On the Implementation of Global Real-Time Schedulers

RTSS'09, Washington, DC
December 3, 2009

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and James H. Anderson

The University of North Carolina at Chapel Hill

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UNC's Implementation Studies (I)

Calandrino et al. (2006)

➡ Are commonly-studied RT schedulers **implementable**?

➡ In Linux on common hardware platforms?

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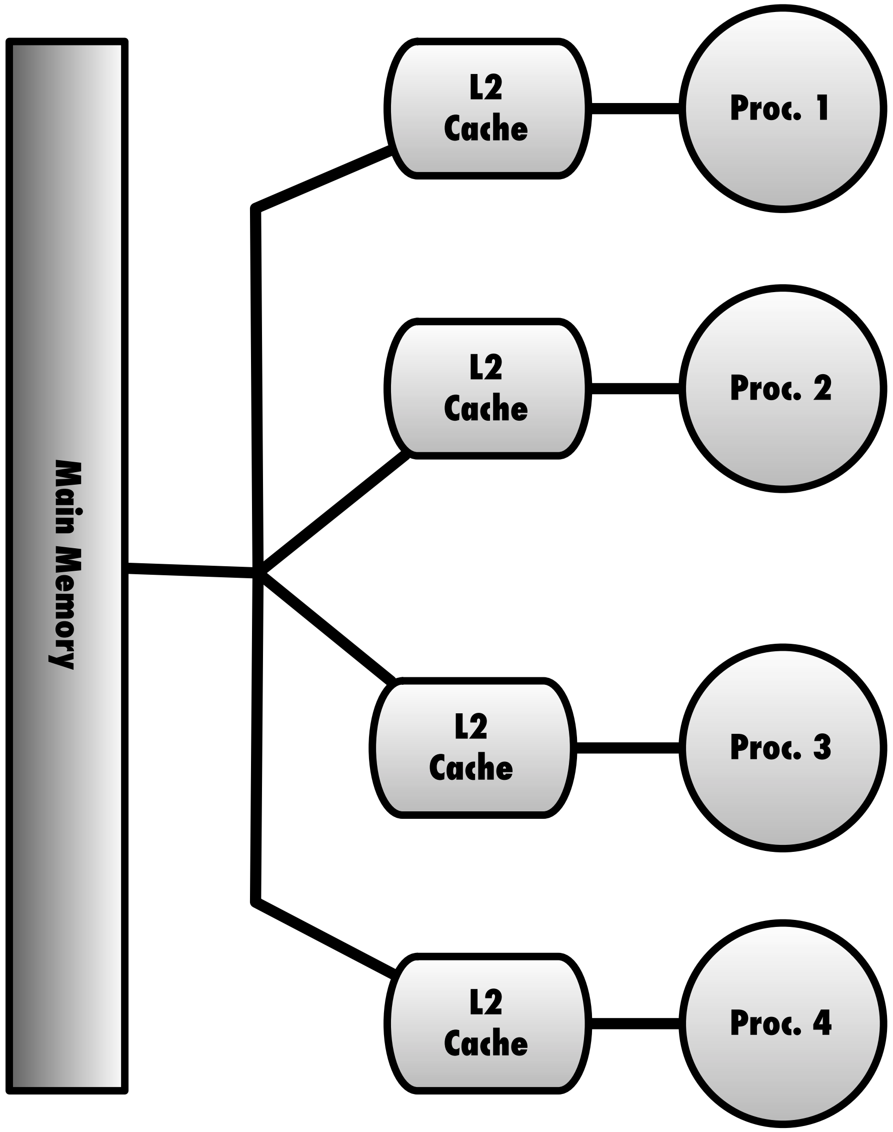

Intel 4x 2.7 GHz Xeon SMP

(few, fast processors; private caches)

