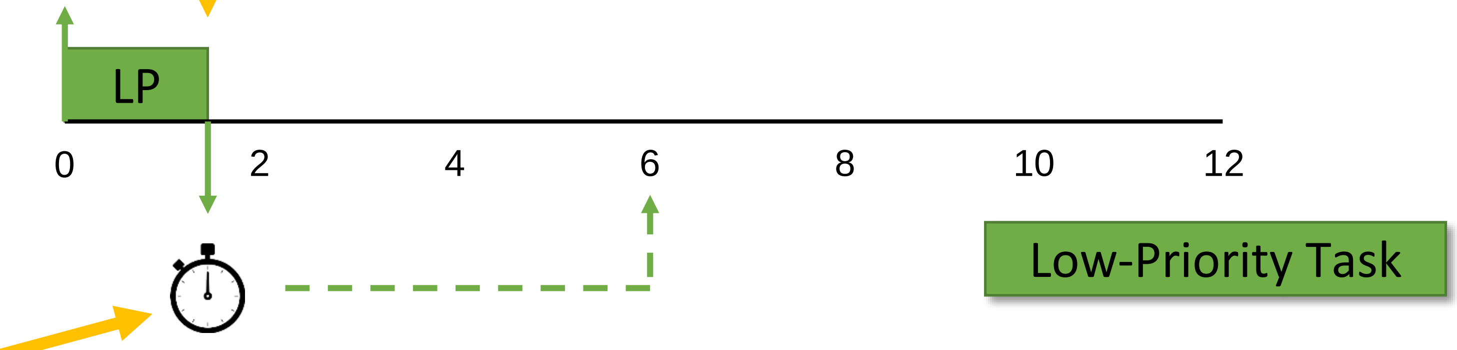


Calls *clock_nanosleep(6)*

Low-Priority Task

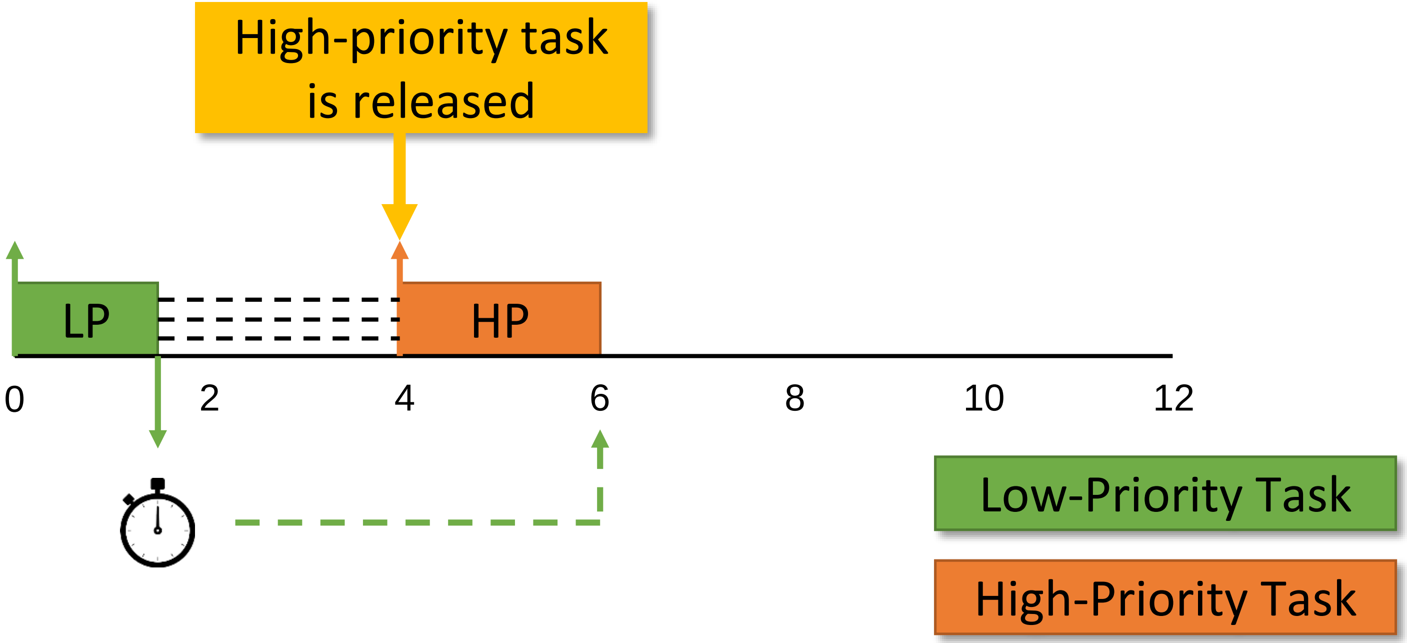
Timer-Interrupt Interference



Calls *clock_nanosleep(6)*

Timer **hardware is programmed** to fire at the specified time

Timer-Interrupt Interference



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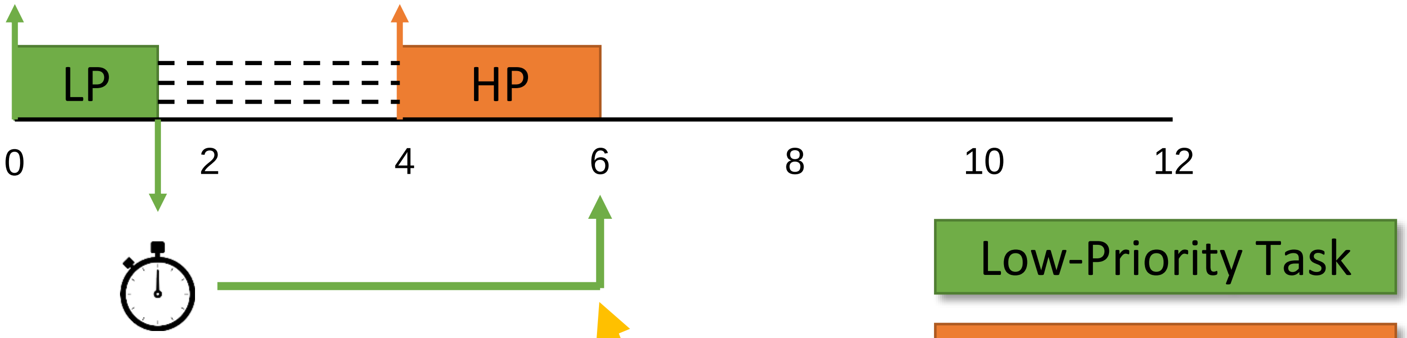


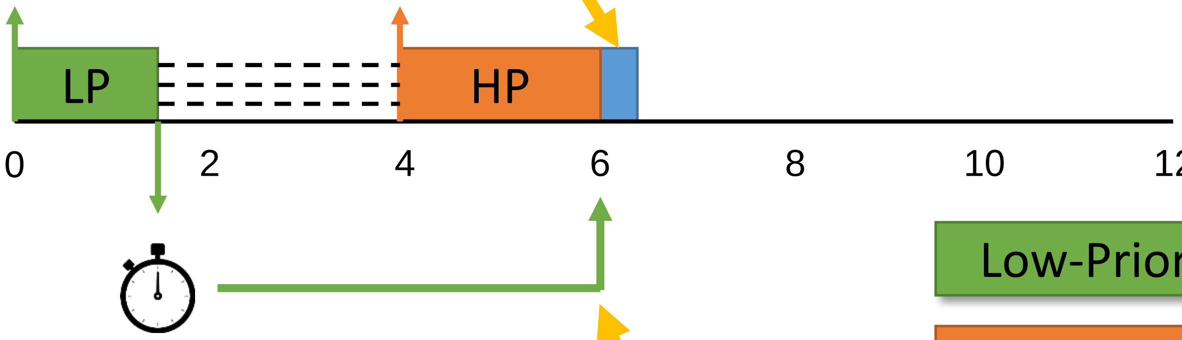
🟩 Low-Priority Task

🟥 High-Priority Task

At t = 6, timer hardware fires an **interrupt**

Timer-Interrupt Interference

HP is preempted to service the interrupt (LP task is woken up)



At t = 6, timer hardware fires an **interrupt**

🟩 Low-Priority Task

🟧 High-Priority Task

🟦 Timer Handler

Timer-Interrupt Interference

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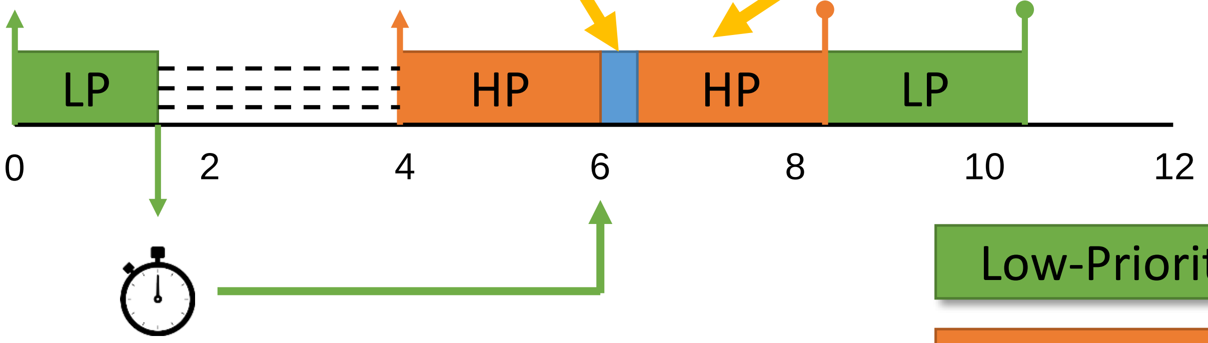
HP task resumes



🟩 Low-Priority Task

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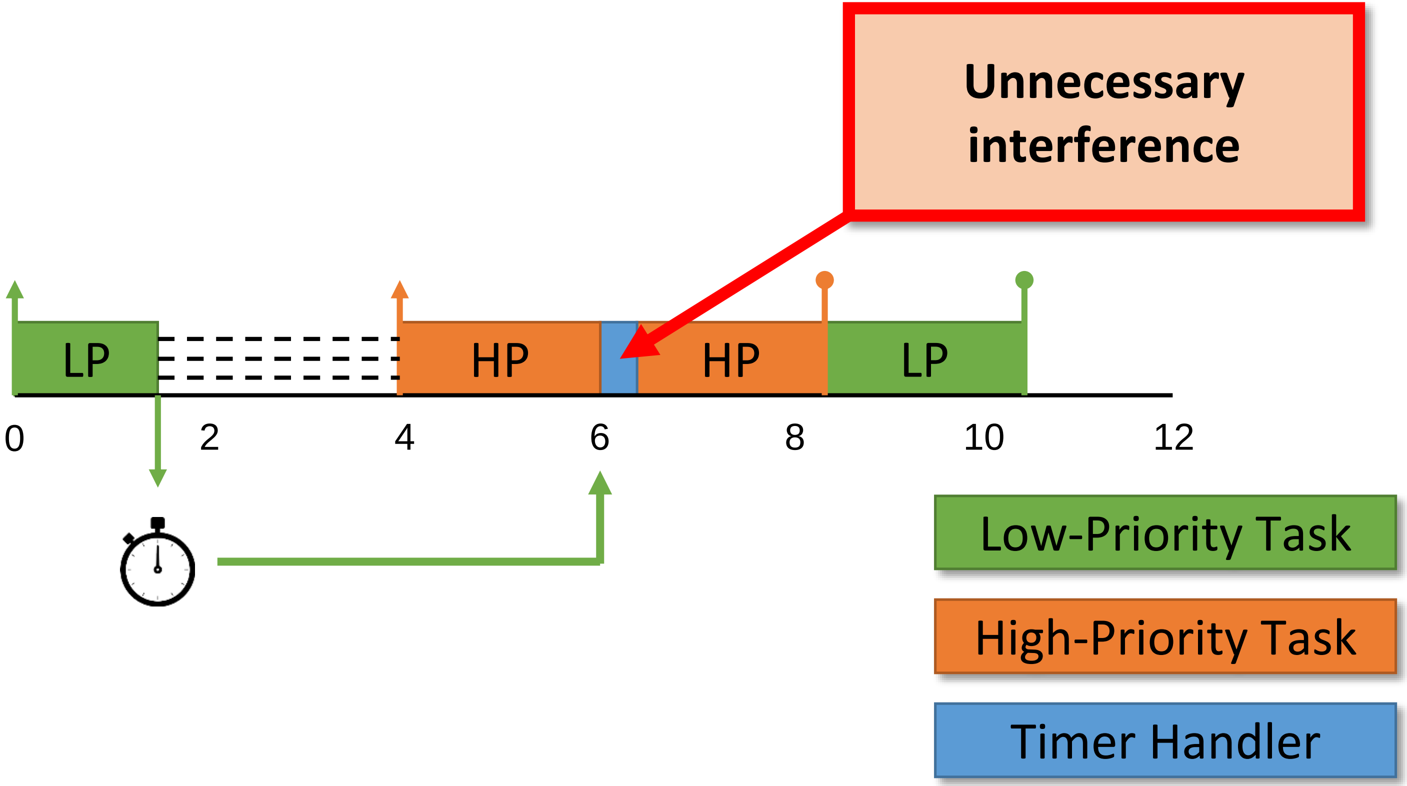
Timer-Interrupt Interference



Unnecessary interference

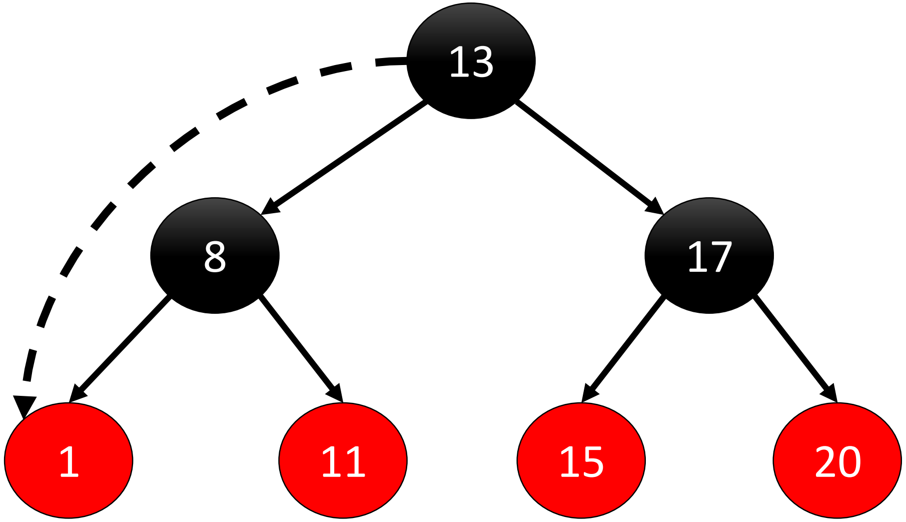
Low-Priority Task

High-Priority Task

Timer Handler

Why Does Interference Occur?

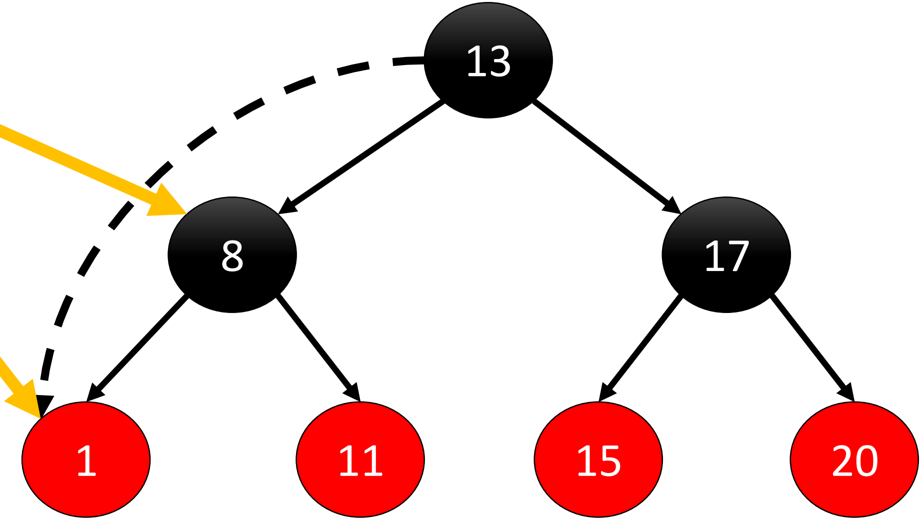
Linux's `hrtimer` subsystem



Why Does Interference Occur?

Multiplexes many software timers on a single hardware timer using a **time-ordered red-black tree**

Linux’s `hrtimer` subsystem



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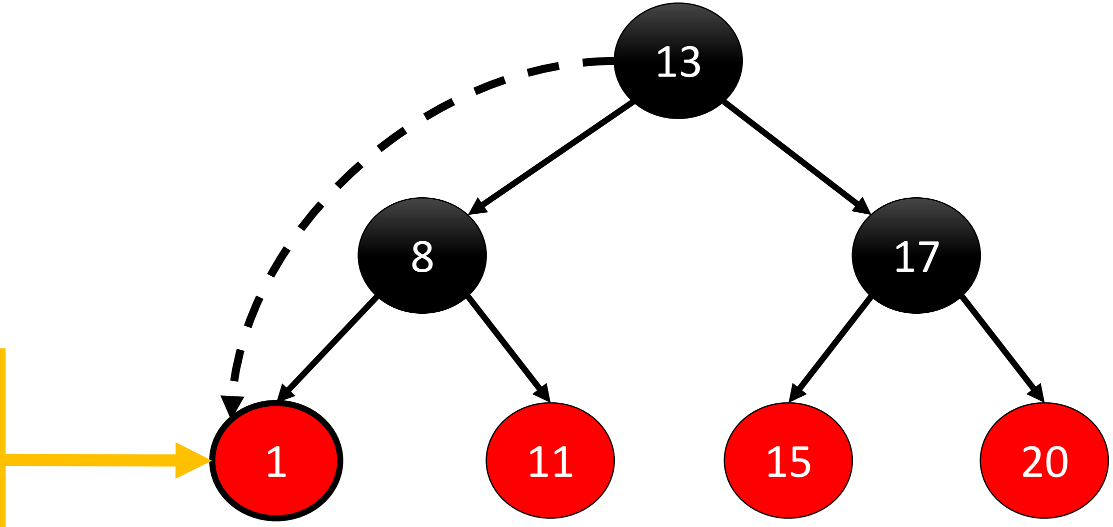

Earliest expiring timer is programmed into hardware

Why Does Interference Occur?

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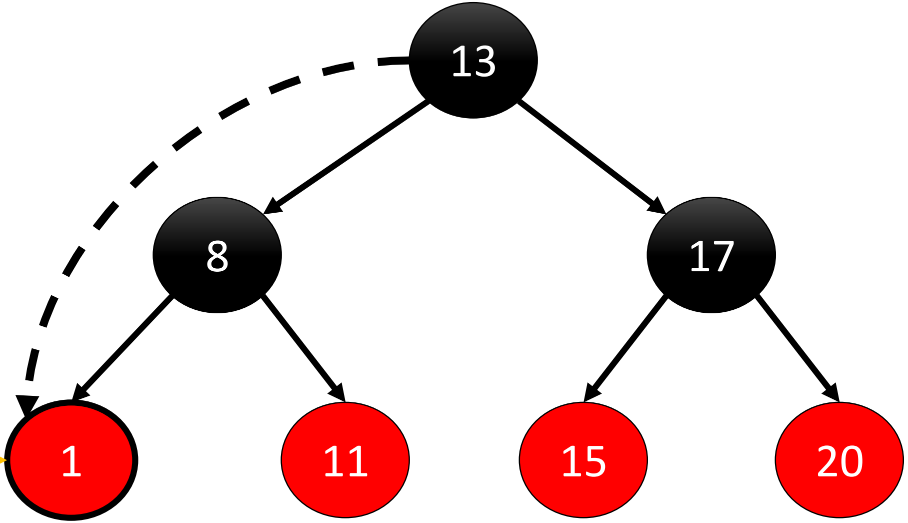
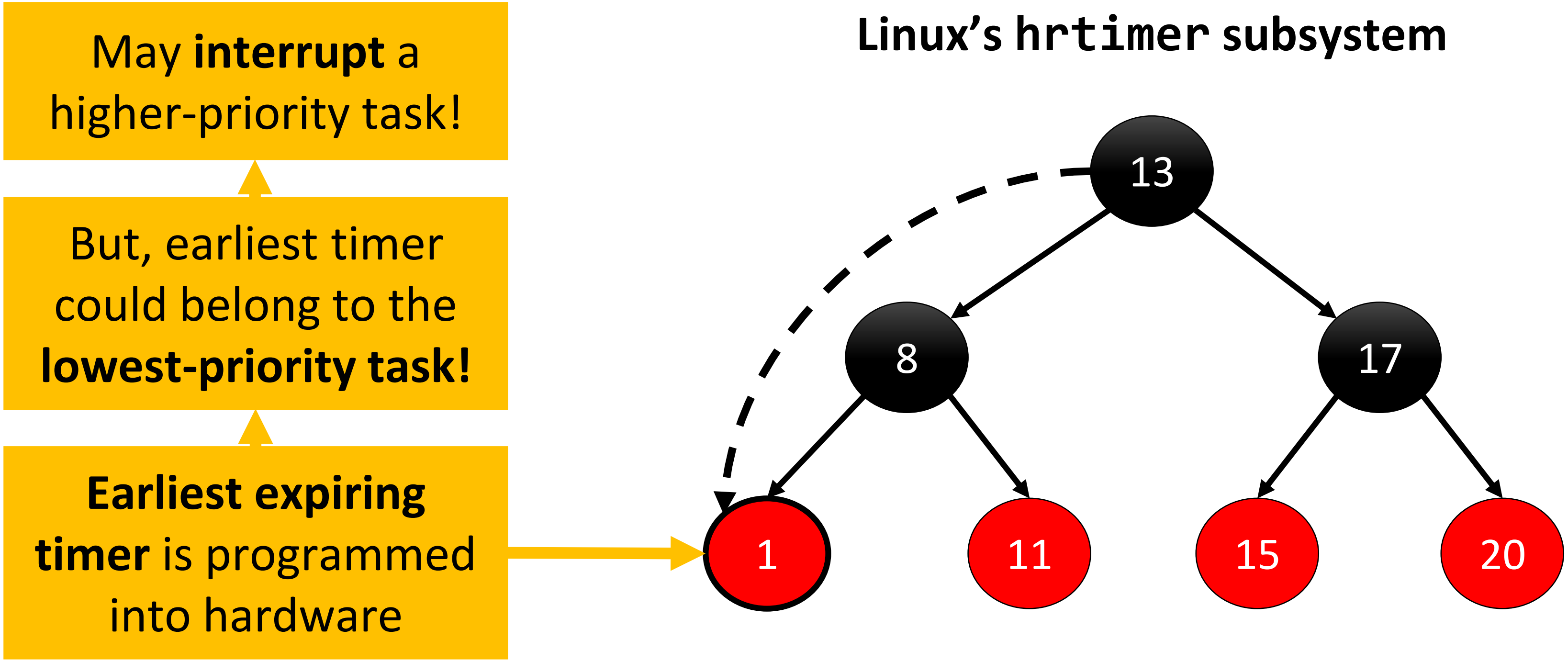


But, earliest timer could belong to the **lowest-priority task!**

Earliest expiring timer is programmed into hardware

Why Does Interference Occur?



May **interrupt** a higher-priority task!

But, earliest timer could belong to the **lowest-priority task!**

Earliest expiring timer is programmed into hardware

Linux's `hrtimer` subsystem

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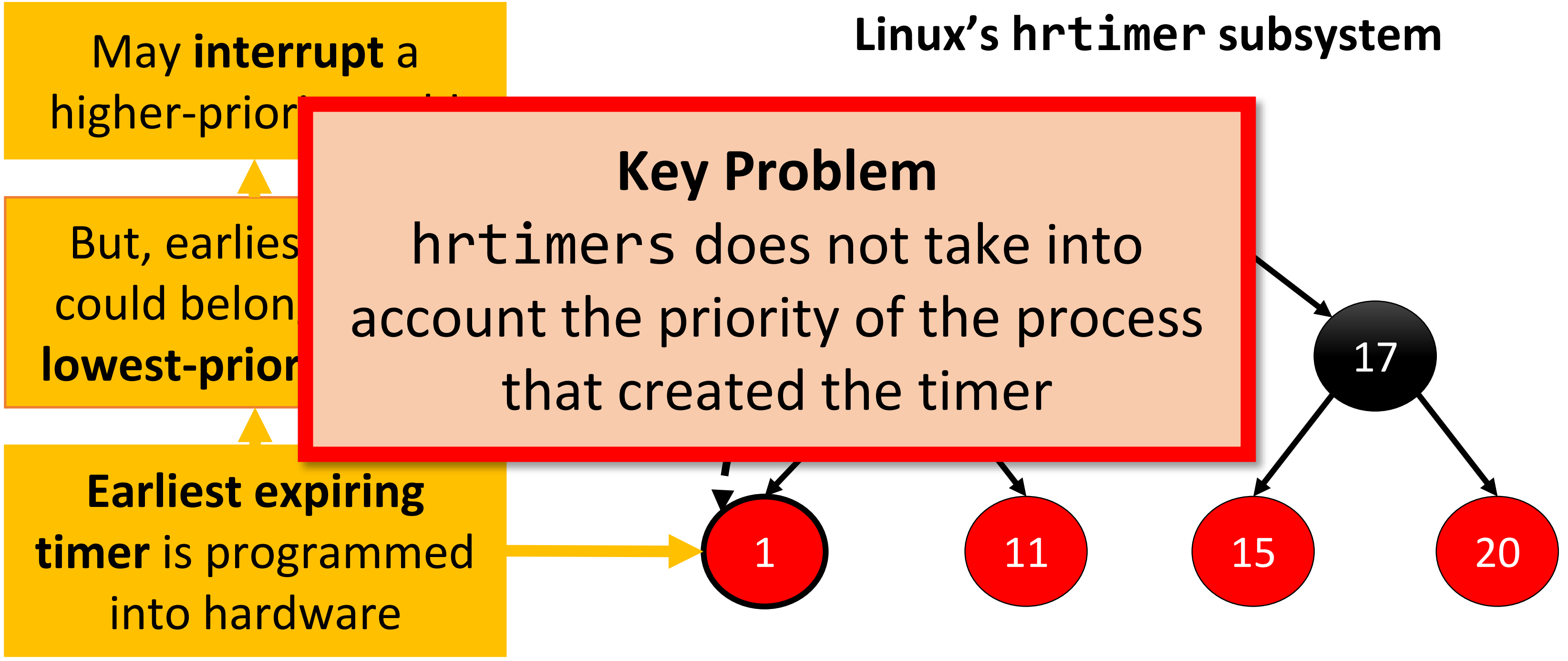

May **interrupt** a higher-prior

But, earlies could belon **lowest-prior**

Earliest expiring timer is programmed into hardware

Linux's `hrtimer` subsystem

Key Problem

`hrtimers` does not take into account the priority of the process that created the timer

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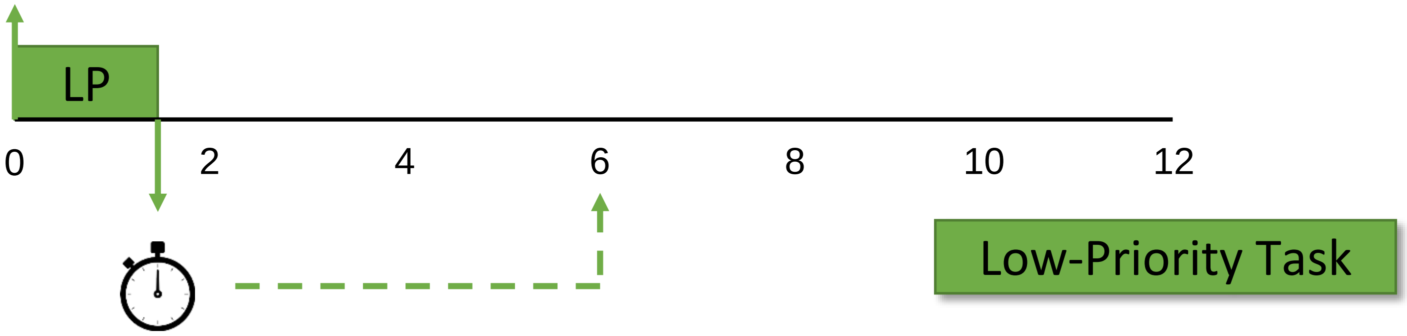
Timers and the Interference Problem

TimerShield Design

Evaluation

How Does TimerShield Work?



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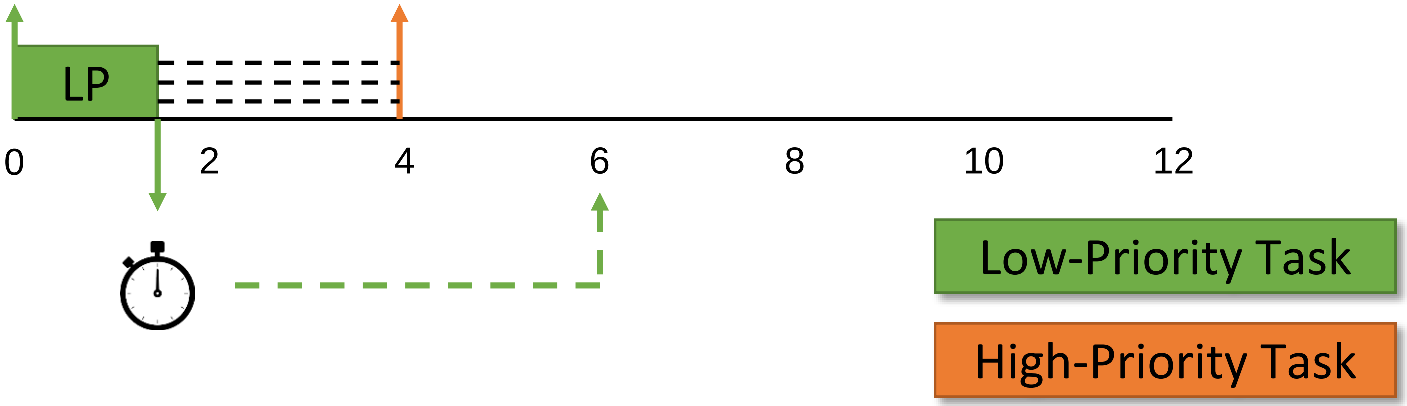

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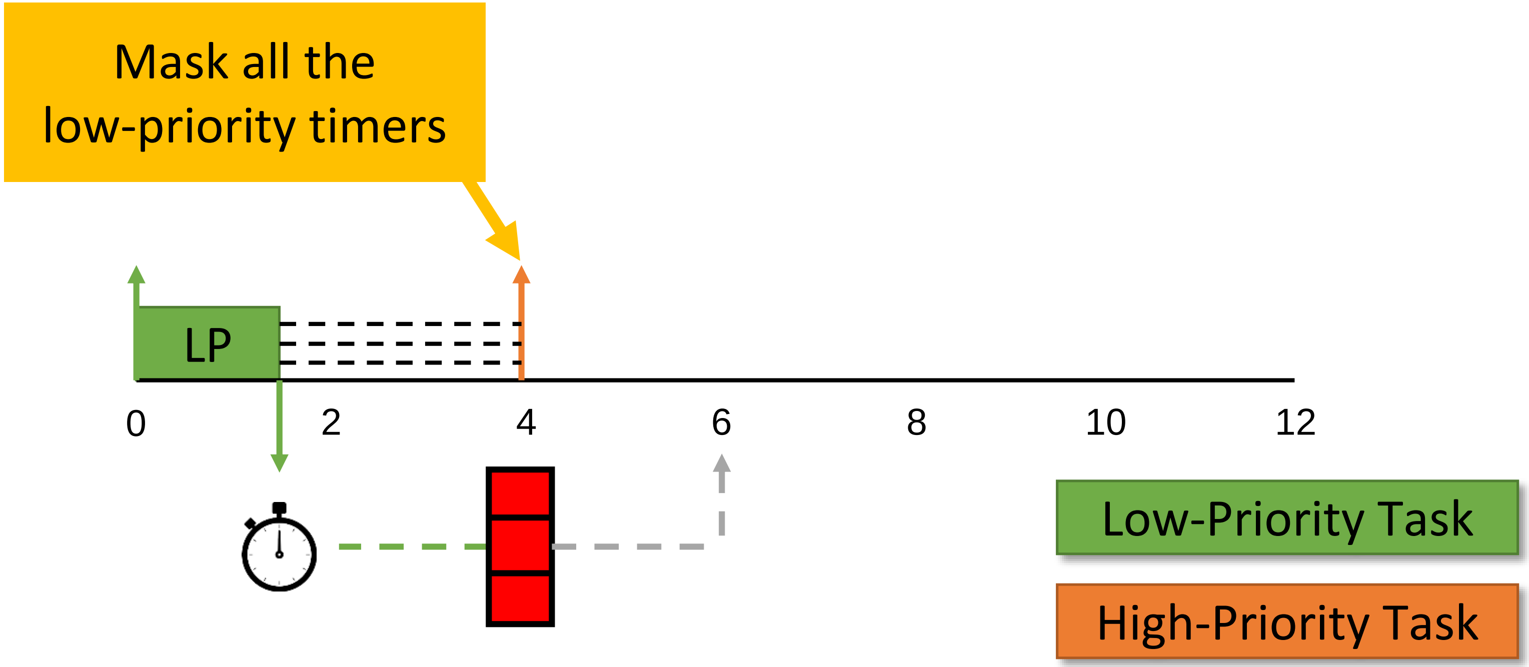
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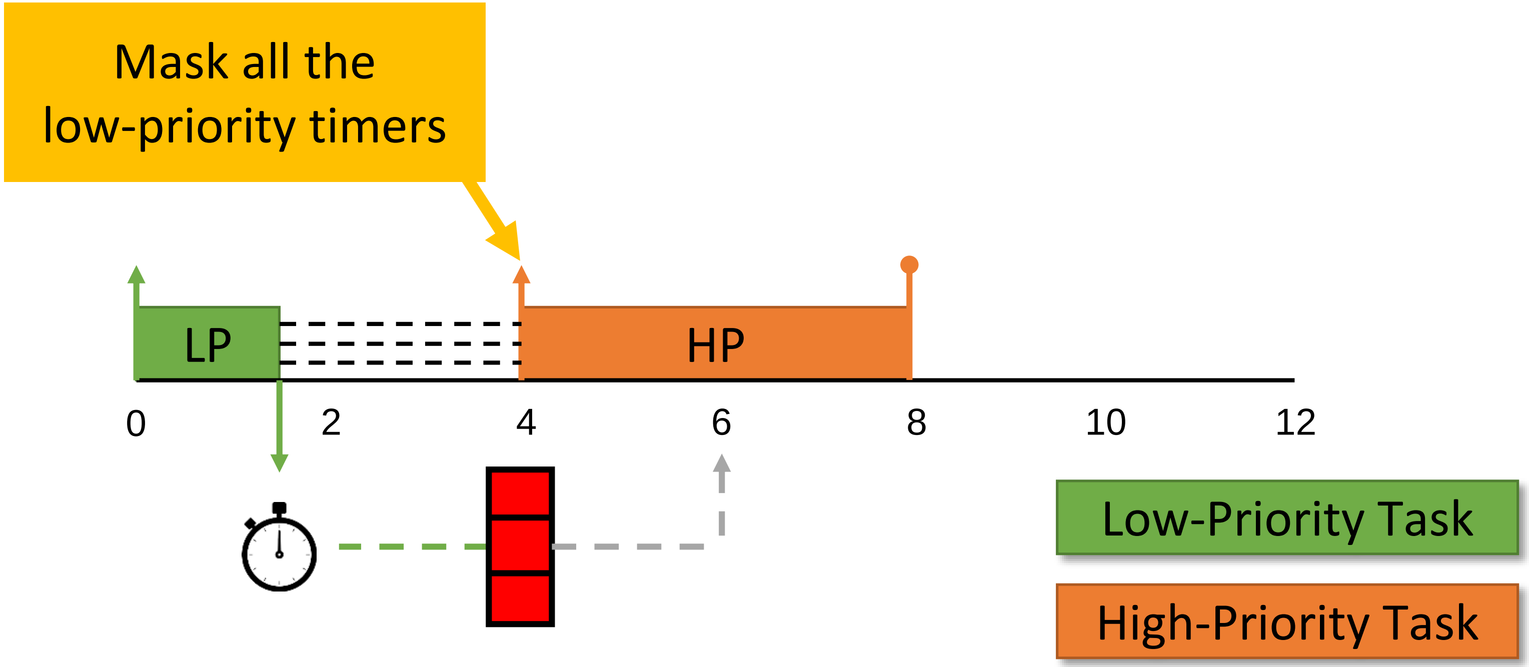

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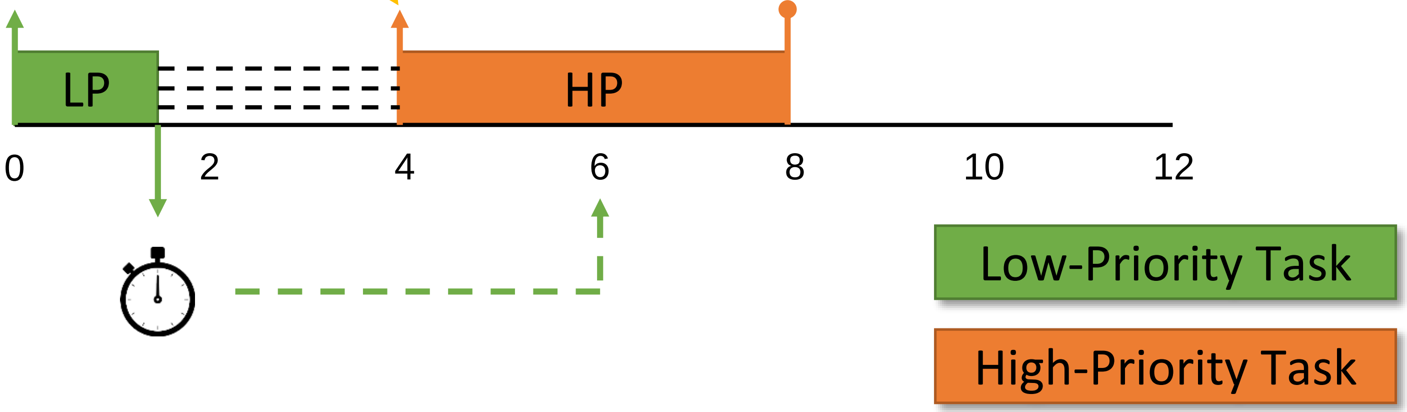
How Does TimerShield Work?

Mask all the low-priority timers

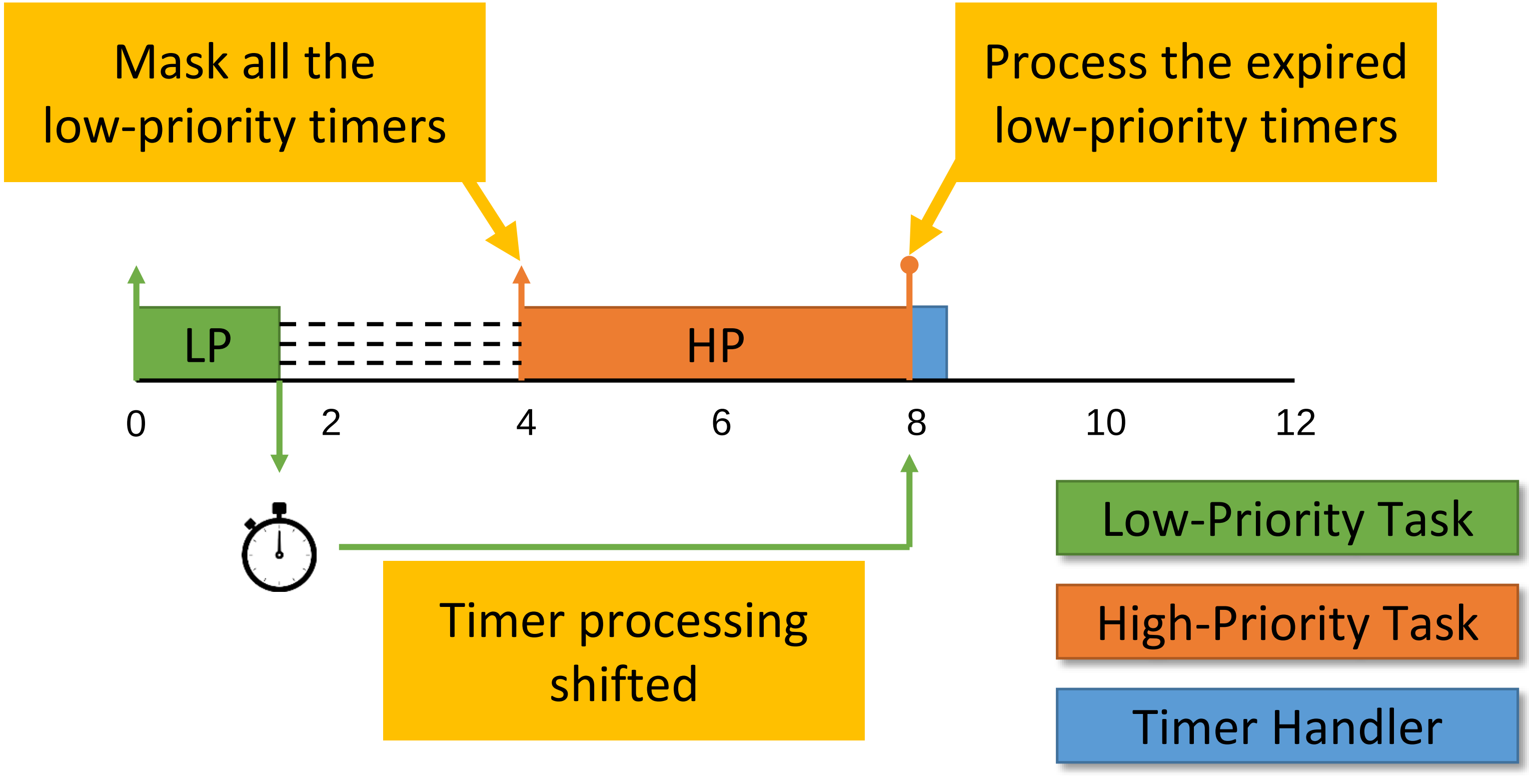
Process the expired low-priority timers



Low-Priority Task

High-Priority Task

How Does TimerShield Work?



Mask all the low-priority timers

Process the expired low-priority timers

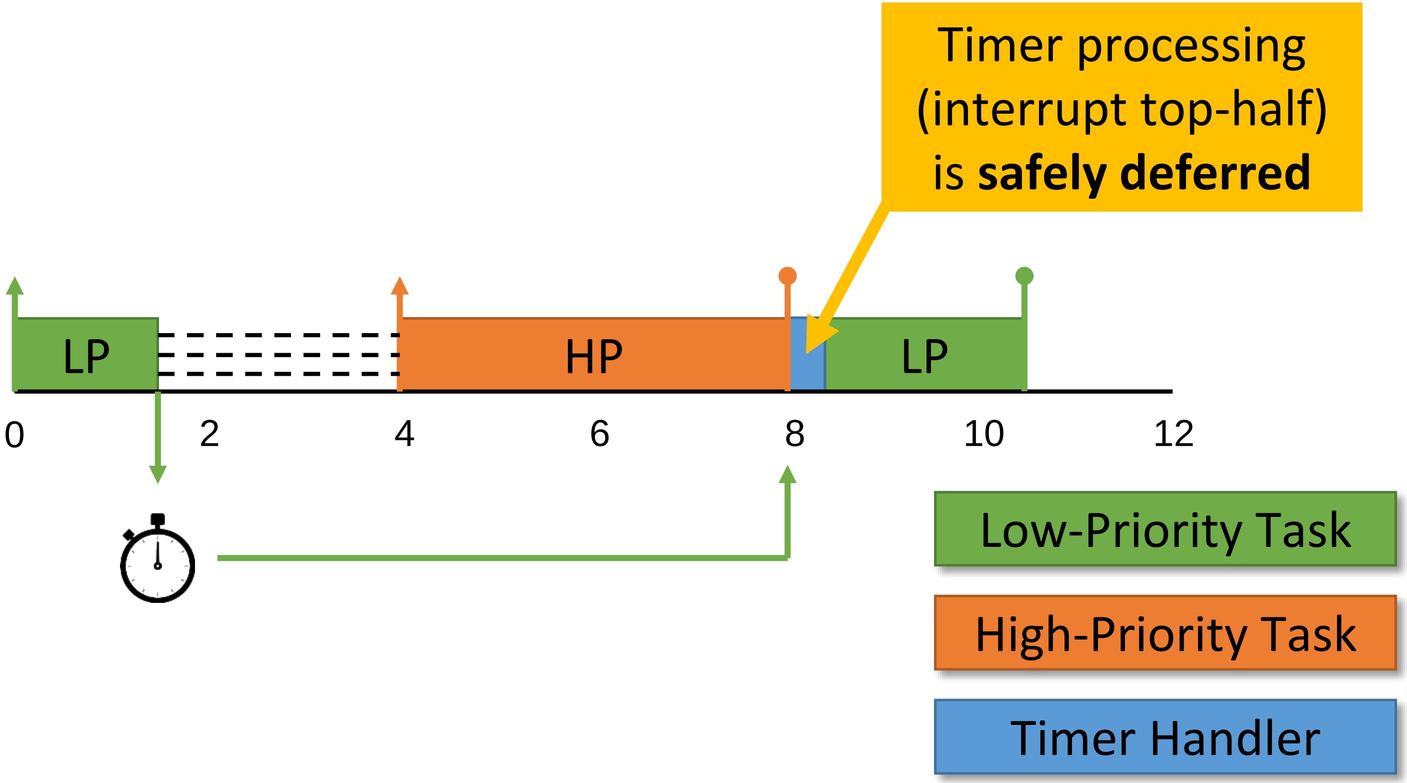
Timer processing shifted

🟩 Low-Priority Task

🟧 High-Priority Task

🟦 Timer Handler

How Does TimerShield Work?