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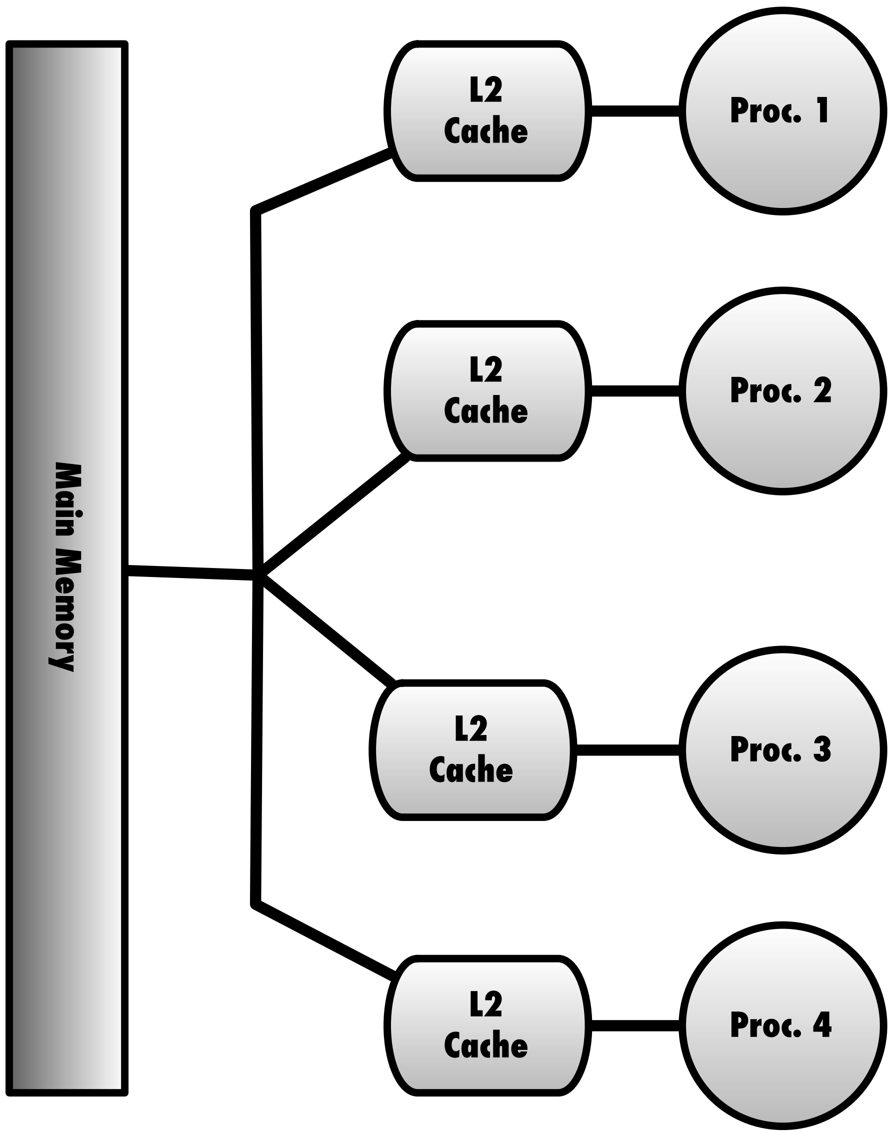

partitioned EDF — **P-EDF**

2 x global EDF — **G-NP-EDF**, **G-EDF**

2 x PFAIR — **PD²**, **S-PD²**

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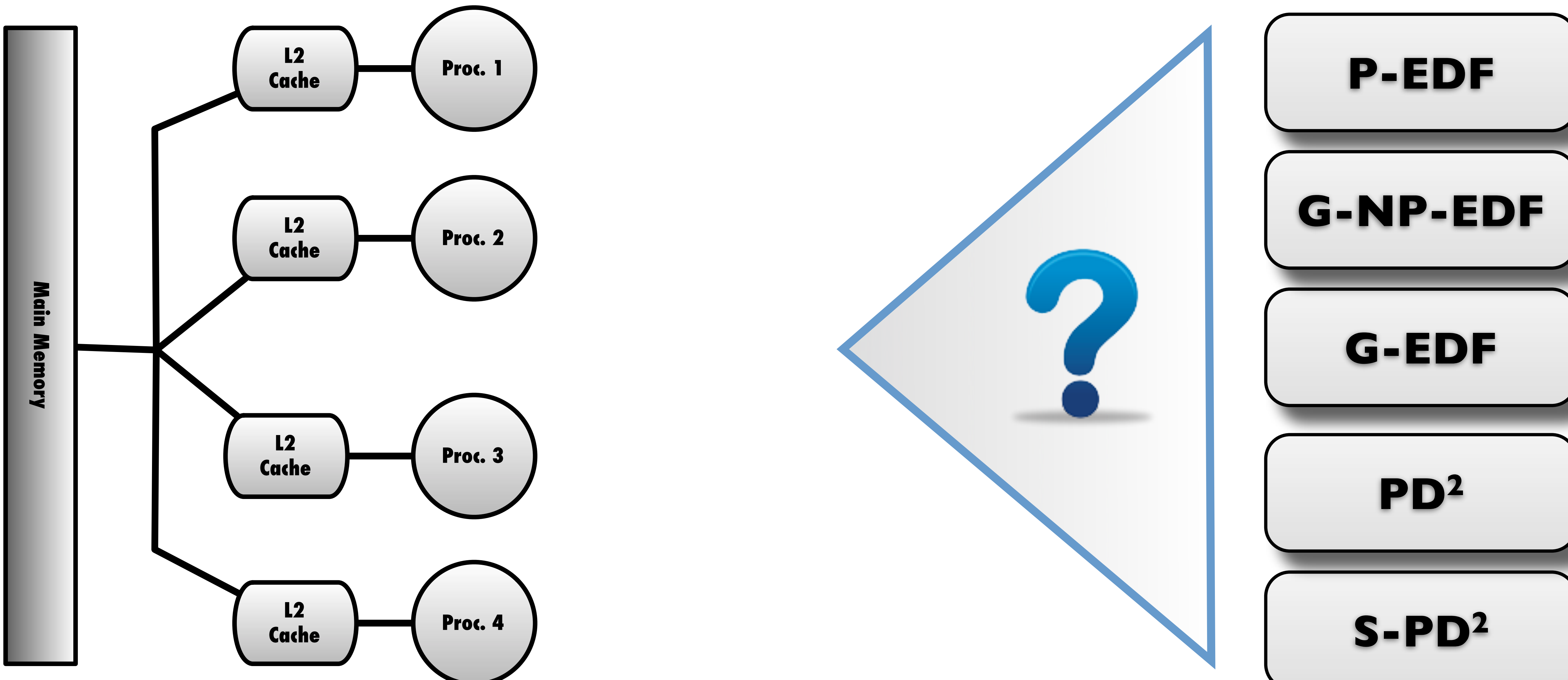
UNC's Implementation Studies (I)

"for each tested scheme, scenarios exist in which it is a viable choice"

Calandrino

- ➡ Are commo
- ➡ In Linux on common hardware platforms?



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➡ What if there are **many slow processors**?

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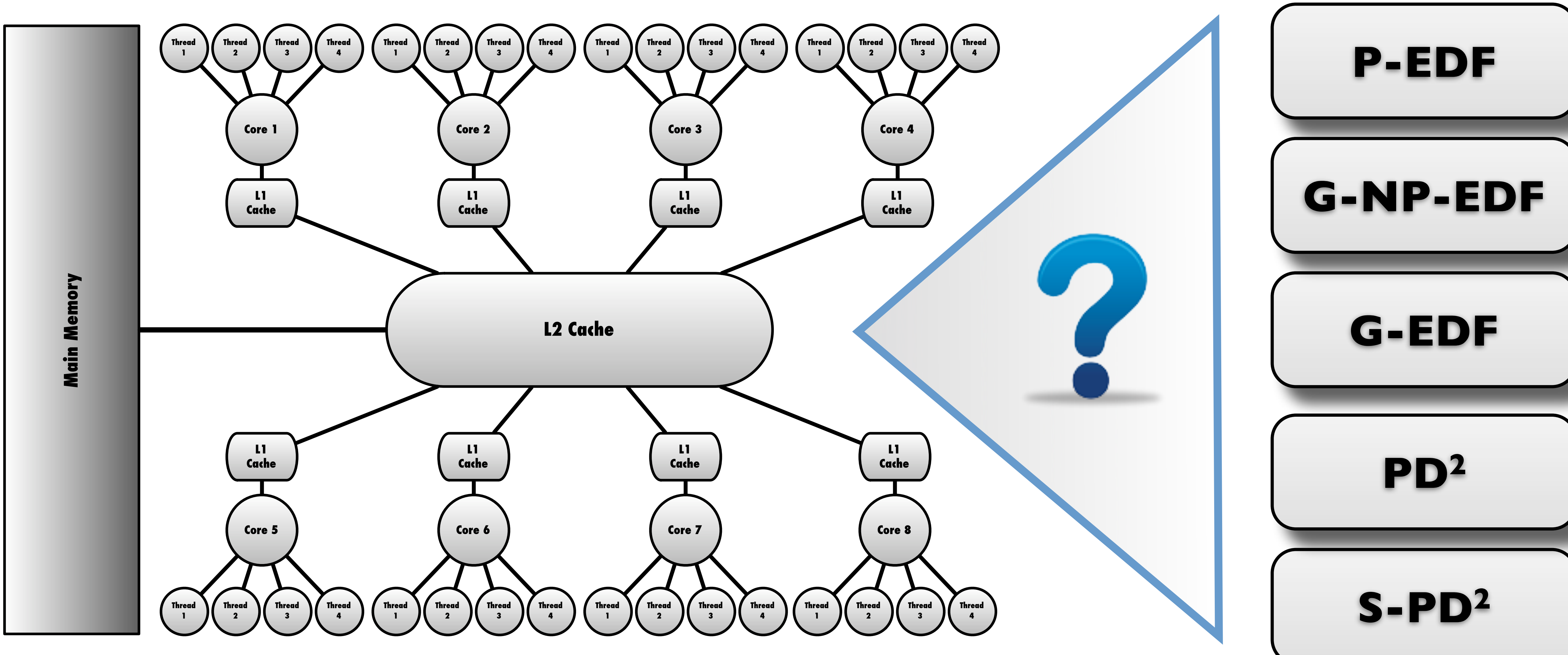
- ➡ What if there are **many slow processors**?
- ➡ Explored **scalability** of RT schedulers on a Sun Niagara.