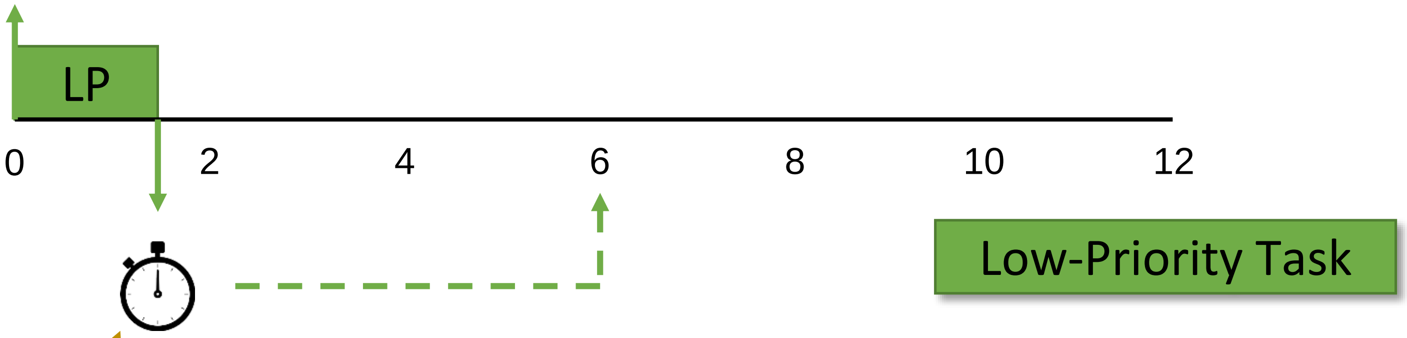
Timer processing (interrupt top-half) is **safely deferred**

Low-Priority Task

High-Priority Task

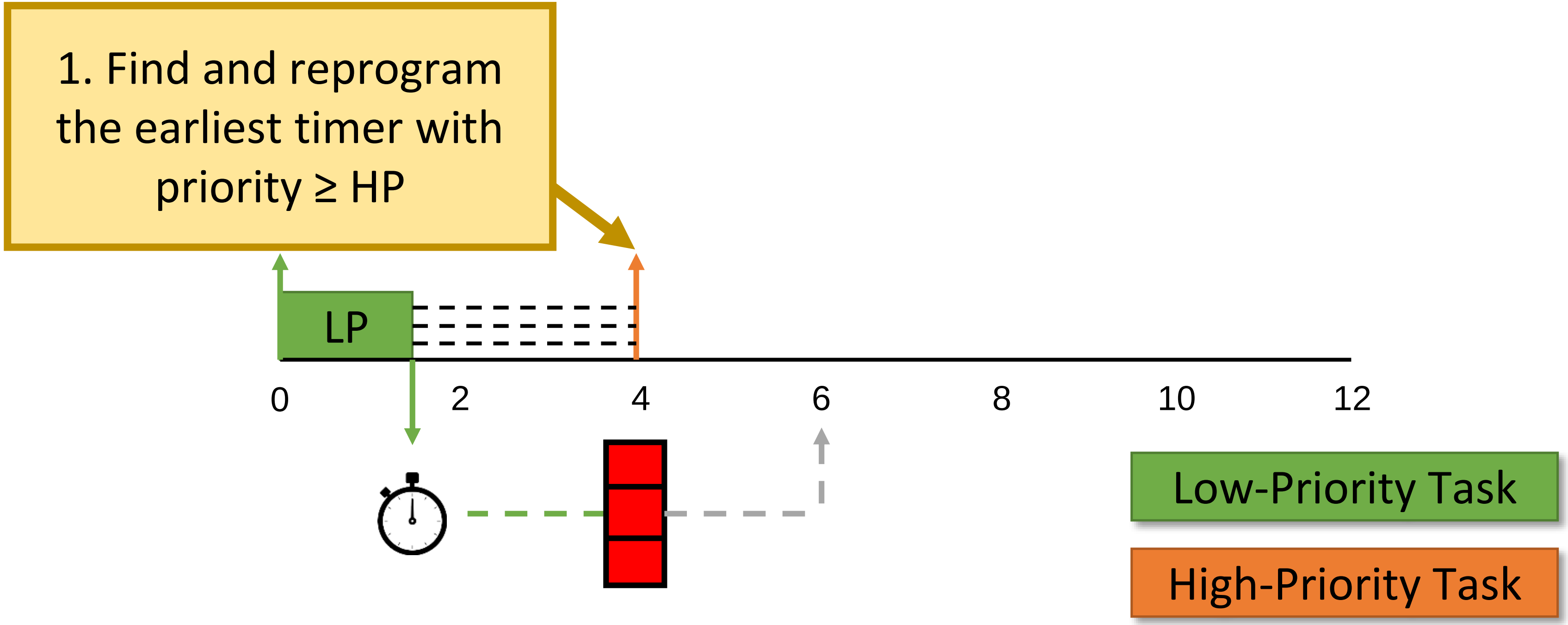
Timer Handler

How is TimerShield Implemented?



Timer inherits task priority

How is TimerShield Implemented?



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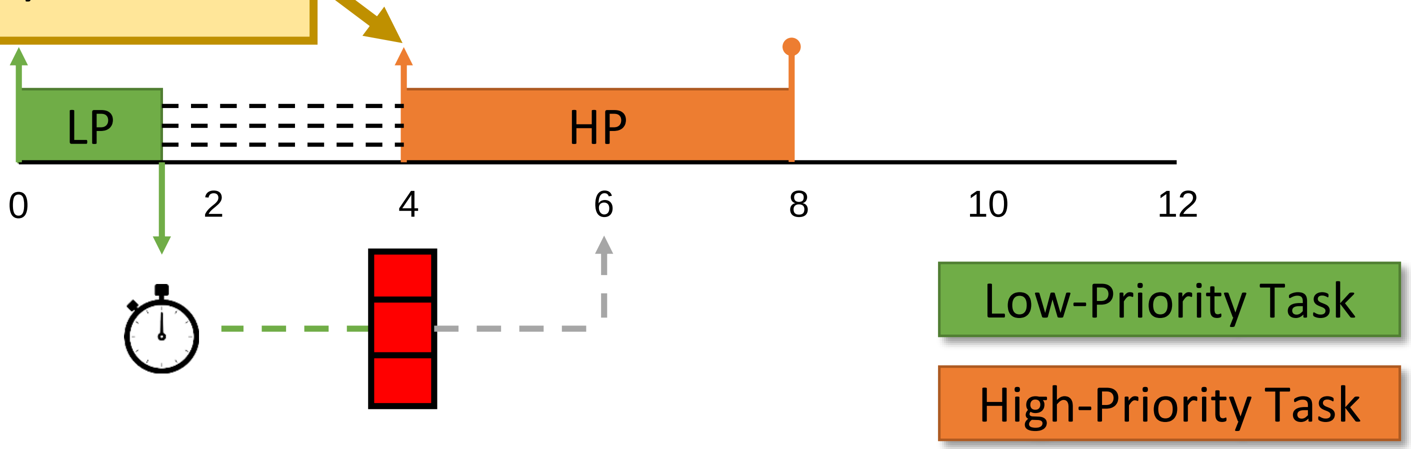

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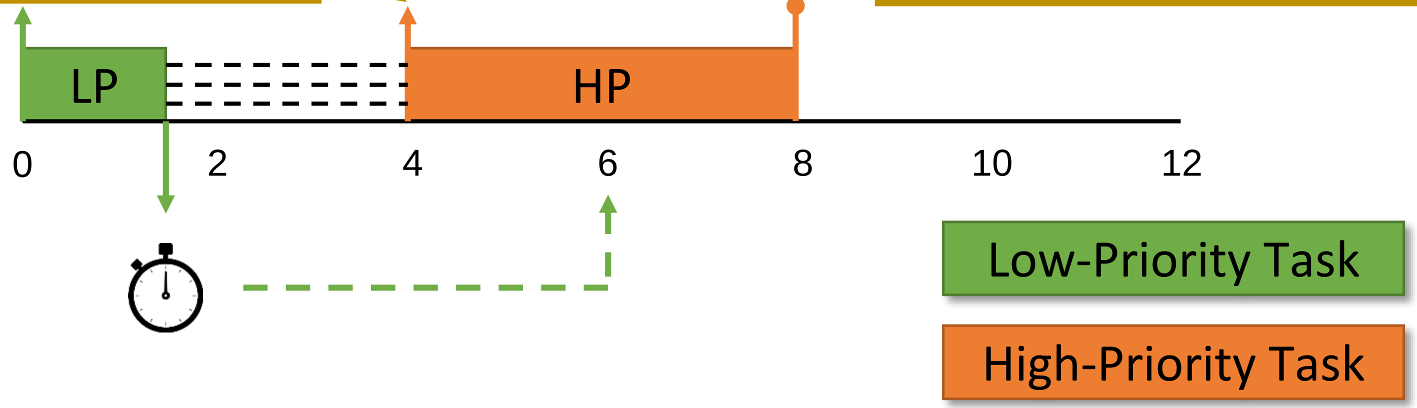

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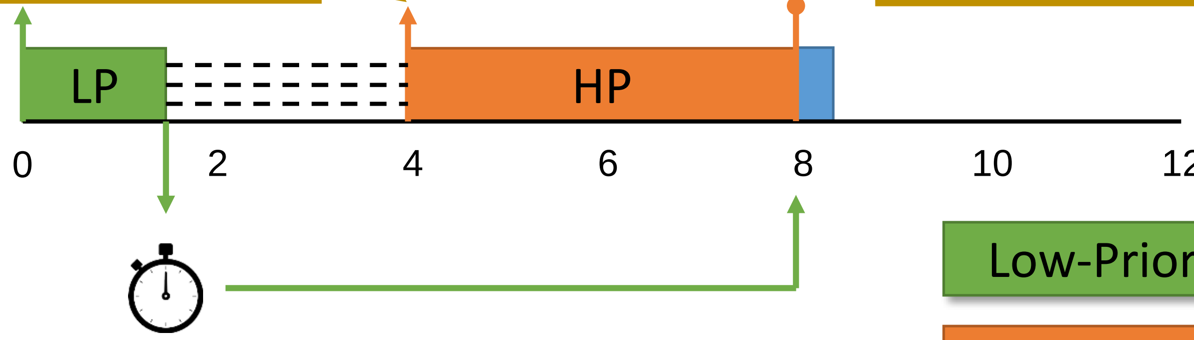

Low-Priority Task

High-Priority Task

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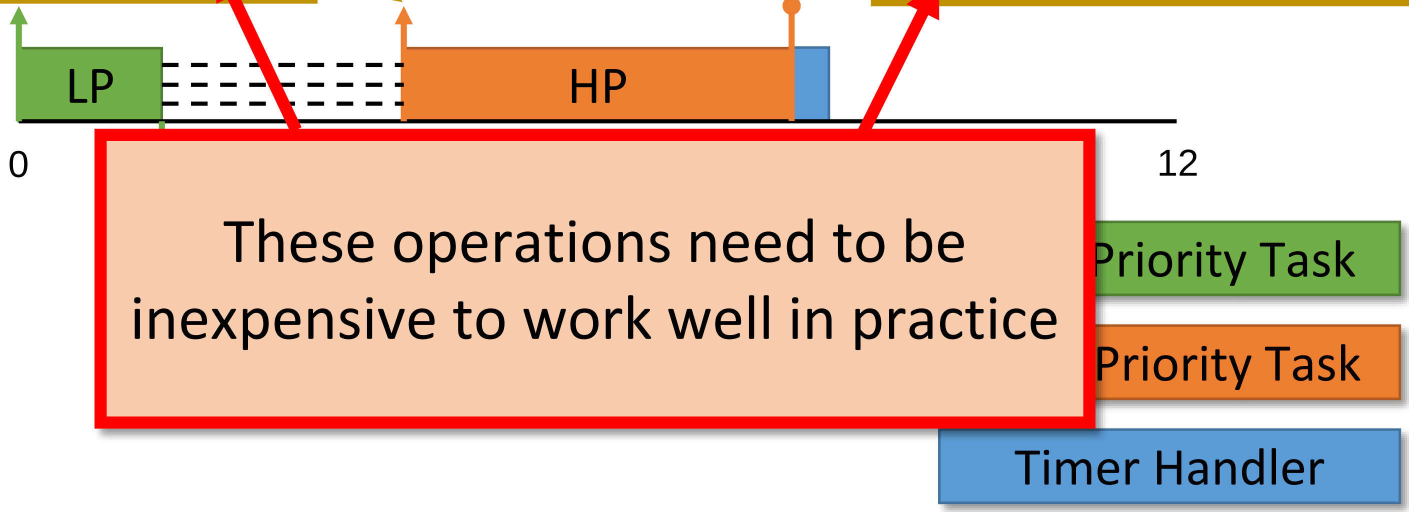

These operations need to be inexpensive to work well in practice

Priority-Based Earliest Timer

1: Find the earliest timer at each priority level

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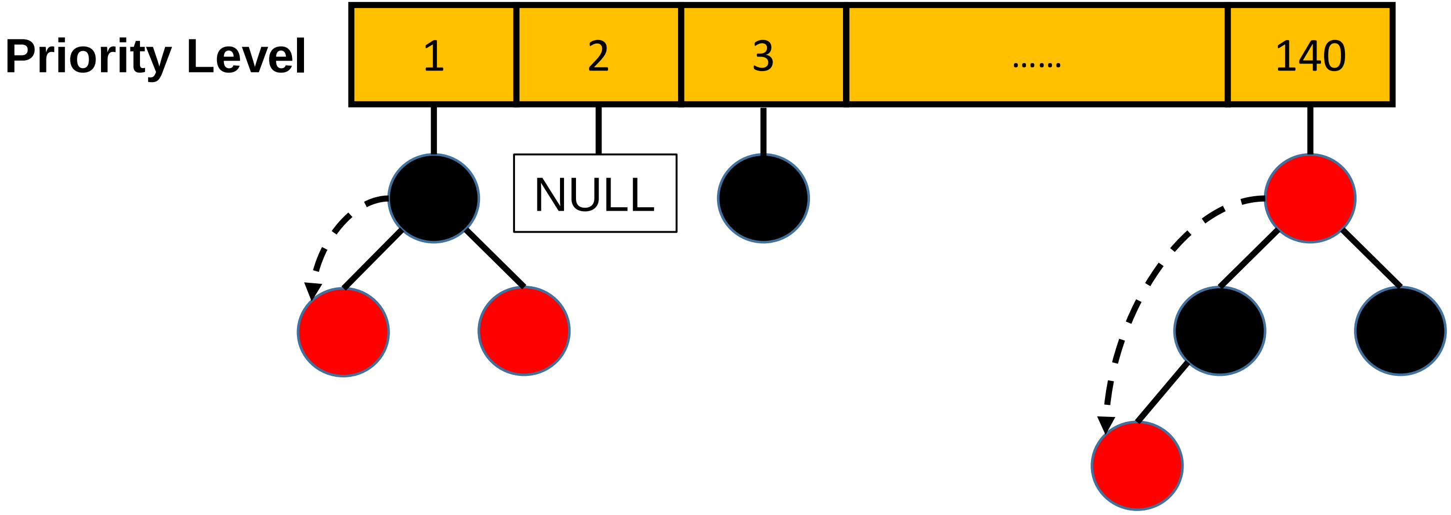
A Range Minimum Query! (RMQ)

1: Replicating Red-Black Trees



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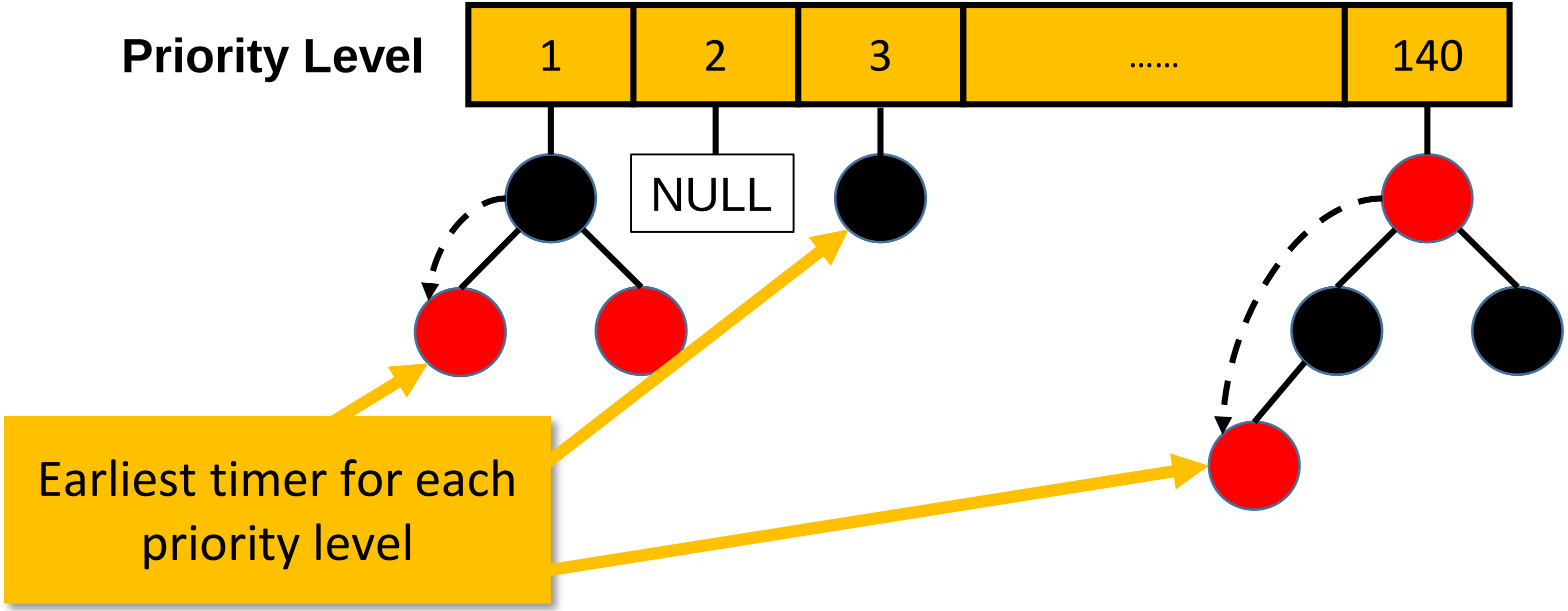
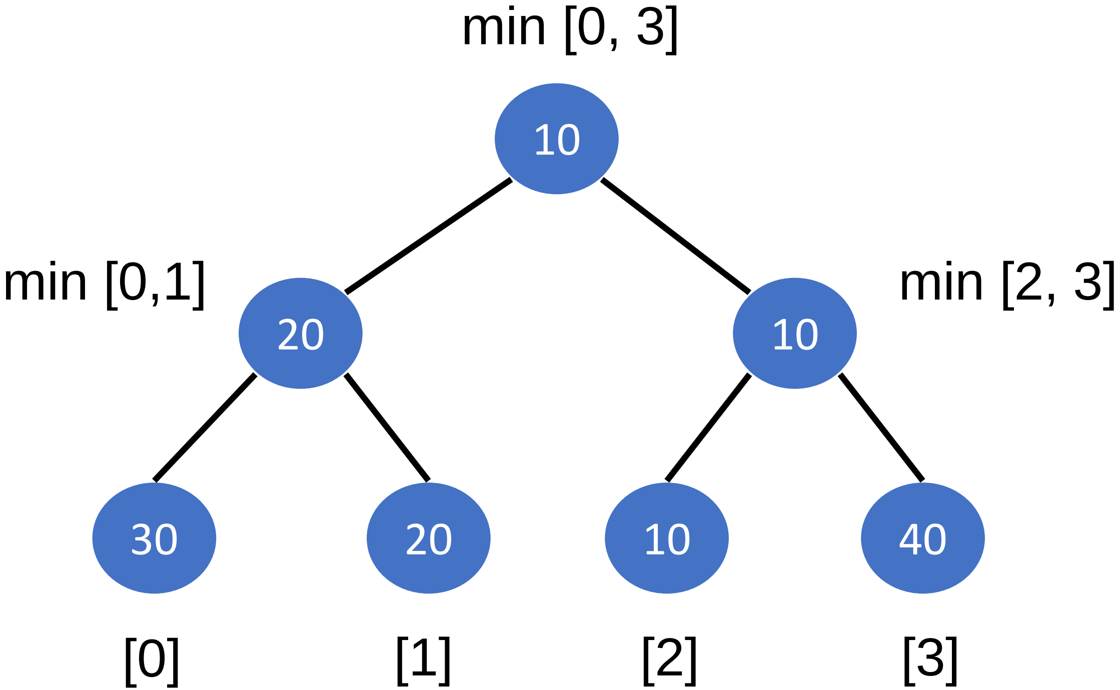


Priority Level	1	2	3	……	140

Earliest timer for each priority level

2: Range Minimum Query – Segment Tree



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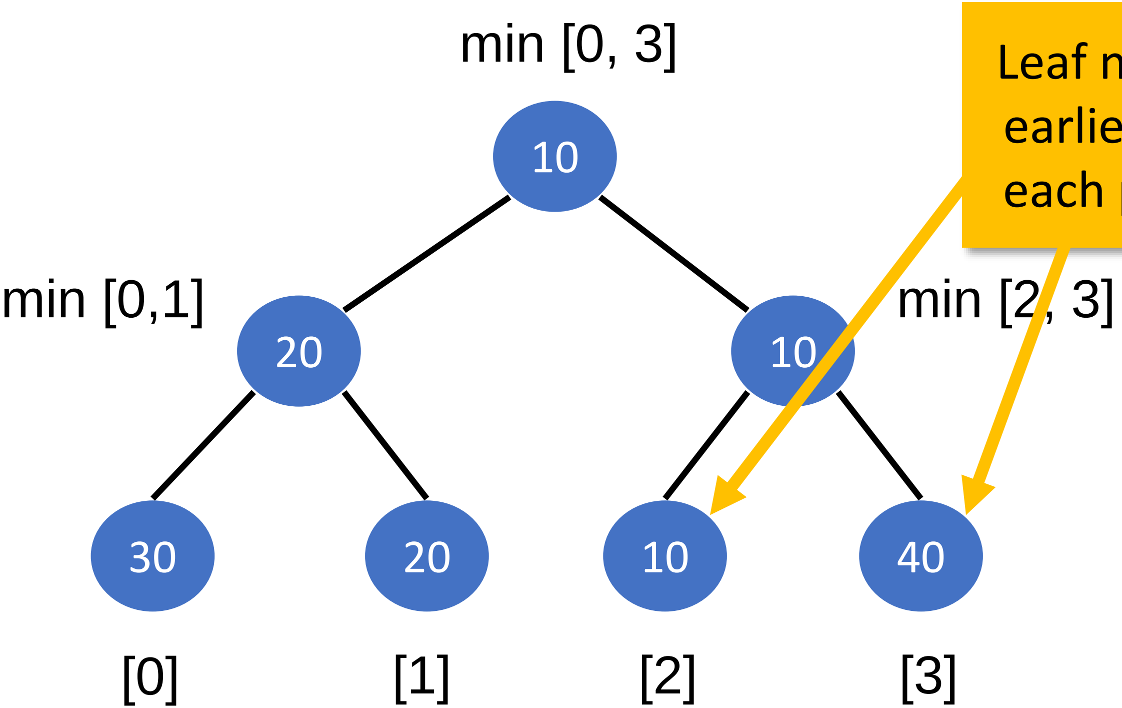

Leaf nodes are the earliest timers for each priority level

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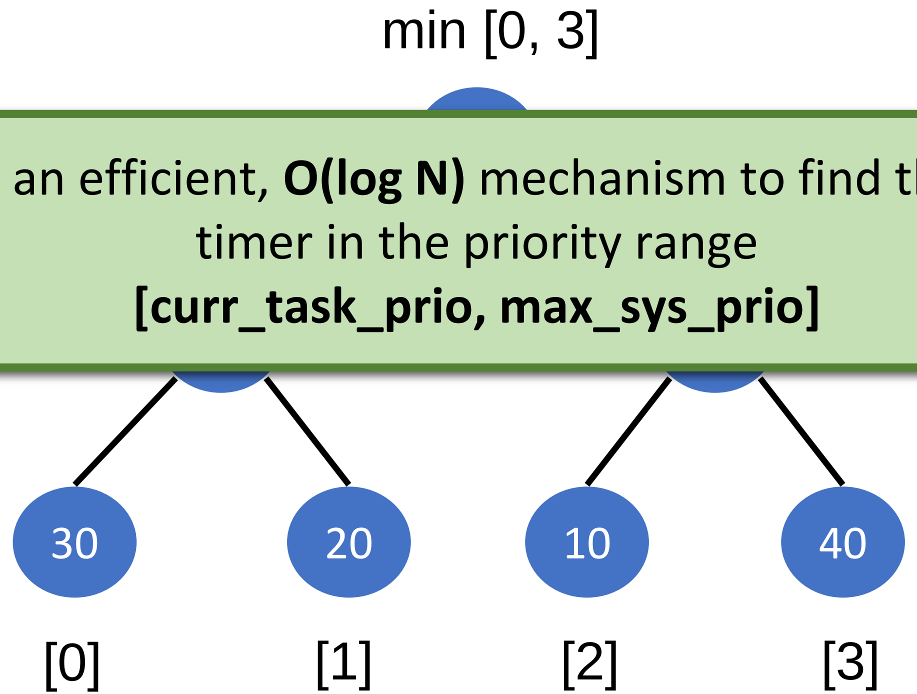

Provides an efficient, **O(log N)** mechanism to find the earliest timer in the priority range **[curr_task_prio, max_sys_prio]**

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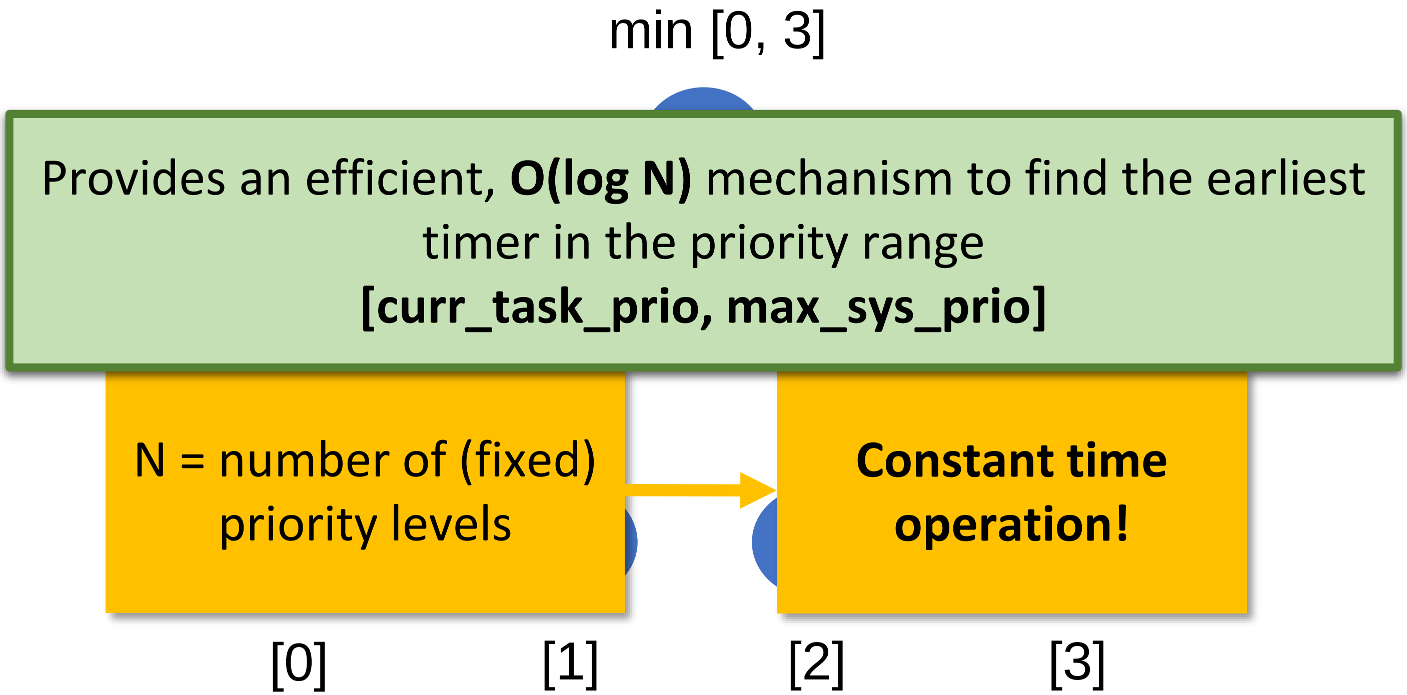

Provides an efficient, **O(log N)** mechanism to find the earliest timer in the priority range **[curr_task_prio, max_sys_prio]**

N = number of (fixed) priority levels

Constant time operation!

TimerShield Implementation

Further details in the paper!

Open-source implementation at
https://people.mpi-sws.org/~bbb/papers/details/rtas17p/

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Prototyped in
PREEMPT_RT

Intel Core-i5
4 x 3.2Ghz

ARM Cortex-A53
4 x 1.2Ghz

Evaluation

Prototyped in **PREEMPT_RT**

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Details in paper

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How effective is TimerShield at isolating high-priority tasks from low-priority timer interrupts?

How is the context-switch duration affected?

How costly are the new queueing data structures?

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HP Task Response Time

We measured the response time of a high-priority task with varying number of low-priority, timer-using tasks

HP Task Response Time

1 KHz control loop with approx. 200µs computation time

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Taskset parameters based on S. Kramer, D. Ziegenbein, and A. Hamann, “Real world automotive benchmark for free,” in WATERS, 2015.

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cyclictest tasks which periodically call *clock_nanosleep()*

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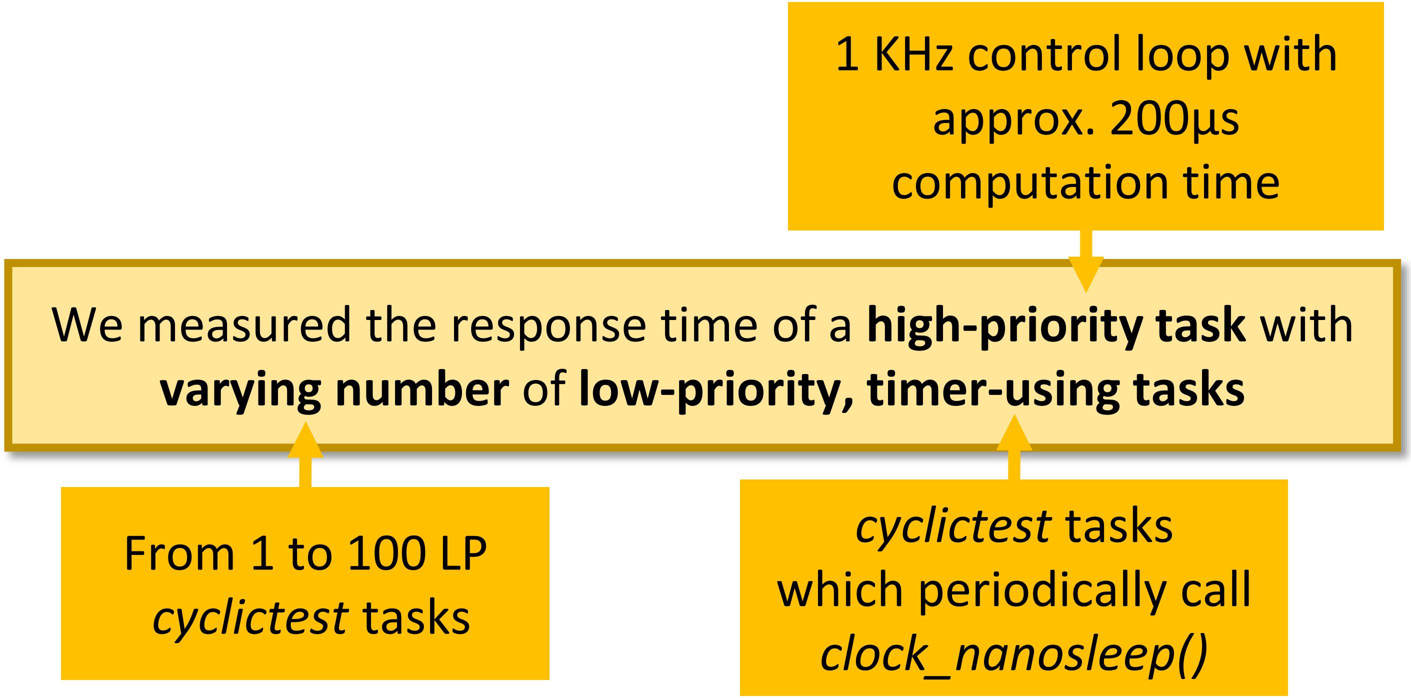

1 KHz control loop with approx. 200µs computation time

We measured the response time of a **high-priority task** with **varying number** of **low-priority, timer-using tasks**

From 1 to 100 LP *cyclictest* tasks

cyclictest tasks which periodically call *clock_nanosleep()*

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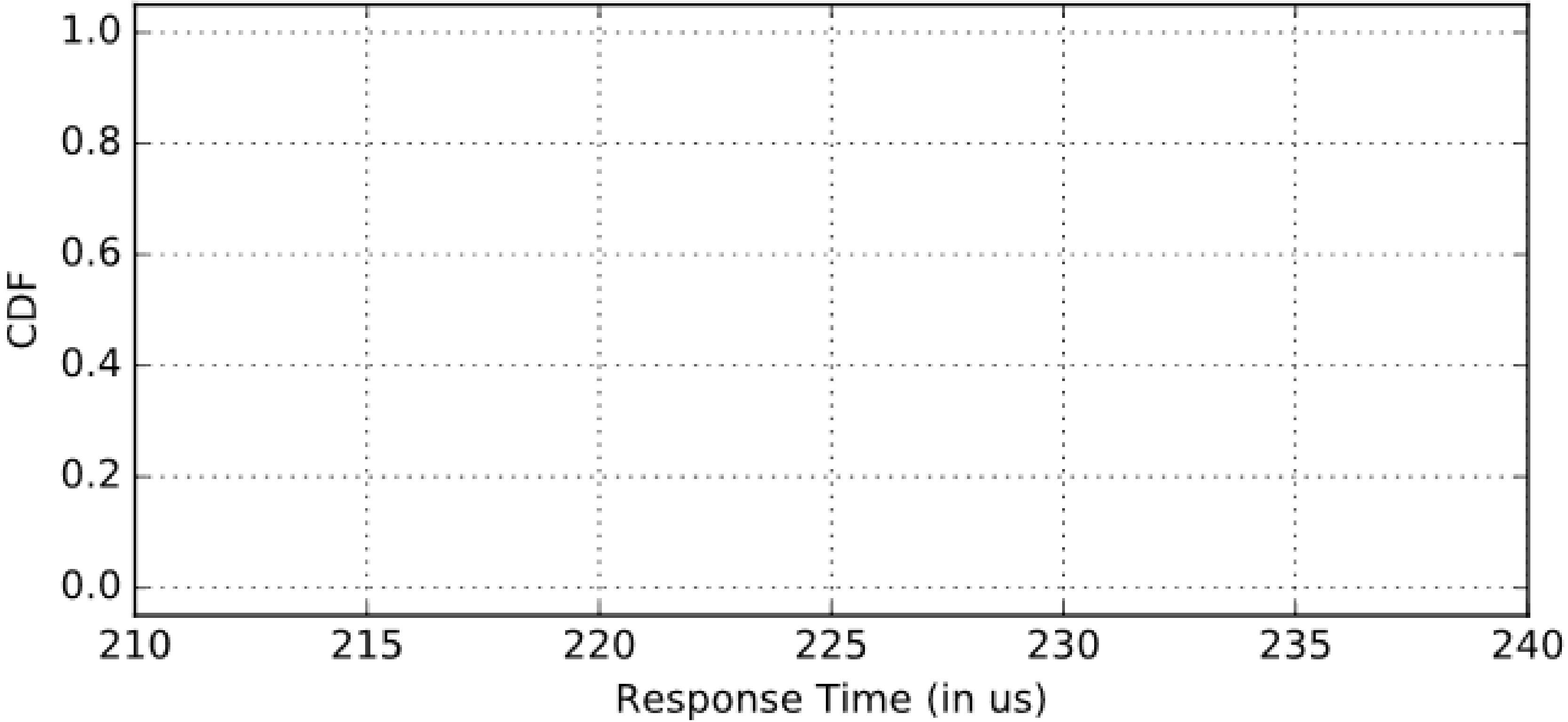

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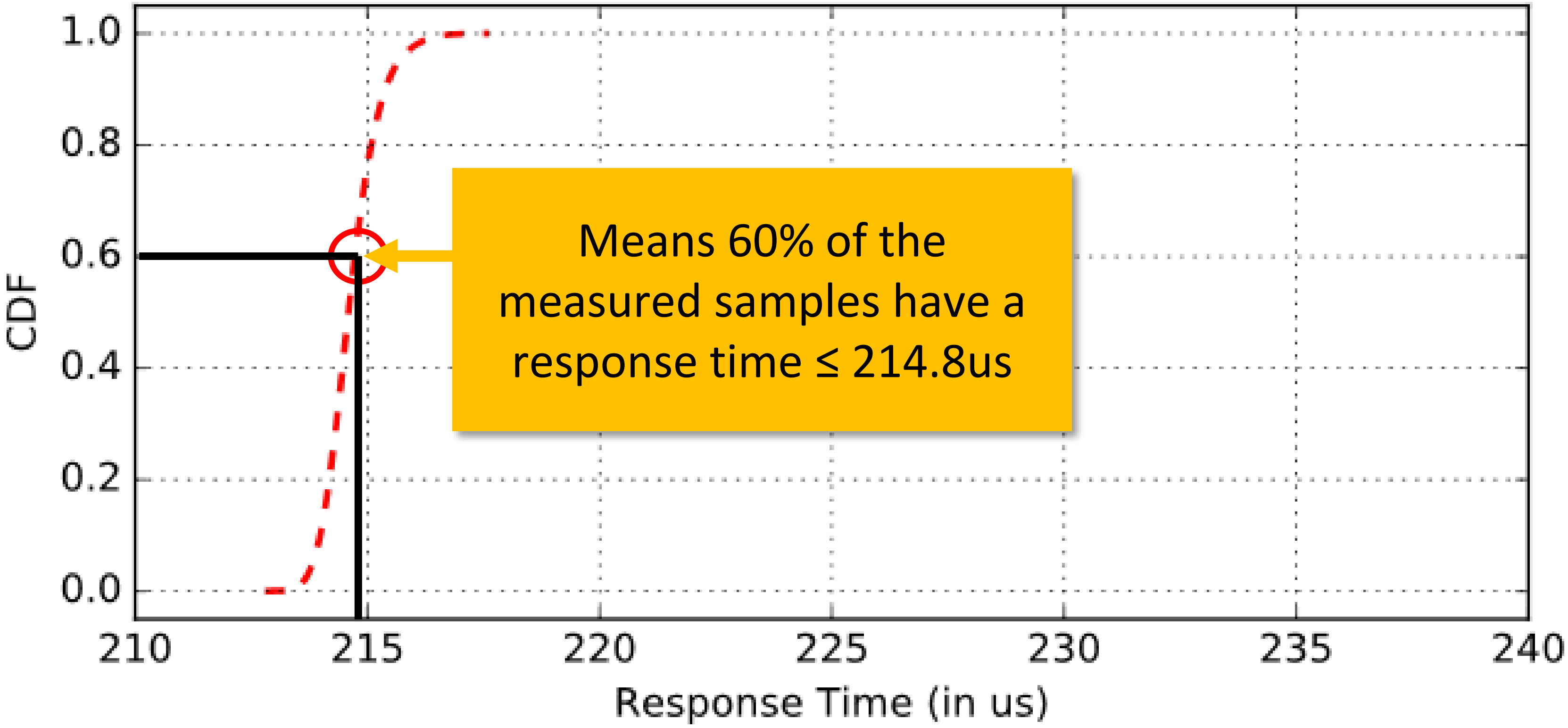
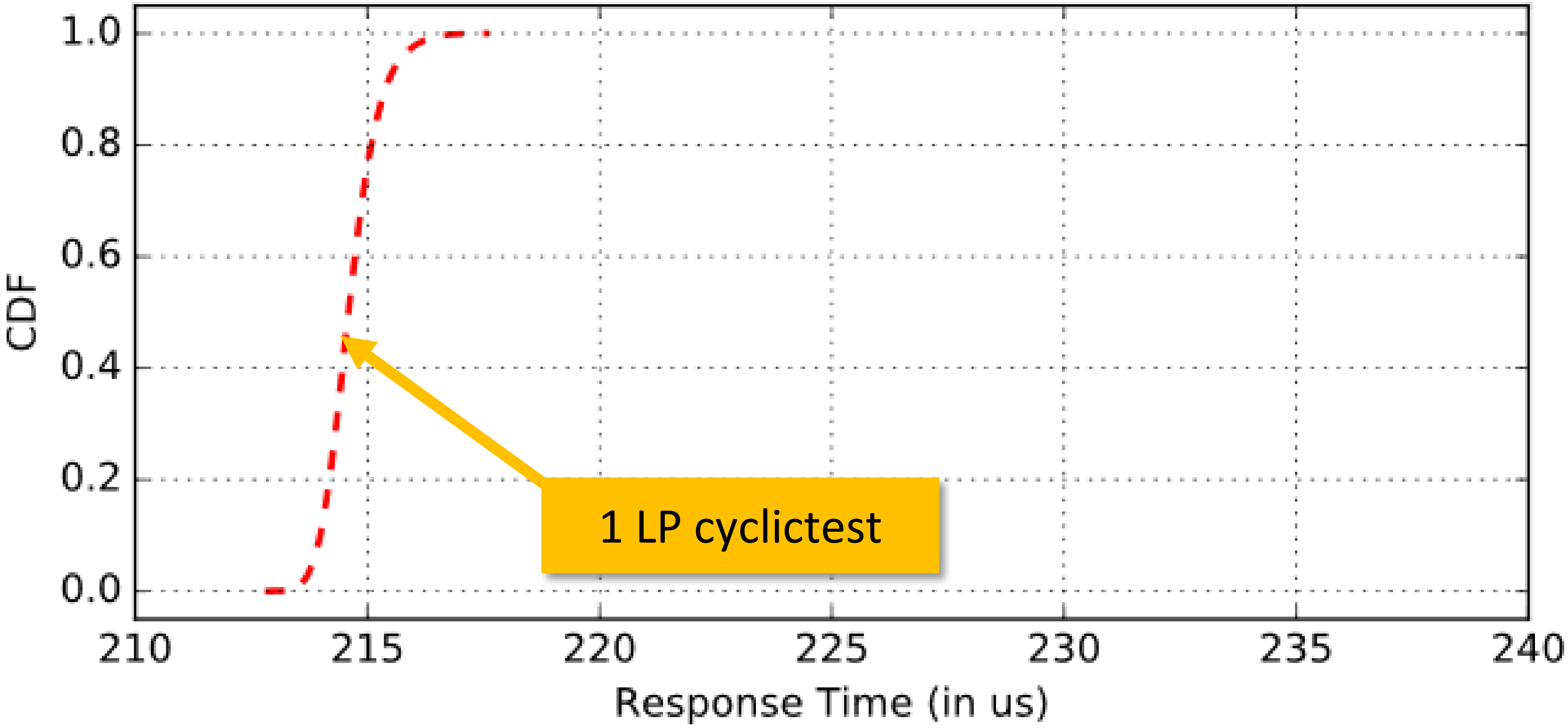


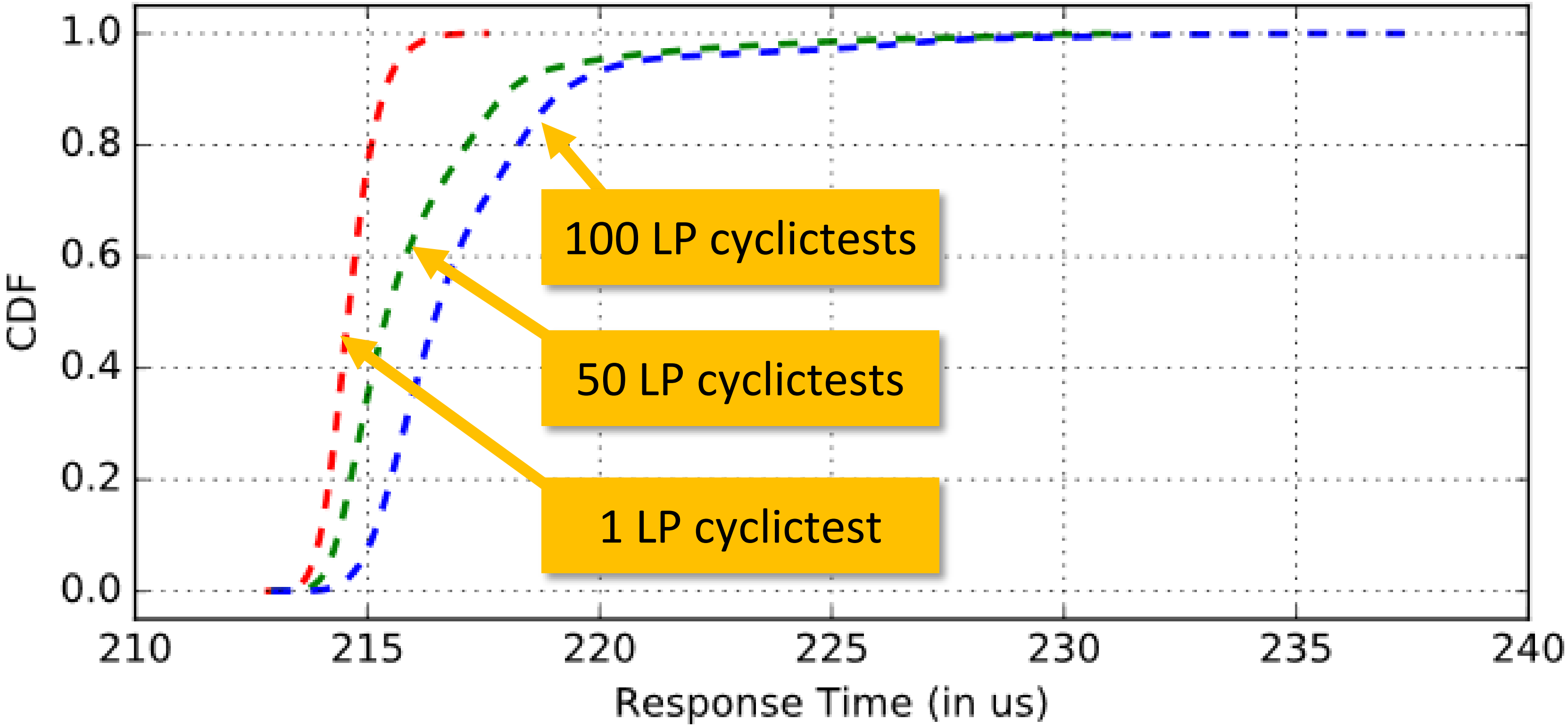
Means 60% of the measured samples have a response time ≤ 214.8us