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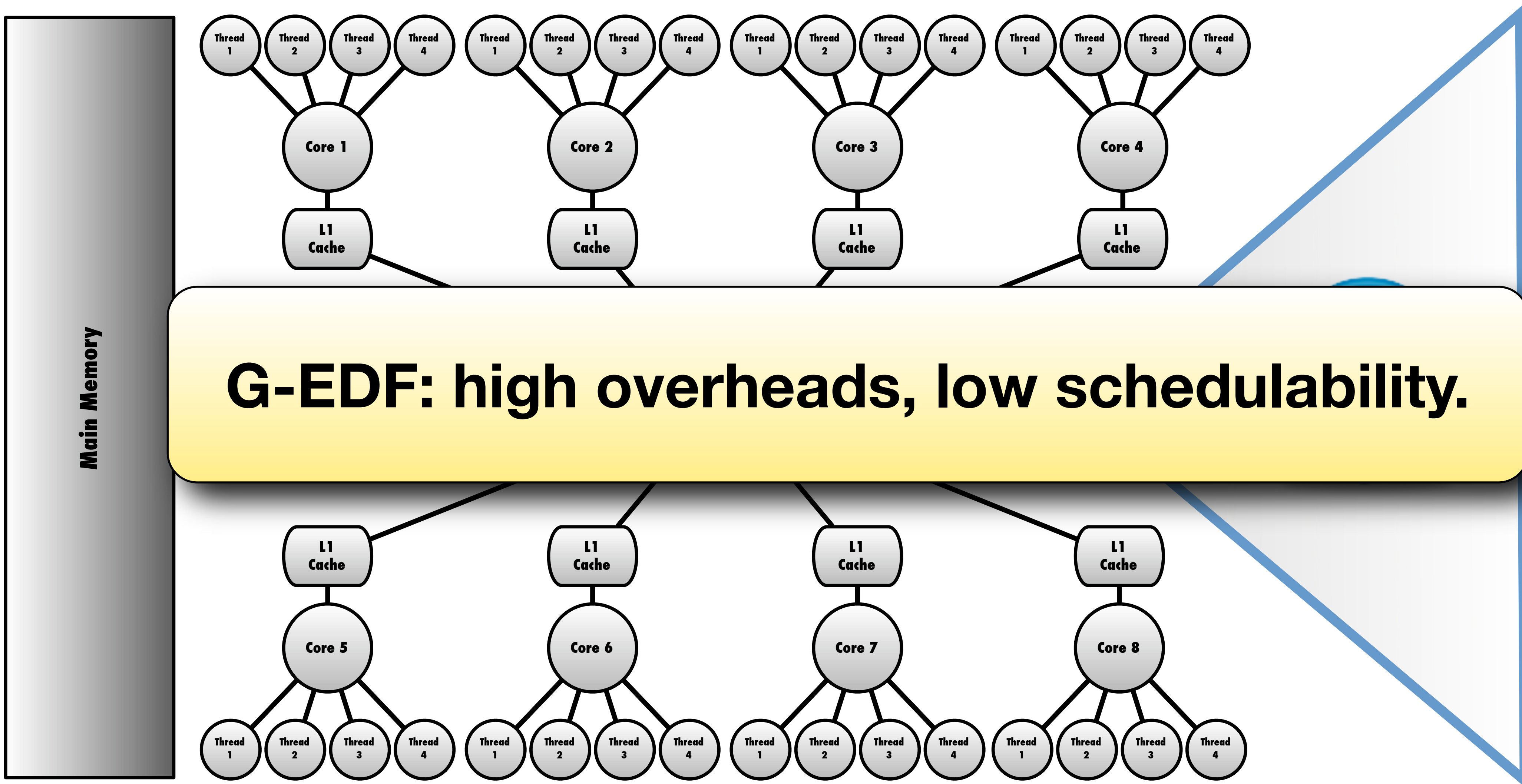