Response Time - hrtimers



1 LP cyclictest

Response Time - hrtimers

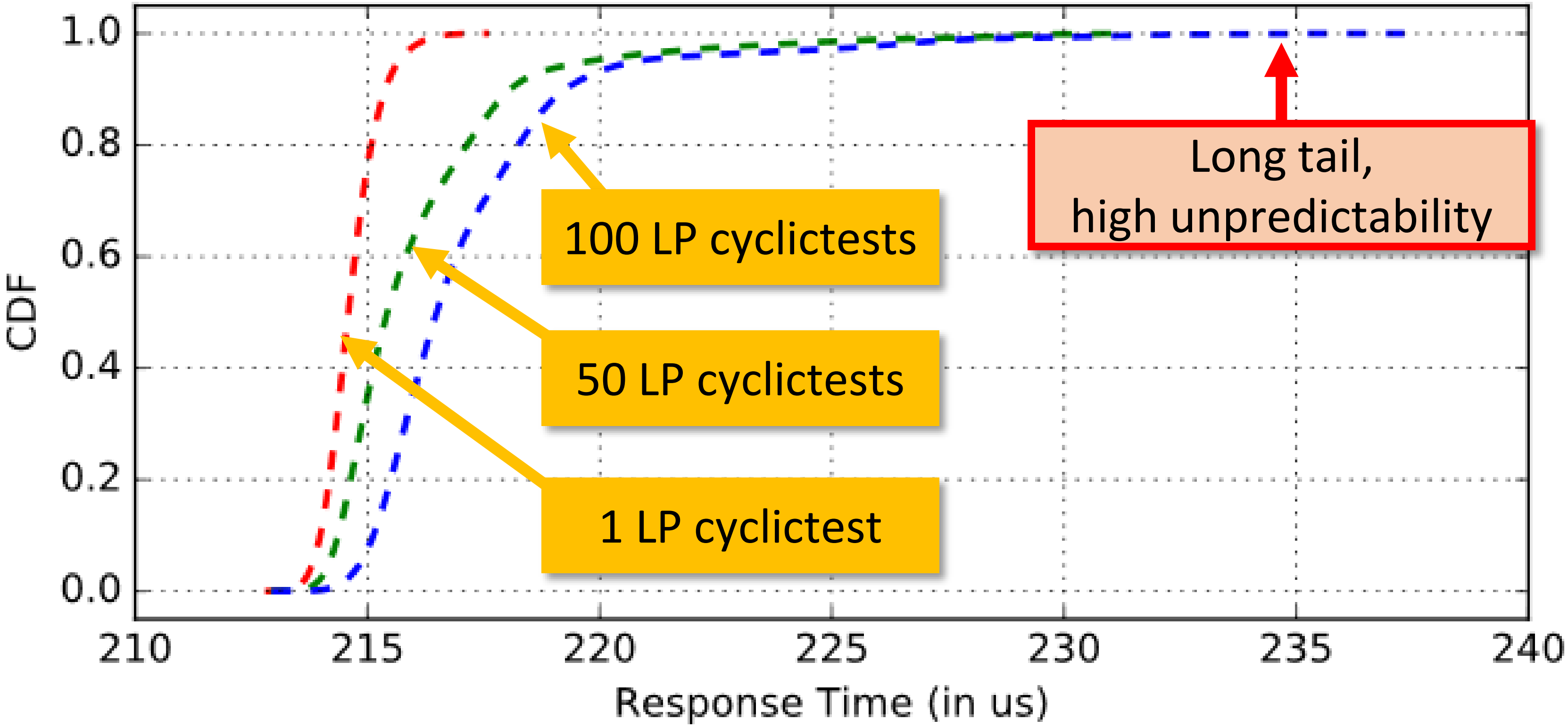


100 LP cyclictests

50 LP cyclictests

1 LP cyclictest

Response Time - hrtimers



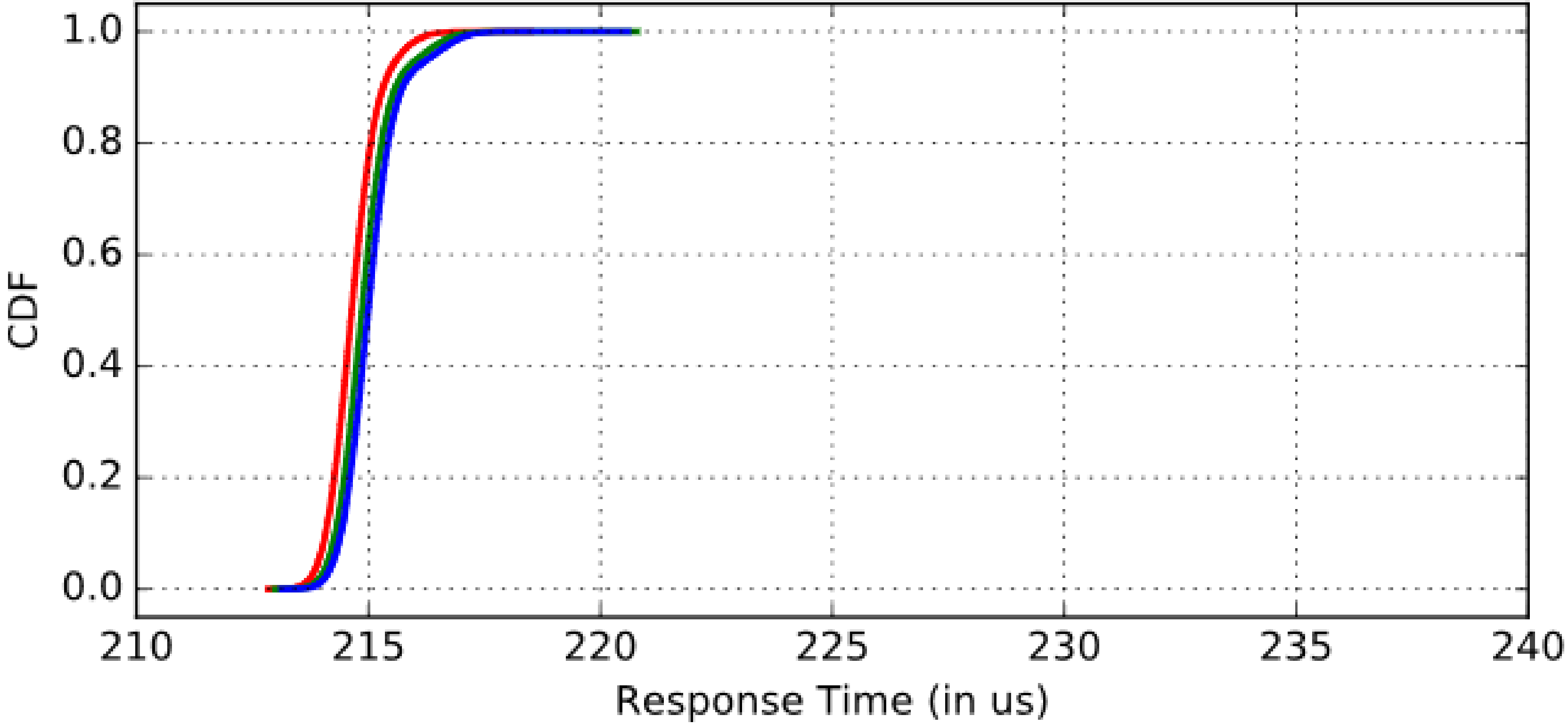
100 LP cyclictests

50 LP cyclictests

1 LP cyclictest

Long tail,
high unpredictability

Response Time - TimerShield



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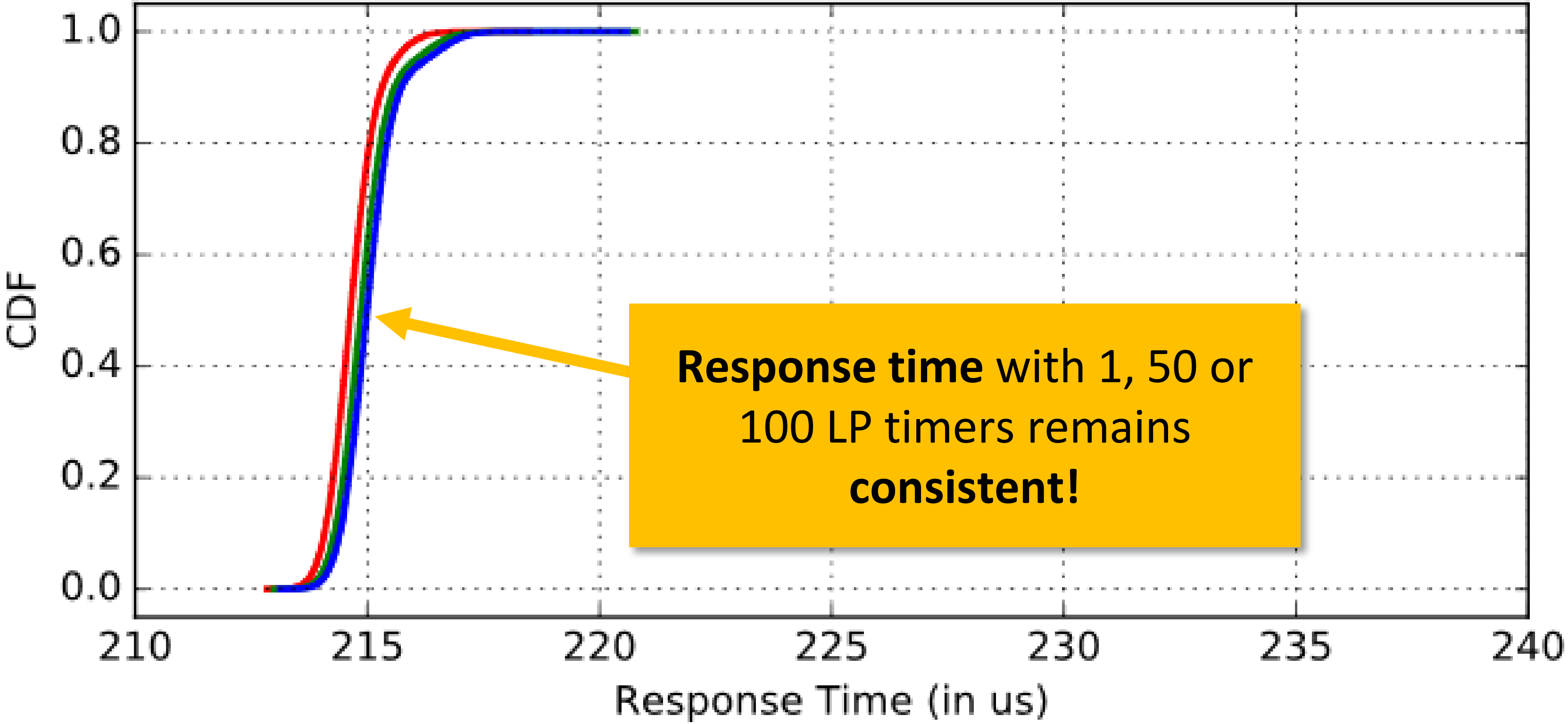
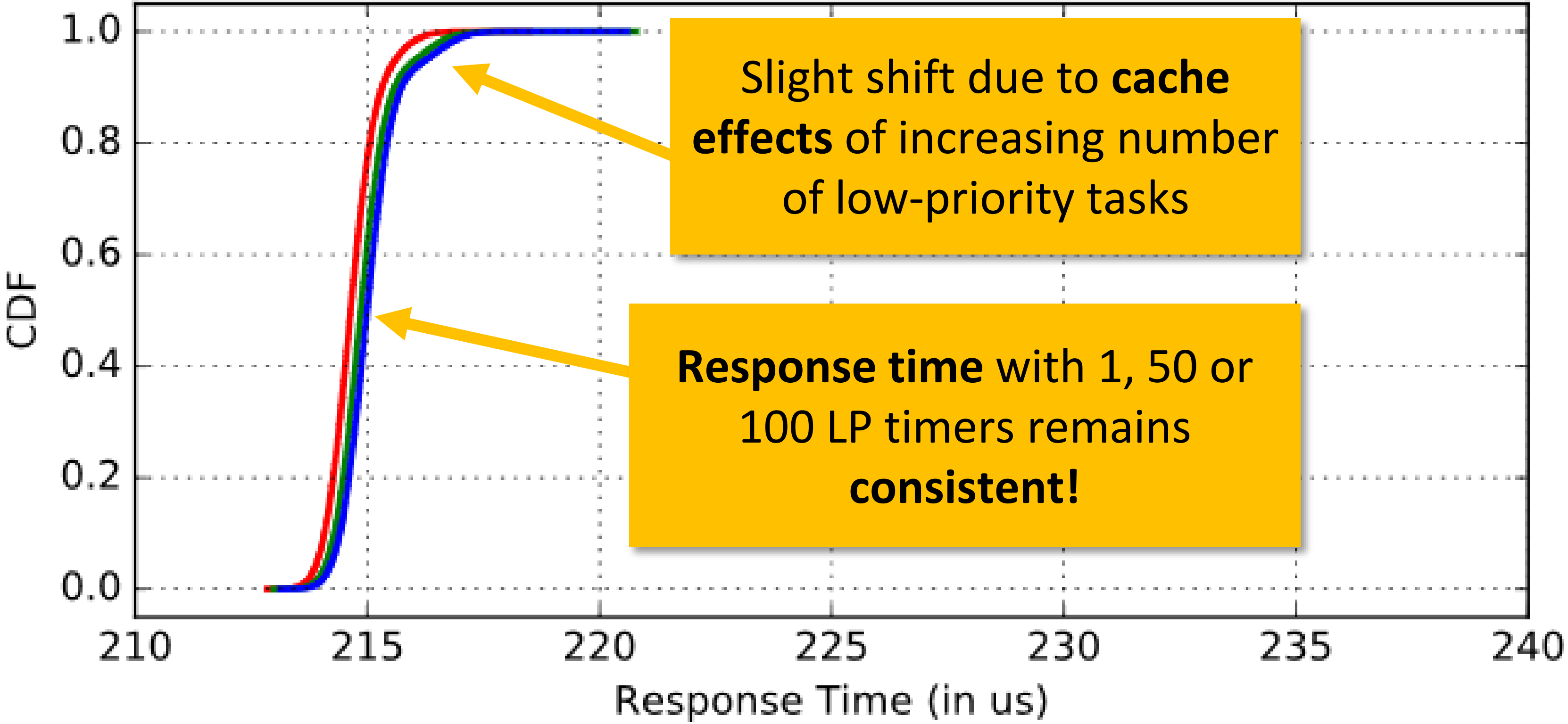


Response time with 1, 50 or 100 LP timers remains **consistent!**

Response Time - TimerShield



Slight shift due to **cache effects** of increasing number of low-priority tasks

Response time with 1, 50 or 100 LP timers remains **consistent!**

How Bad Can It Get?

Linux (and POSIX) provide **no protection**, and specifies **no upper limit** on timer creation

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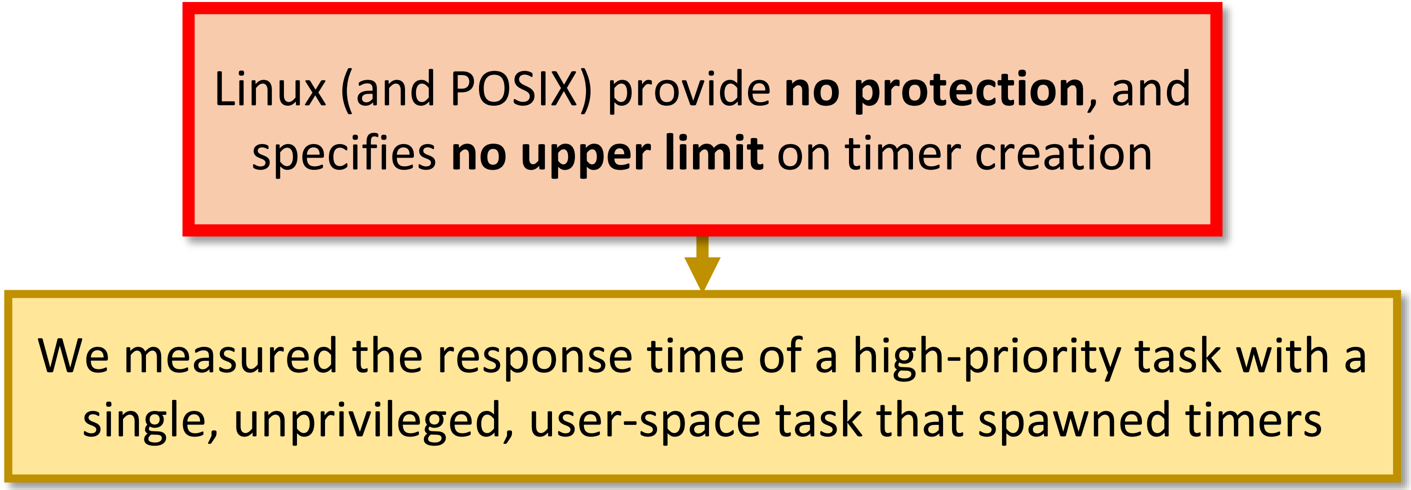

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We measured the response time of a high-priority task with a single, unprivileged, user-space task that spawned timers

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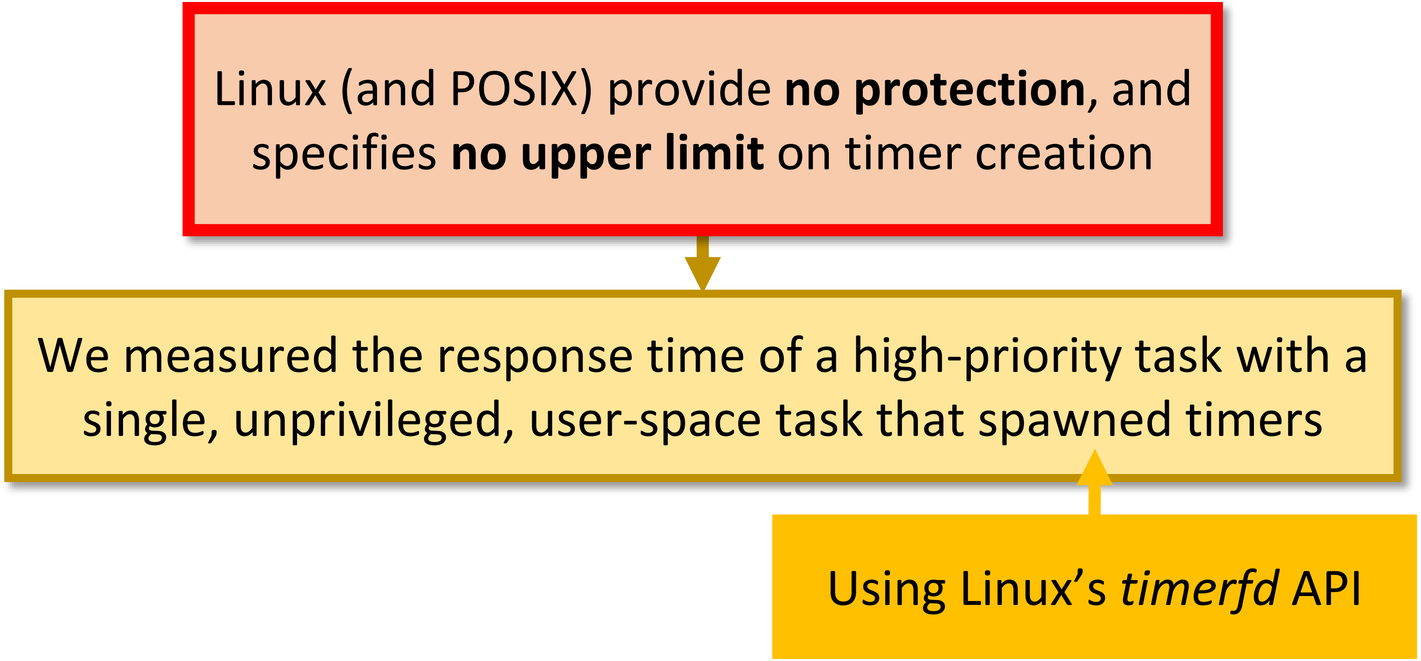


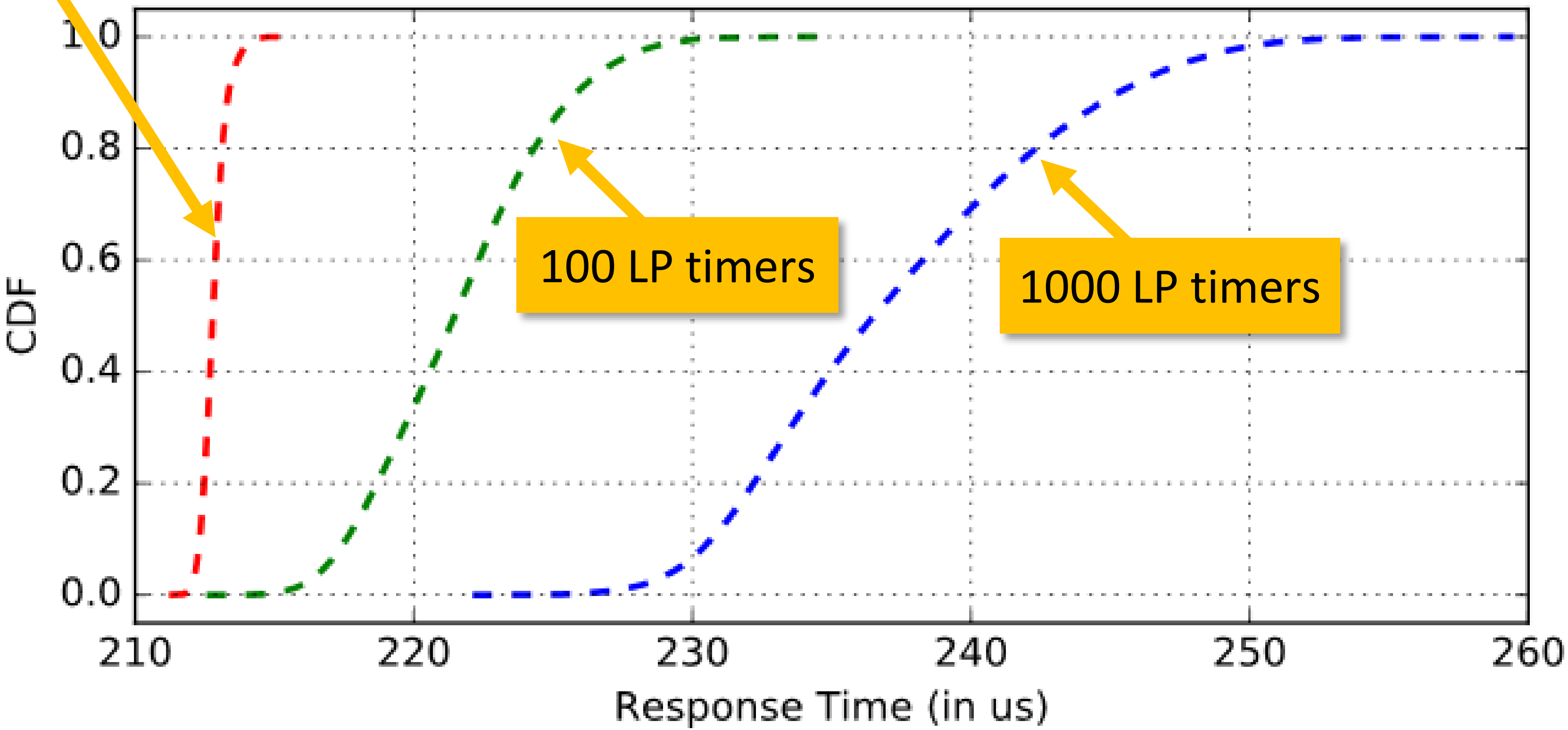
Linux (and POSIX) provide **no protection**, and specifies **no upper limit** on timer creation

We measured the response time of a high-priority task with a single, unprivileged, user-space task that spawned timers

Using Linux’s *timerfd* API

esponse Time - `hrtimers`

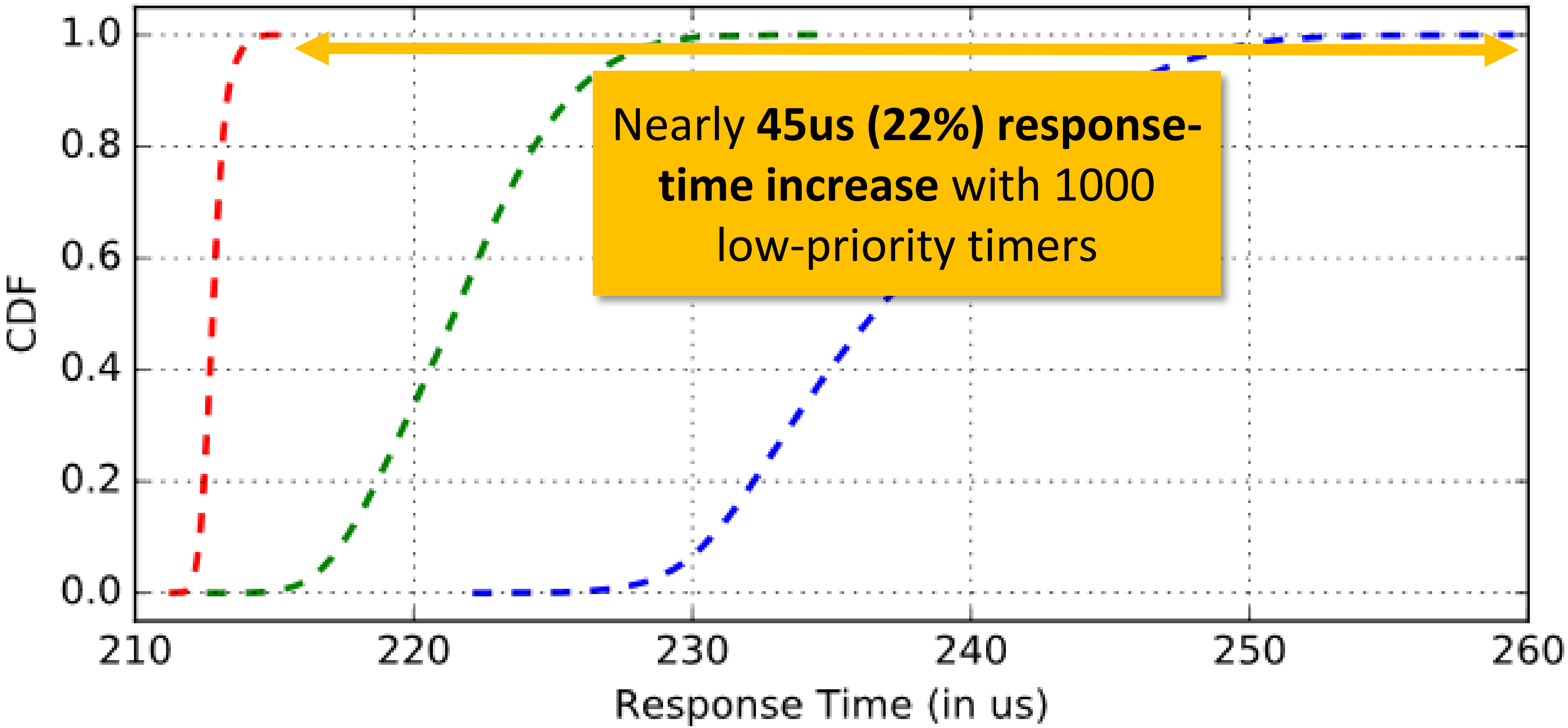
Idle system



100 LP timers

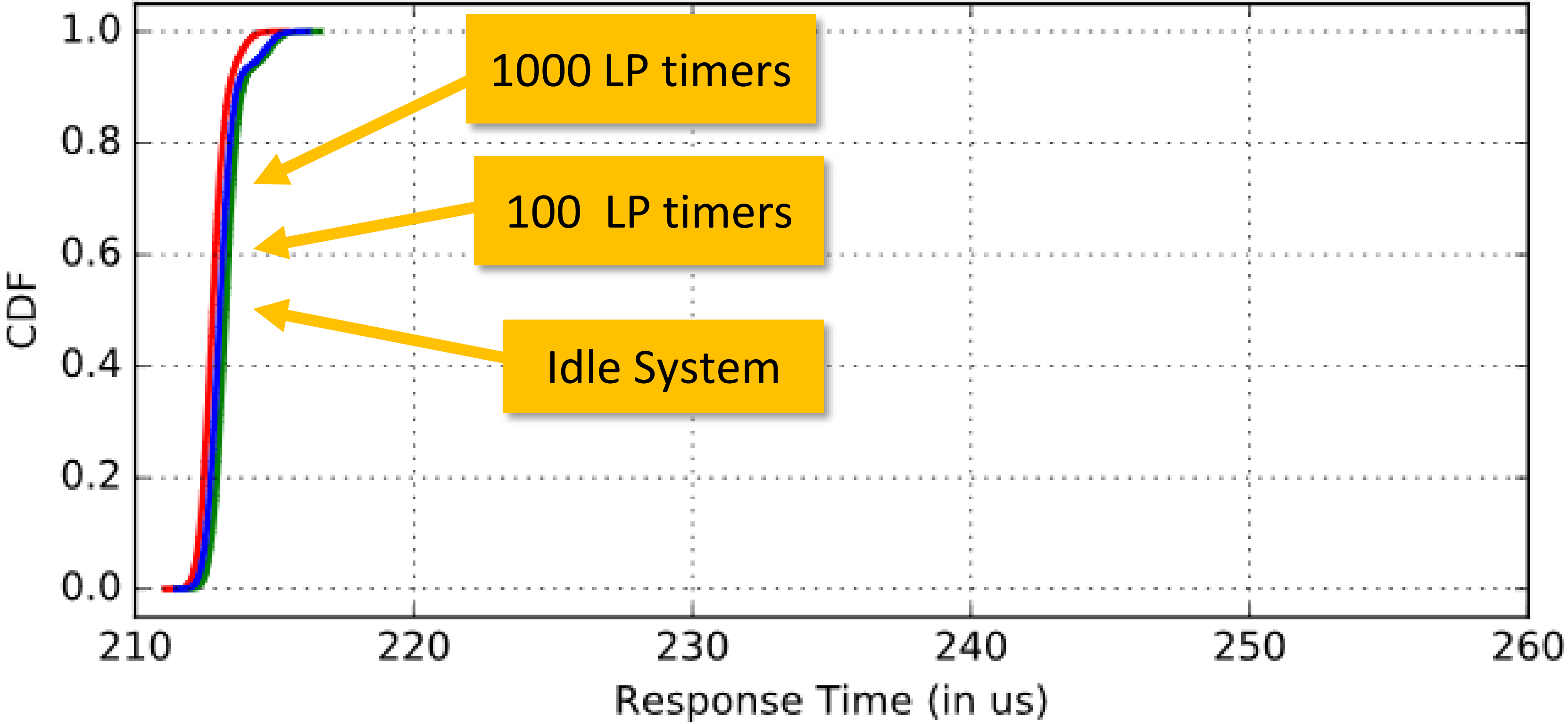
1000 LP timers

Response Time - `hrtimers`



Nearly **45us (22%) response-time increase** with 1000 low-priority timers

Response Time - TimerShield

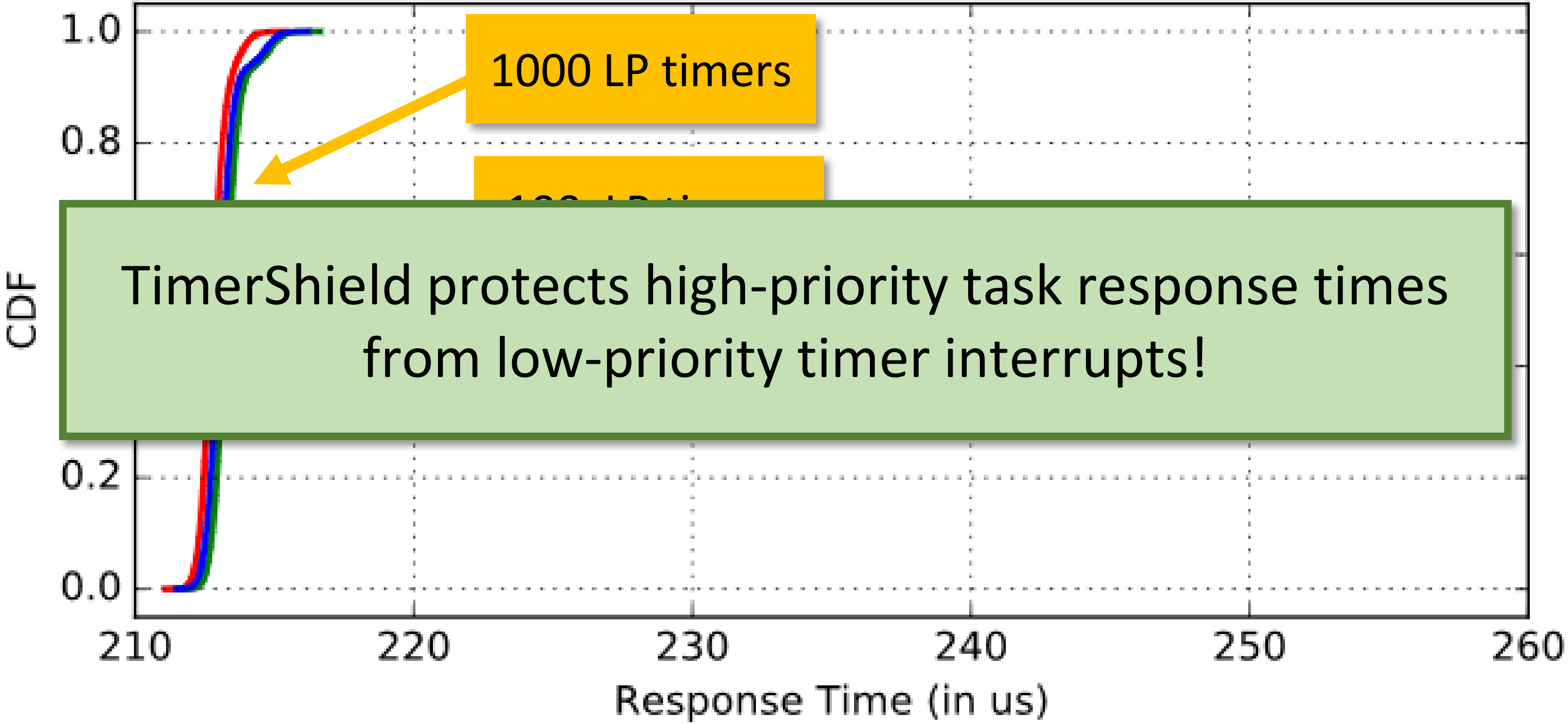


1000 LP timers

100 LP timers

Idle System

Response Time - TimerShield



1000 LP timers

TimerShield protects high-priority task response times from low-priority timer interrupts!

Evaluation

How effective is TimerShield at isolating high-priority tasks from low-priority timer interrupts?

How is the context-switch duration affected?

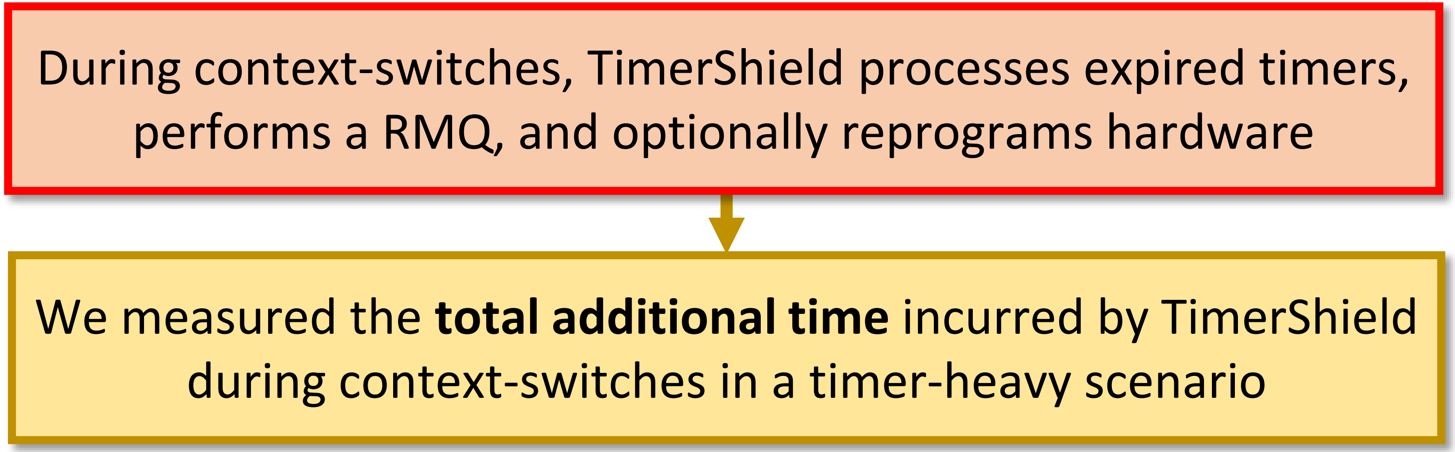
How costly are the new queueing data structures?

Additional Context-Switch Delay

During context-switches, TimerShield processes expired timers, performs a RMQ, and optionally reprograms hardware

Note: Results for a scenario without a timer-heavy load can be found in the paper.

Additional Context-Switch Delay



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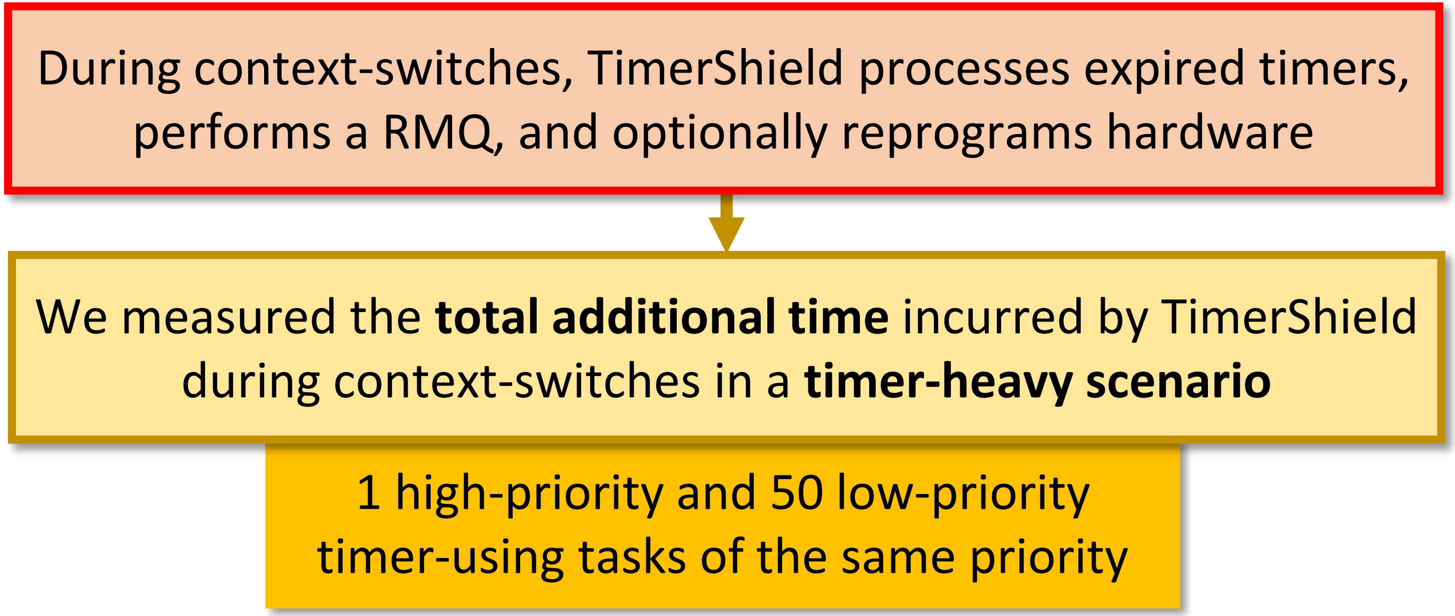


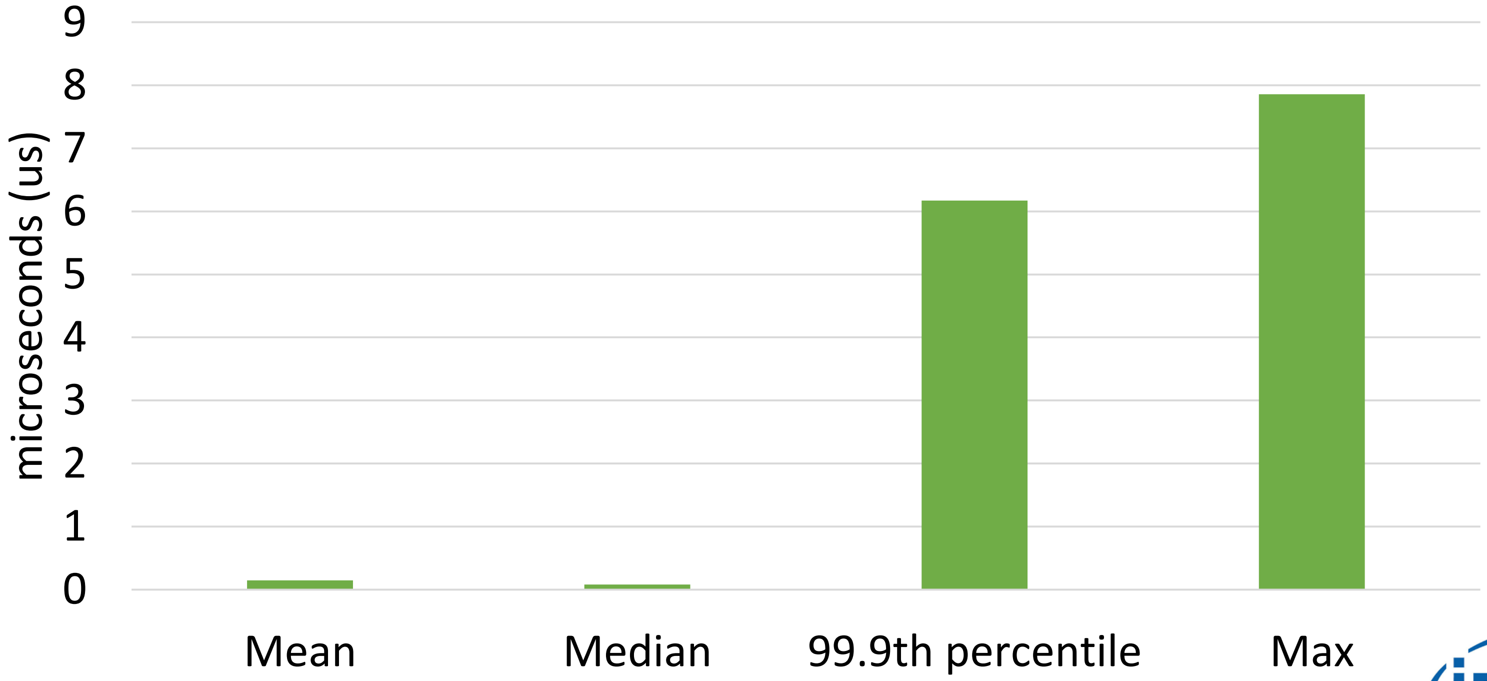
During context-switches, TimerShield processes expired timers, performs a RMQ, and optionally reprograms hardware

We measured the **total additional time** incurred by TimerShield during context-switches in a **timer-heavy scenario**

1 high-priority and 50 low-priority timer-using tasks of the same priority

Note: Results for a scenario without a timer-heavy load can be found in the paper.