G-EDF: high overheads, low schedulability.

- **P-EDF**
- **G-NP-EDF**
- **G-EDF**
- **PD^2**
- **$S\text{-}PD^2$**

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This Study

How to implement global schedulers?

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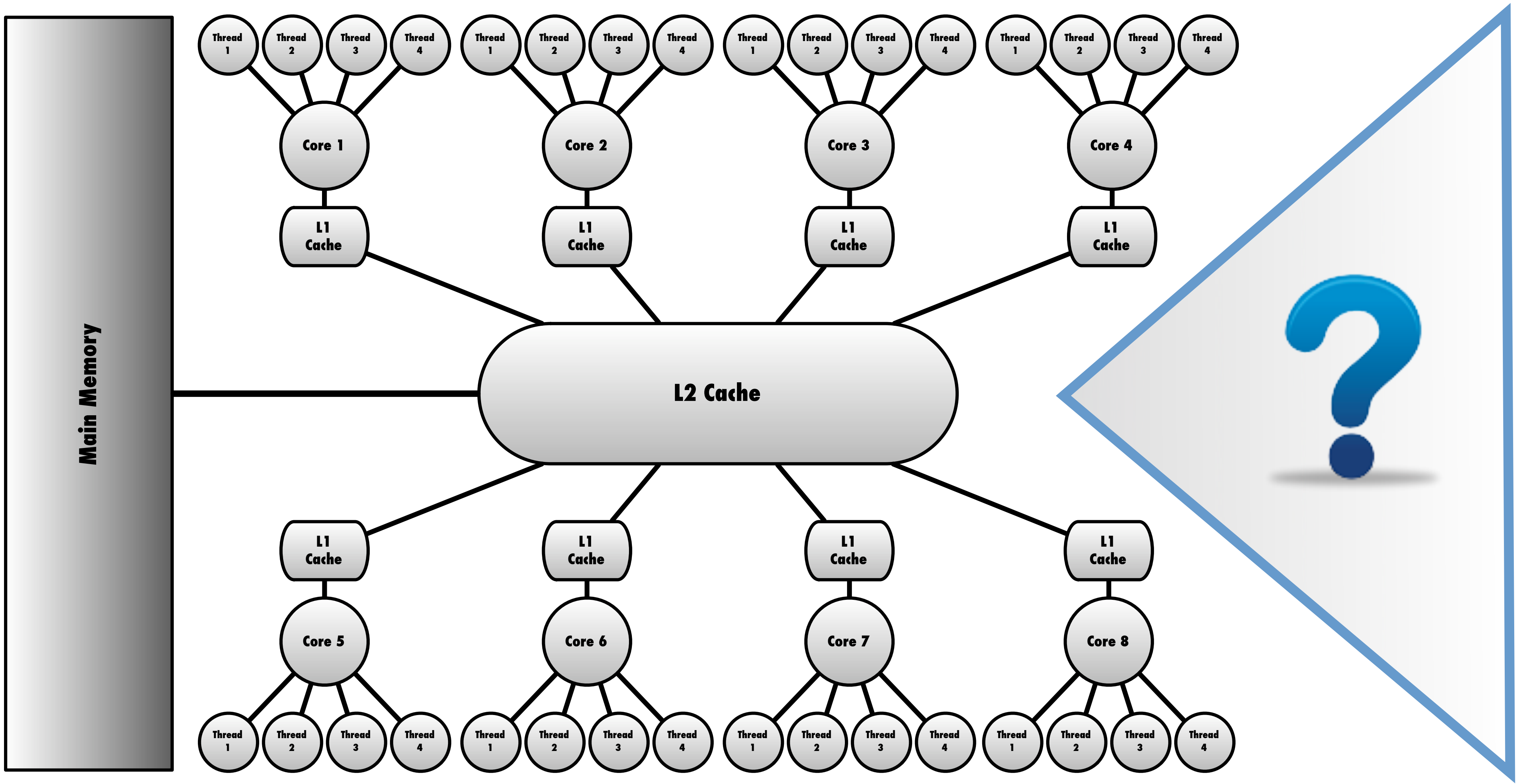
➡ Explore how **implementation tradeoffs** affect **schedulability**.



Instead of considering **one** implementation of several **different** scheduling algorithms…

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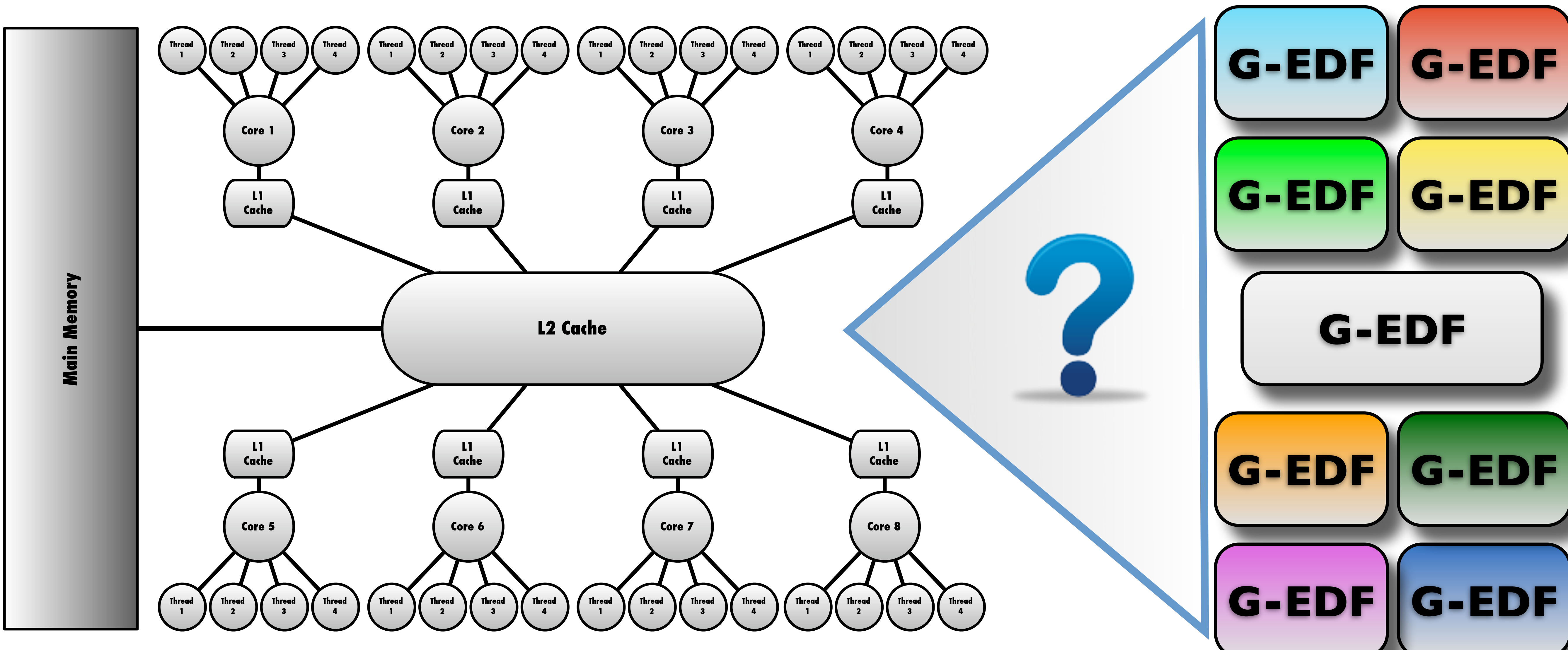
This Study

How to implement global schedulers?