Additional Context-Switch Delay



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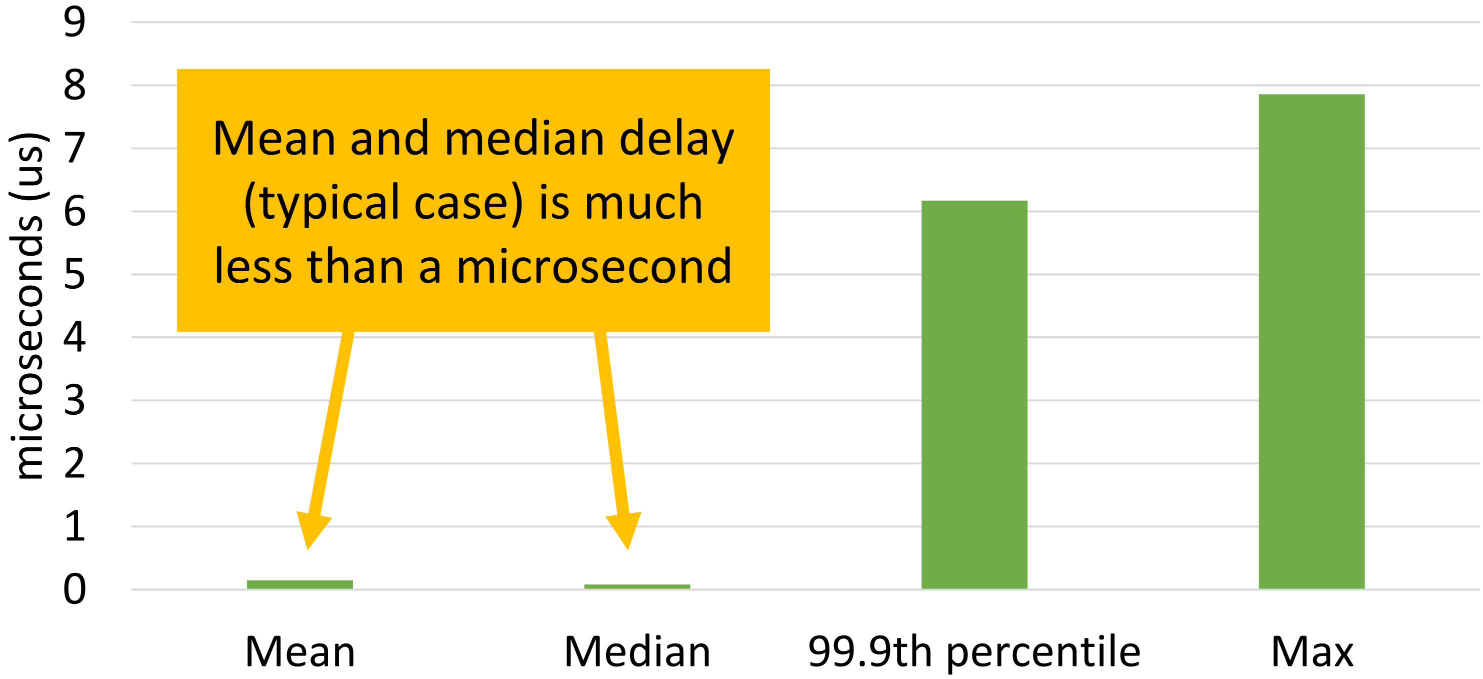
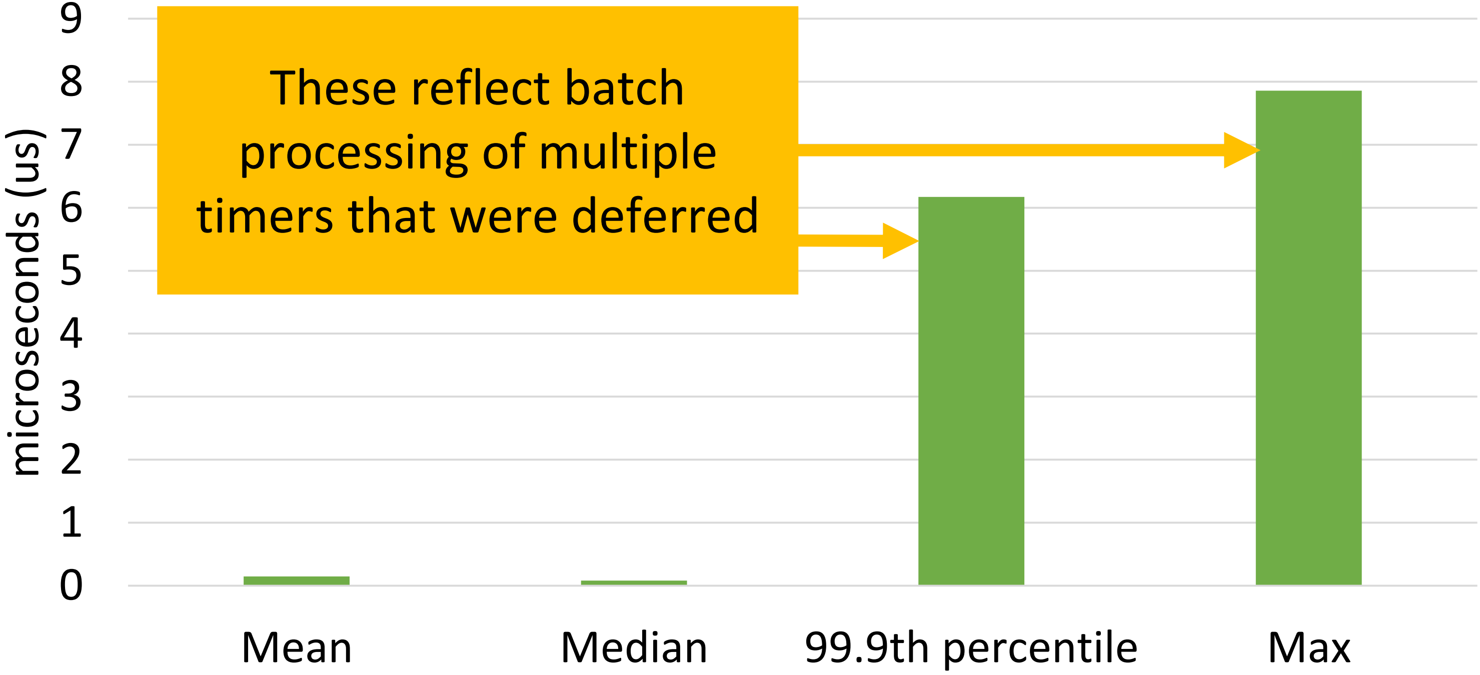


Mean and median delay (typical case) is much less than a microsecond

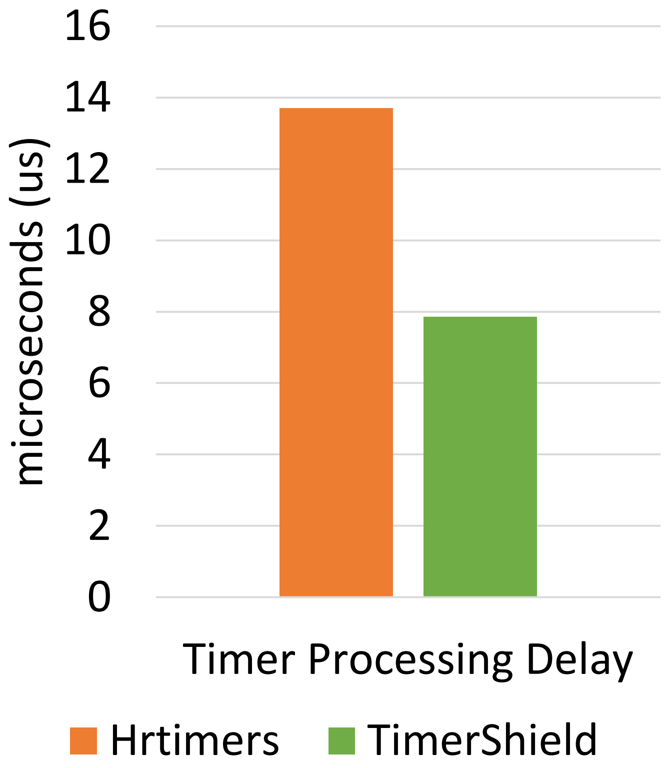
Additional Context-Switch Delay



These reflect batch processing of multiple timers that were deferred

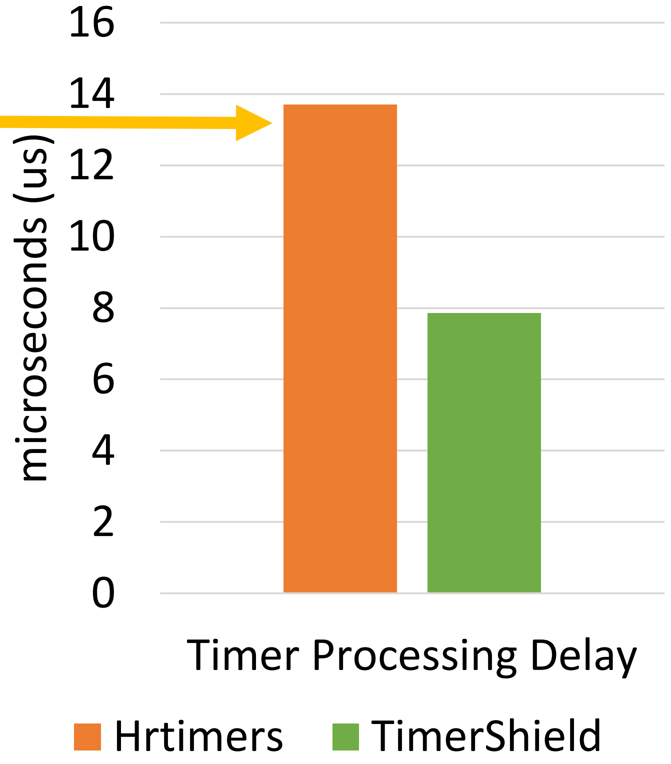
Timer Processing Delay

We measured the **worst-case increase** in HP task response time under `hrtimers` with the same experimental setup



Batch Processing is Better!

`hrtimers` takes longer due to the **repetitive switches to interrupt context!**



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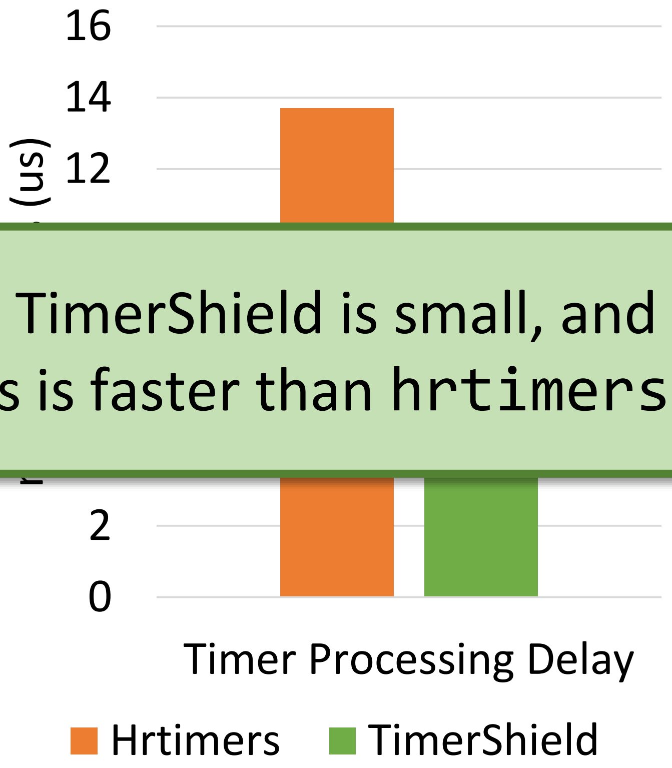


Context-switch delay due to TimerShield is small, and its batch processing of timers is faster than `hrtimers`

Evaluation

How effective is TimerShield at isolating high-priority tasks from low-priority timer interrupts?

How is the context-switch duration affected?

How costly are the new queueing data structures?

Data-Structure Overheads

The **worst case** for TimerShield’s data-structures is with a **single timer**, because each operation modifies the segment tree

Note: Results for a scenario with a timer-heavy load can be found in the paper.

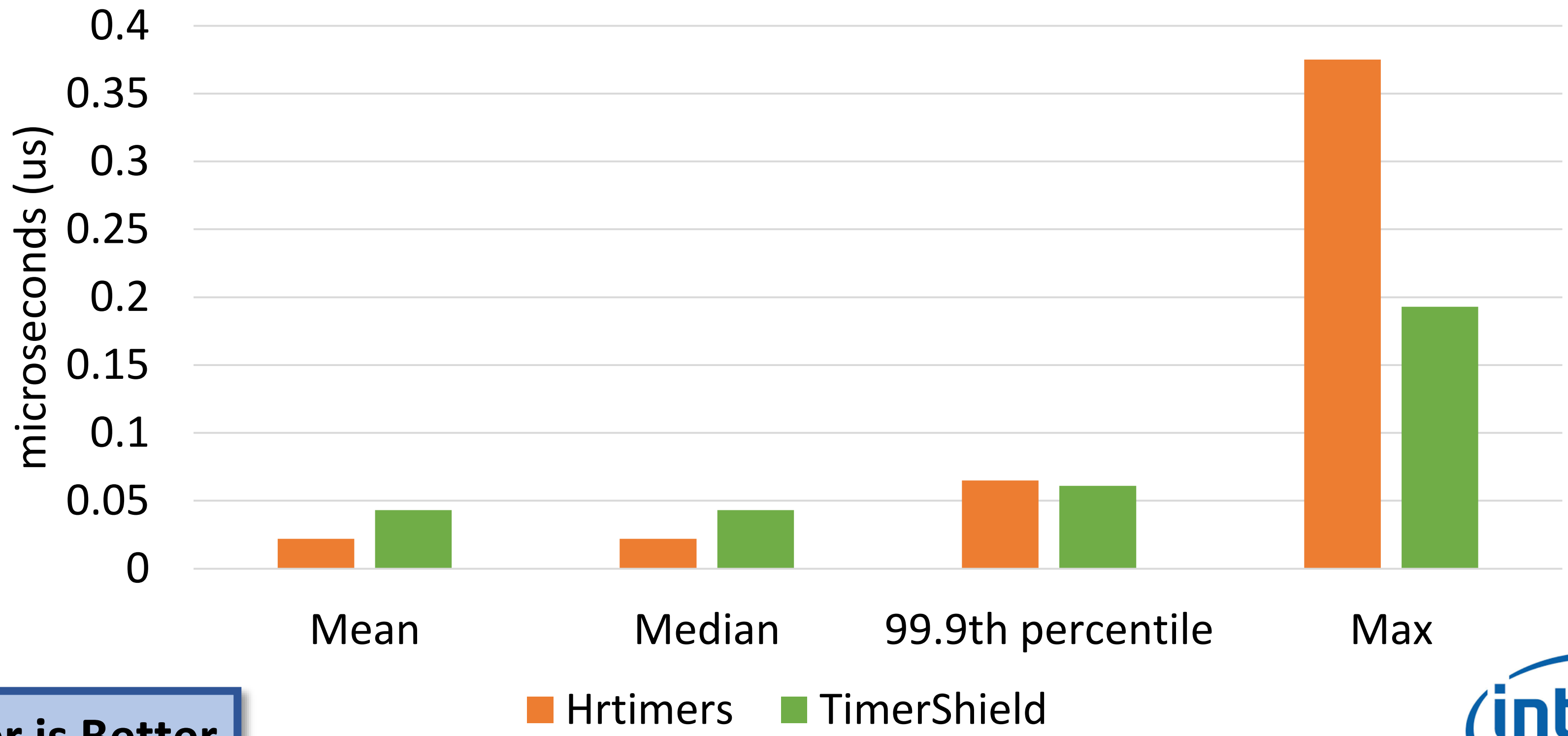
Data-Structure Overheads

The **worst case** for TimerShield’s data-structures is with a **single timer**, because each operation modifies the segment tree

We measured the timer **enqueue and dequeue cost** on both subsystems for this setup

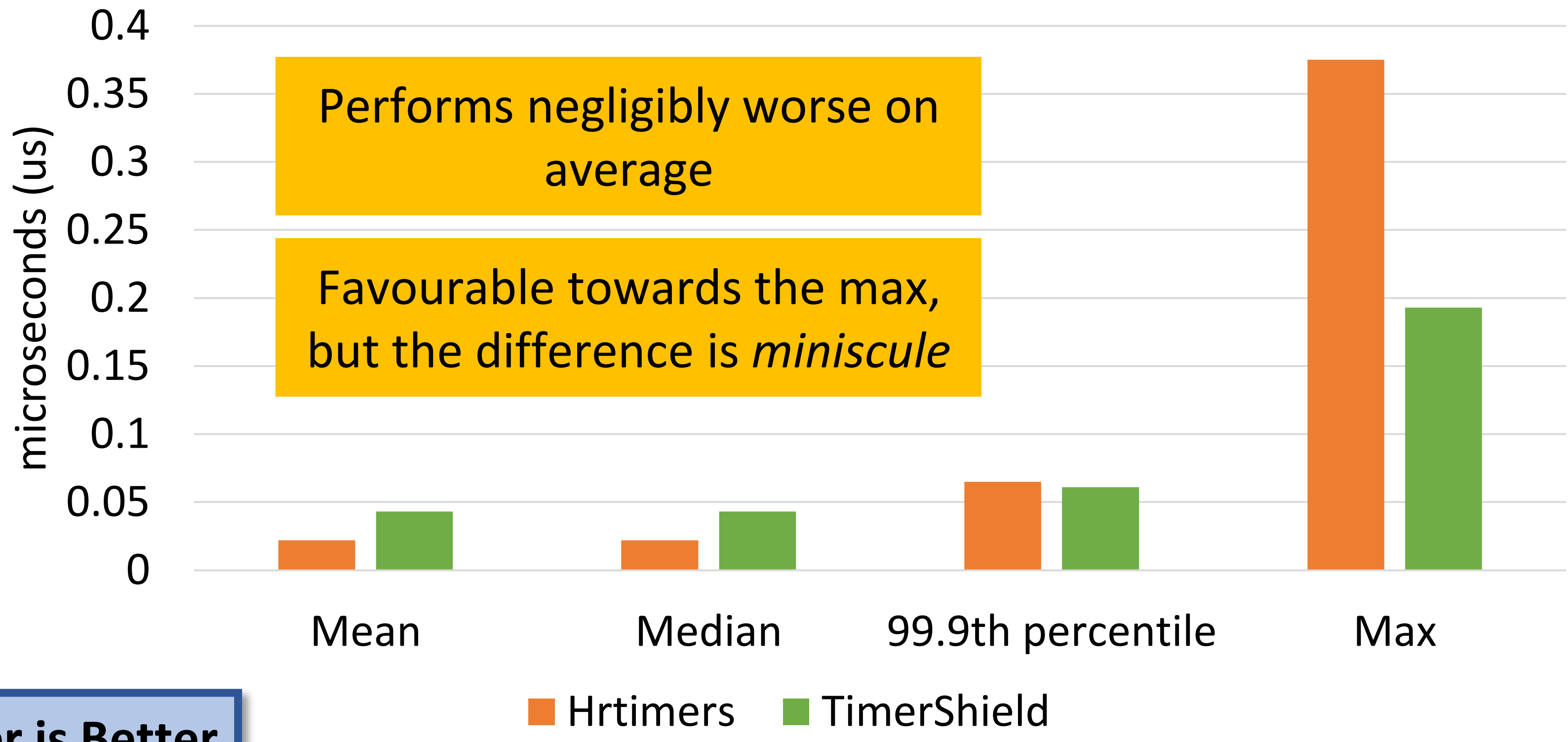
Note: Results for a scenario with a timer-heavy load can be found in the paper.

Timer Enqueue Cost



Lower is Better

Timer Enqueue Cost

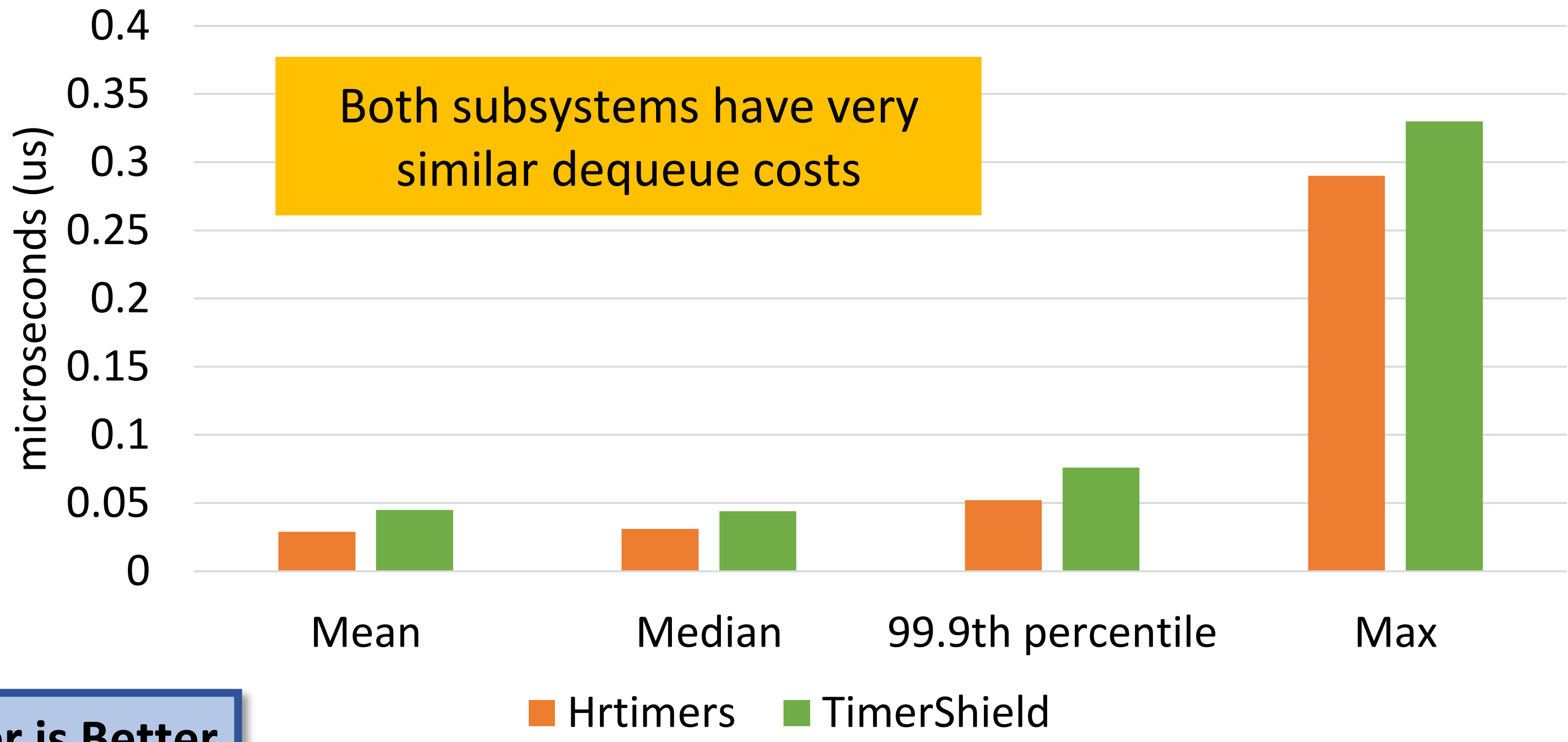


Performs negligibly worse on average

Favourable towards the max, but the difference is *miniscule*

Lower is Better

Timer Dequeue Cost



Both subsystems have very similar dequeue costs

Lower is Better

Evaluation Summary

Impossible for high-priority tasks to be interrupted by low-priority timers under TimerShield

Note: Further experiments, including results for ARM, can be found in the paper.

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Additional **context-switch delay is small**, and batch **timer processing is faster** with TimerShield

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Evaluation Summary

Impossible for high-priority tasks to be interrupted by low-priority timers under TimerShield

Additional **context-switch delay is small**, and batch **timer processing is faster** with TimerShield

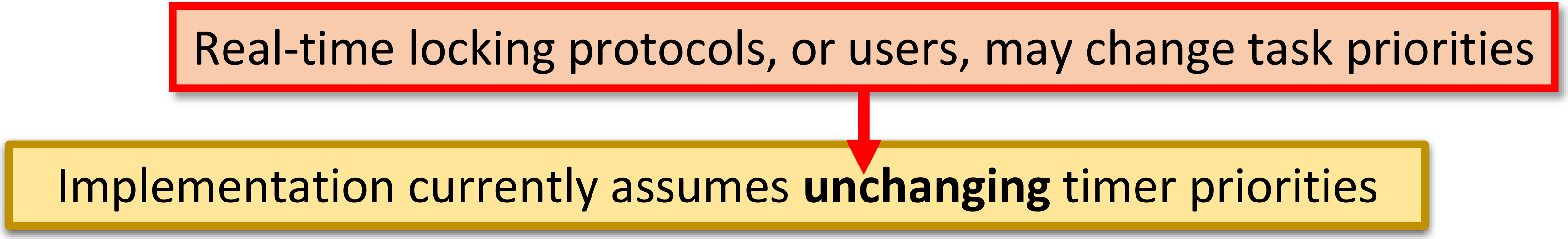
TimerShield’s data structure costs are **comparable to hrtimers**

Note: Further experiments, including results for ARM, can be found in the paper.

Dynamic Timer Priorities

Implementation currently assumes unchanging timer priorities

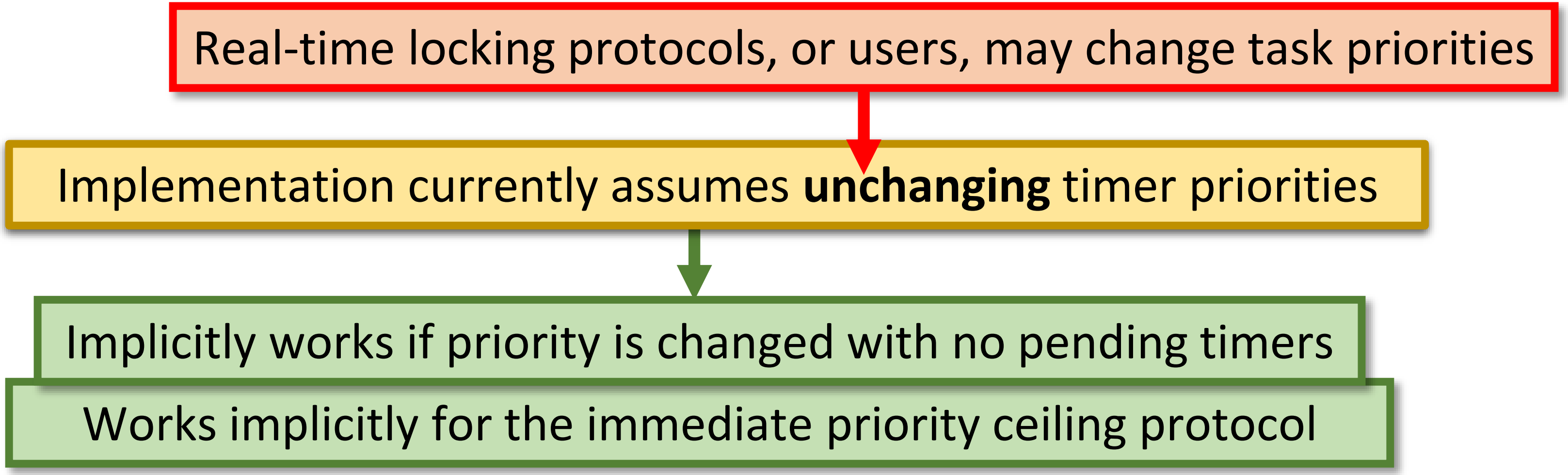
Dynamic Timer Priorities



Real-time locking protocols, or users, may change task priorities

Implementation currently assumes **unchanging** timer priorities

Dynamic Timer Priorities



Real-time locking protocols, or users, may change task priorities

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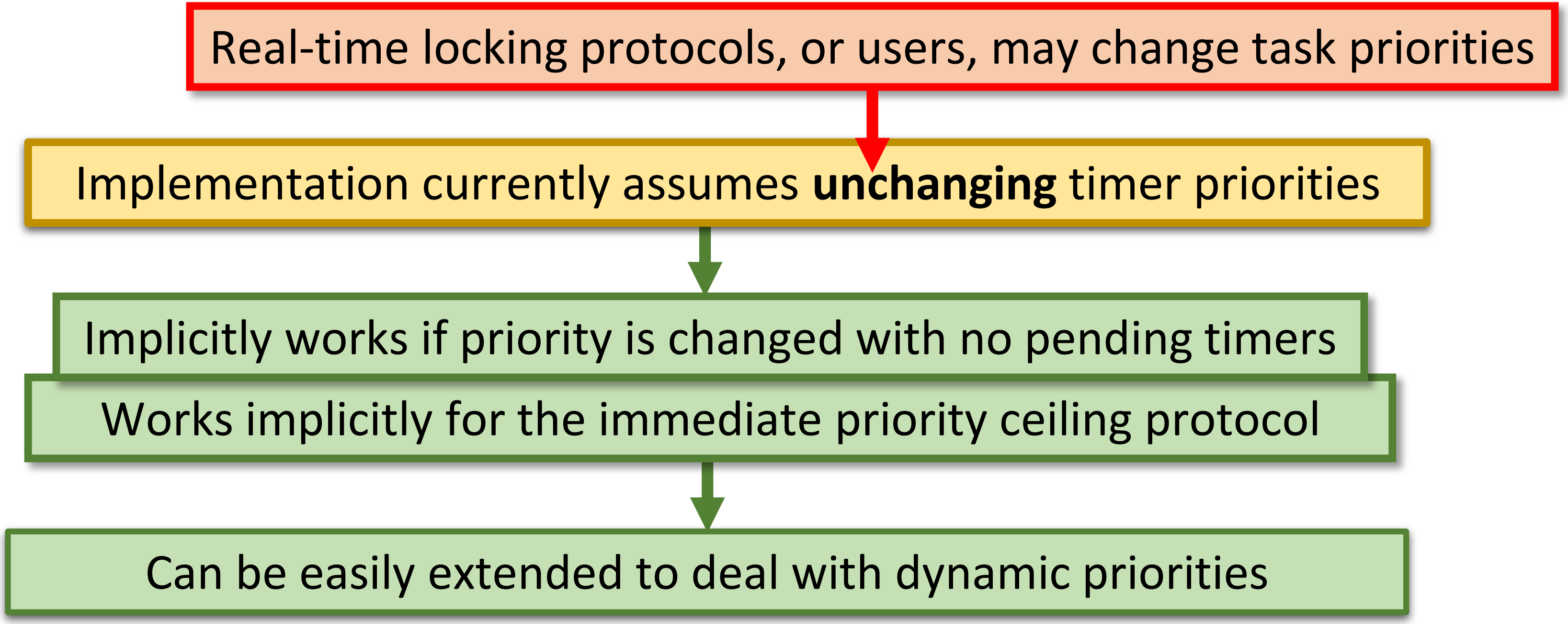
Implicitly works if priority is changed with no pending timers

Works implicitly for the immediate priority ceiling protocol

Dynamic Timer Priorities



Real-time locking protocols, or users, may change task priorities

Implementation currently assumes **unchanging** timer priorities

Implicitly works if priority is changed with no pending timers

Works implicitly for the immediate priority ceiling protocol

Can be easily extended to deal with dynamic priorities

Future Work

Support for Earliest Deadline First (EDF) schedulers

Applying similar techniques to other, multiplexed interrupt sources such as network packet interrupts

Summary

FP scheduling on uniprocessor/partitioned multiprocessors

Summary

Low-priority timer interrupts have a **significant negative impact on high-priority task execution**

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Existing high-resolution timer subsystems, such as Linux `hrtimers`, **are not priority aware**

FP scheduling on uniprocessor/partitioned multiprocessors

Summary

Low-priority timer interrupts have a **significant negative impact on high-priority task execution**

Existing high-resolution timer subsystems, such as Linux `hrtimers`, **are not priority aware**

TimerShield completely avoids low-priority **timer interrupt interference** with **small overheads**

Thank you!

Source Code

https://people.mpi-sws.org/~bbb/papers/details/rtas17p/

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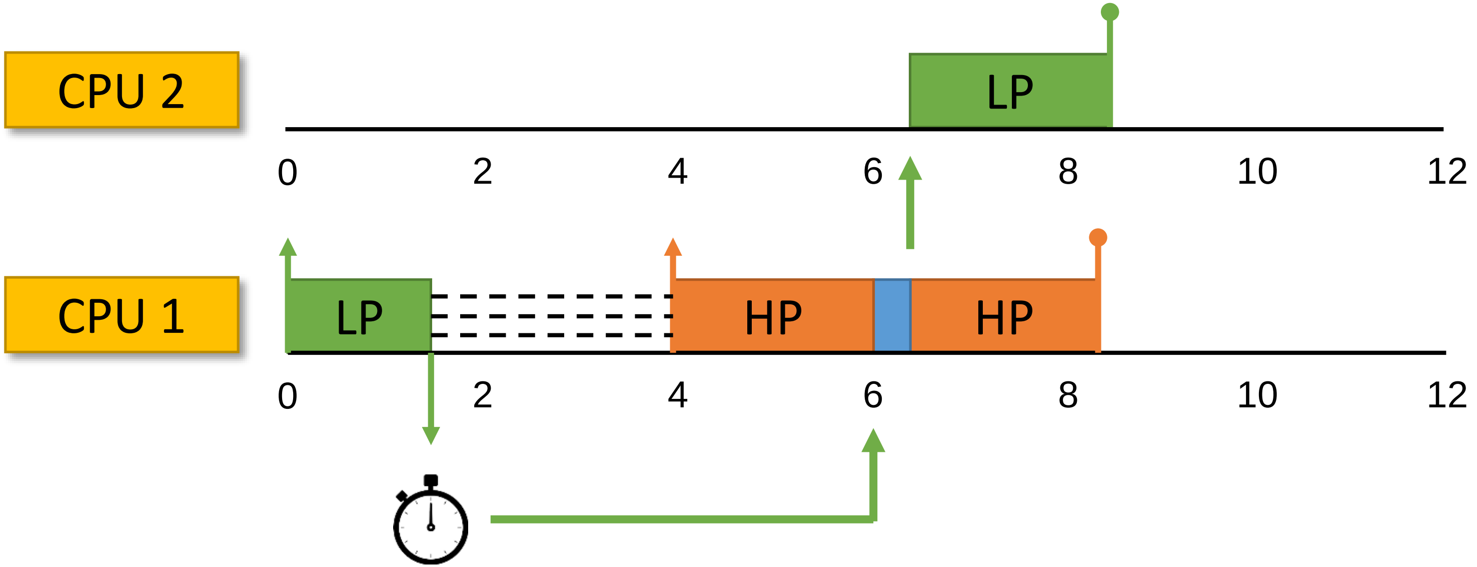
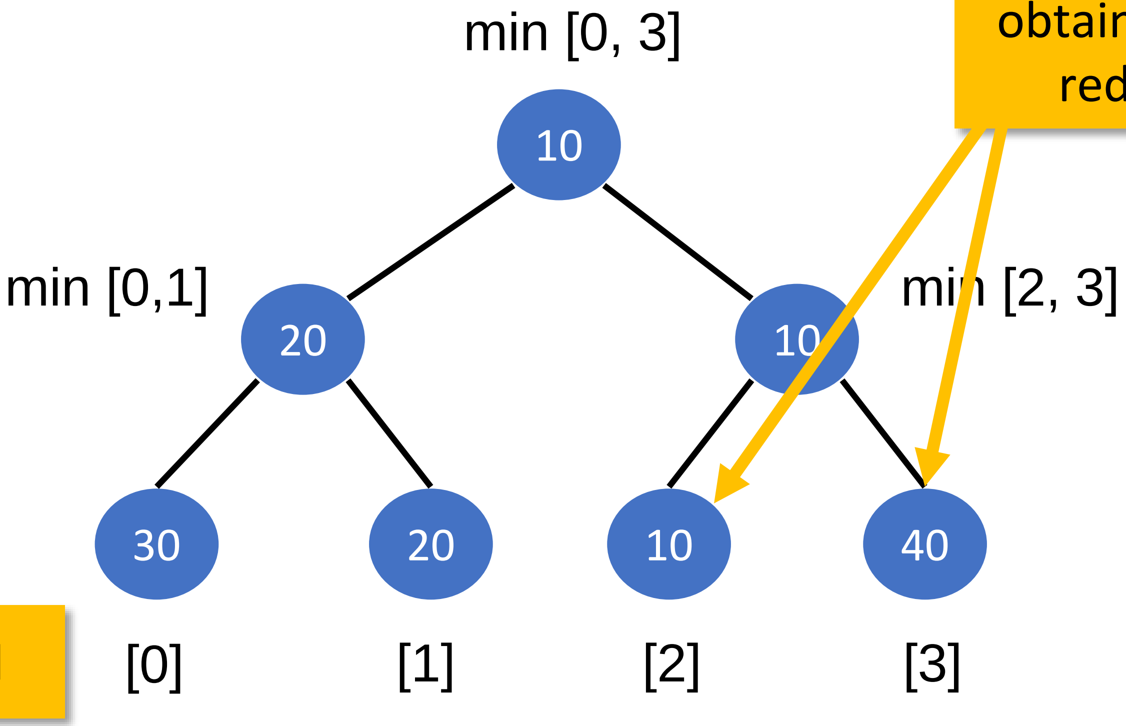
Appendix

Why Not Global Scheduling?

Not deferring the wakeup of a low-priority task might allow it to execute on a different, possibly idle CPU



Segment Tree



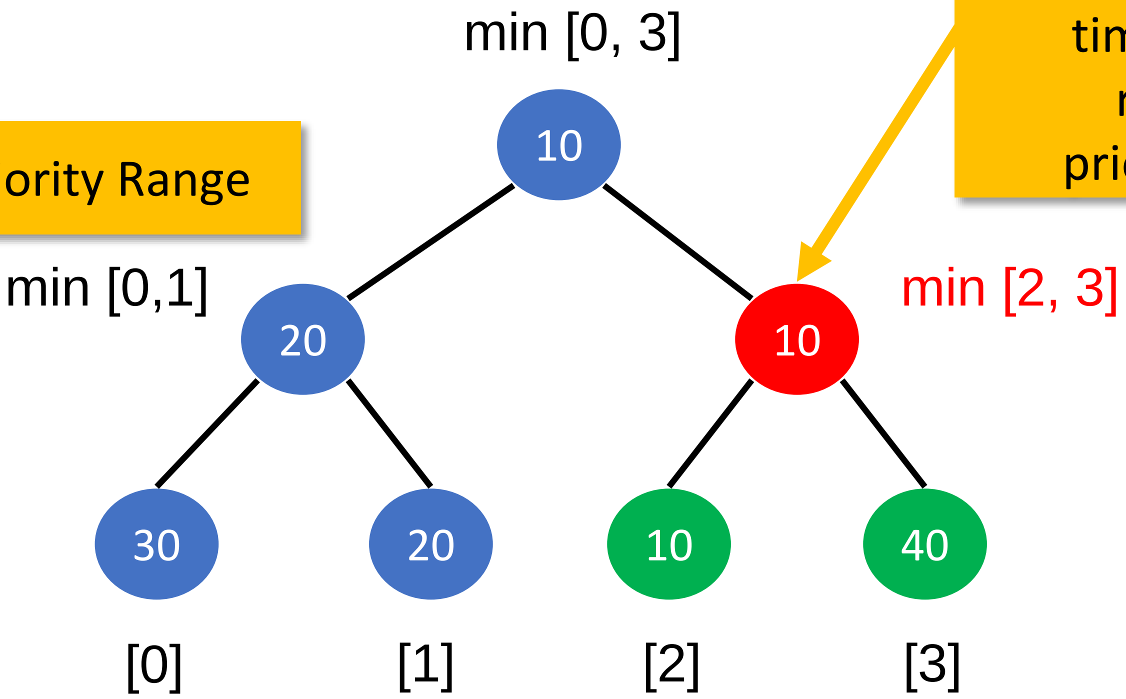
Leaf nodes correspond to the earliest timer obtained from each red-black tree

Priority Level

Segment Tree

Parent nodes store the minimum of their child nodes, and depict the earliest timer for the resulting priority range

Priority Range

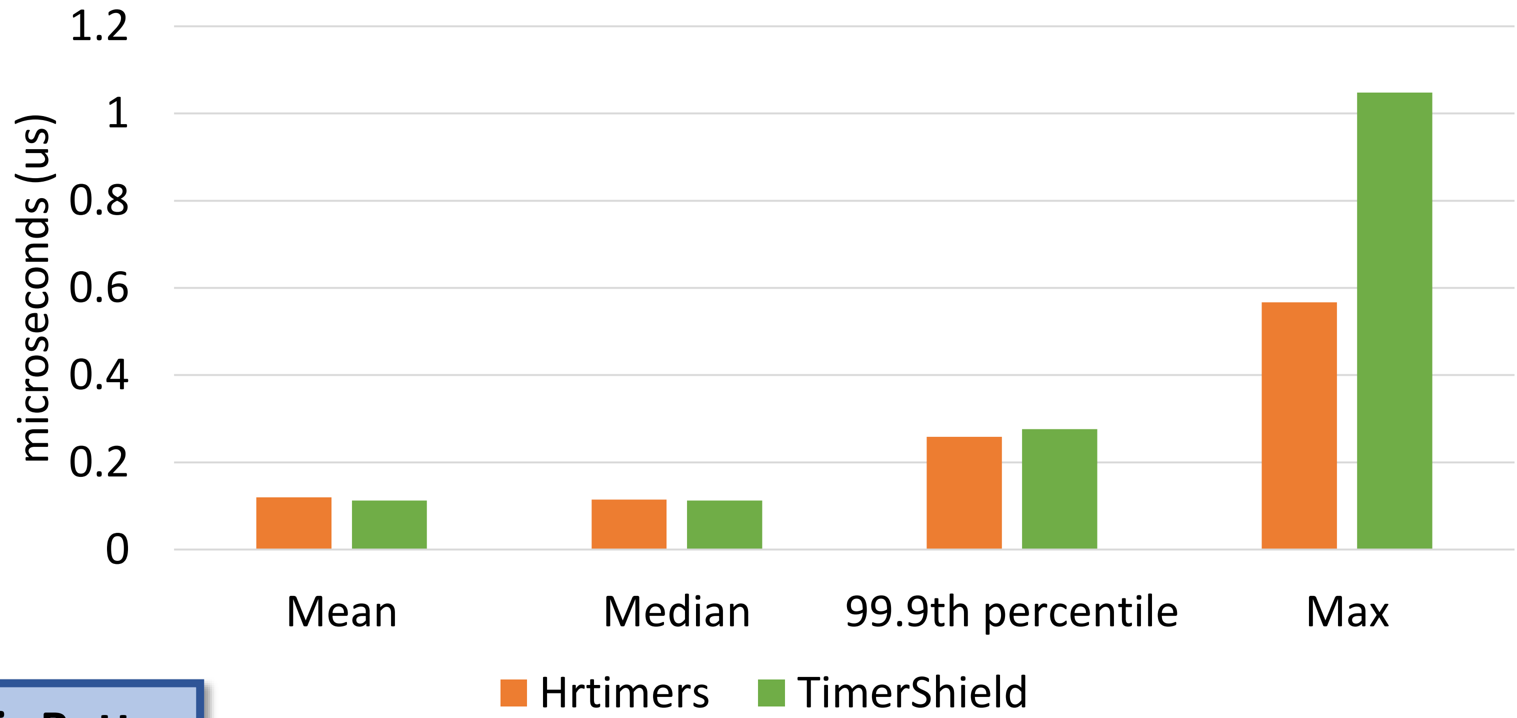


Code Size and Memory

How big is TimerShield code, and what are it’s memory requirements?

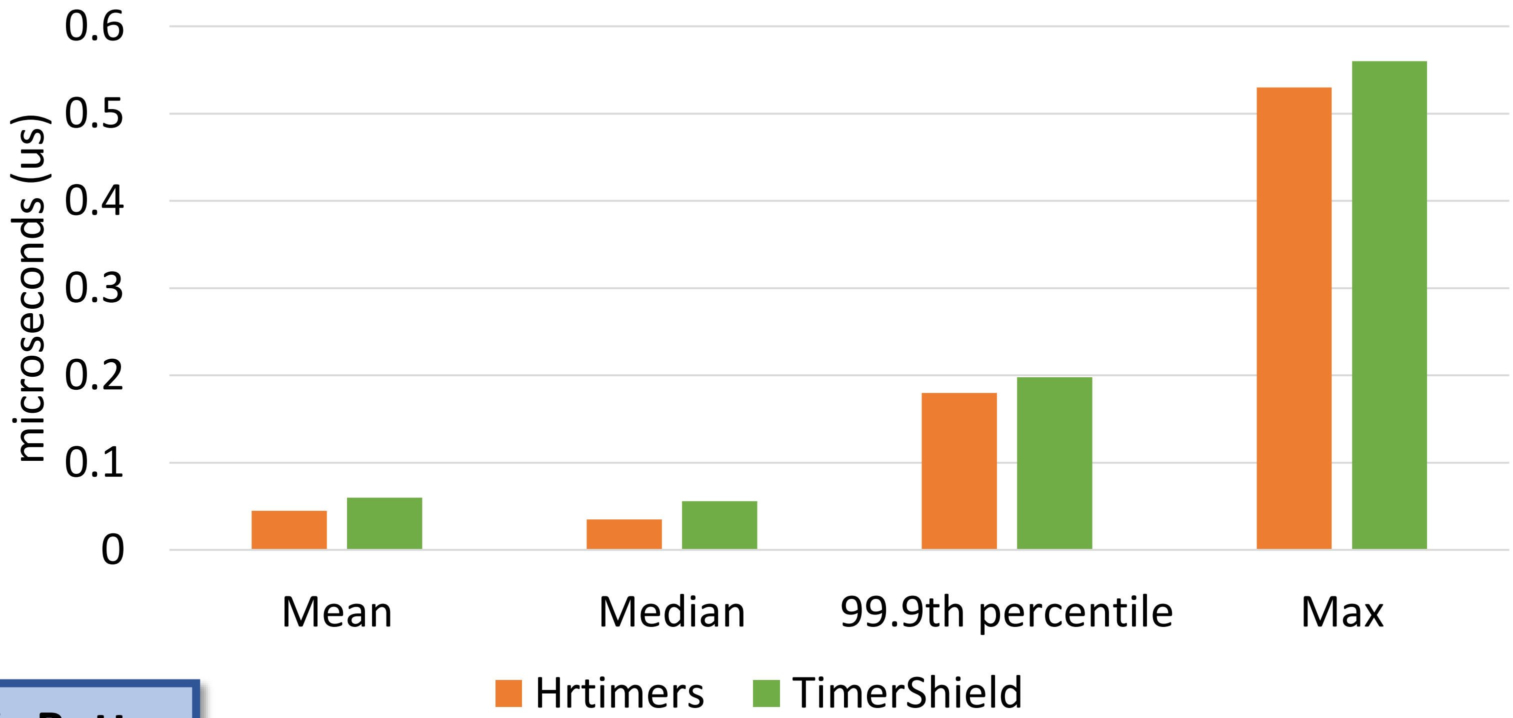
Increase in text segment	**2 KiB**
Increase in data segment	**35 KiB per core**

Timer Enqueue Cost (timer-heavy)



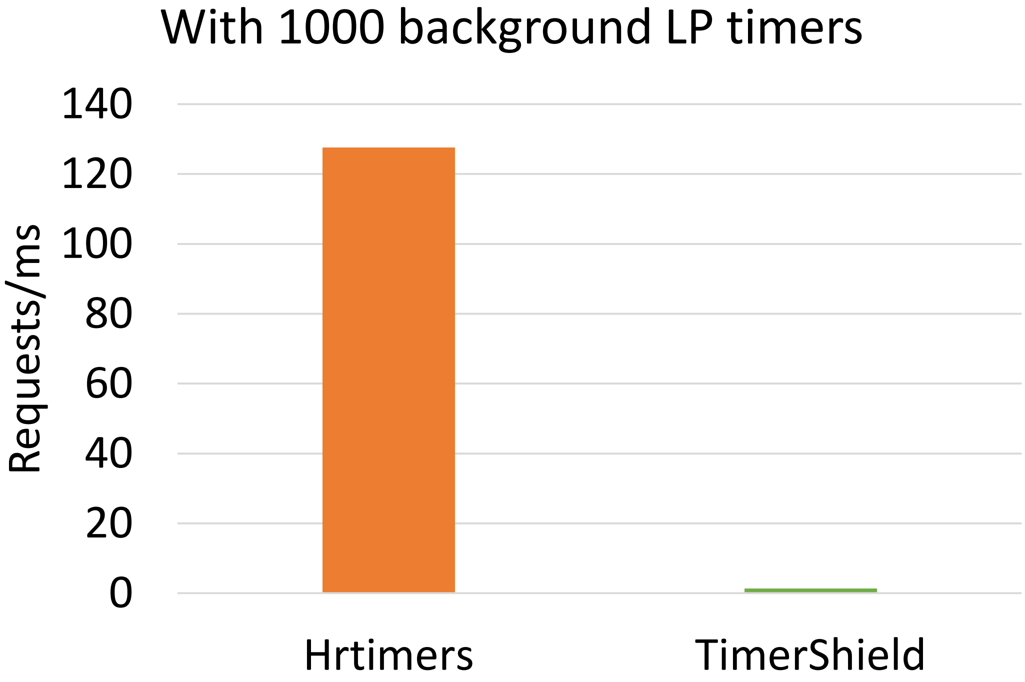
Lower is Better

Timer Dequeue Cost (timer-heavy)



Lower is Better

HP Task Throughput Reduction



Lower is Better

Idle Throughput: 7044.4 requests/ms