➡ Explore how **implementation tradeoffs** affect **schedulability**.

➡ Case study: **nine G-EDF variants** on a Sun Niagara.



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Design Choices

Design Choices

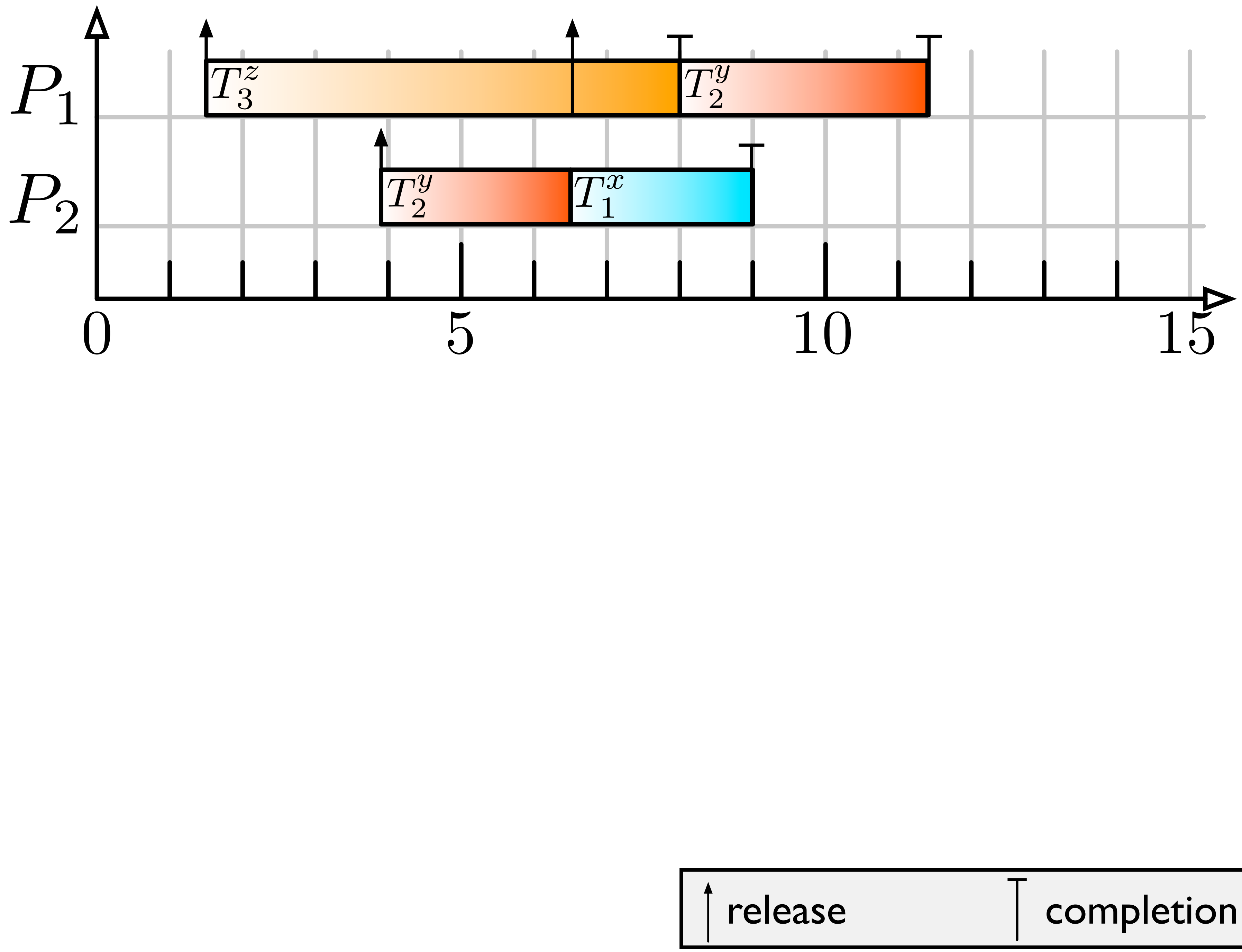
- ➡ When to schedule.
- ➡ Quantum alignment.
- ➡ How to handle interrupts.
- ➡ How to queue pending jobs.
- ➡ How to manage future releases.
- ➡ How to avoid unnecessary preemptions.

Scheduler Invocation

Scheduler Invocation

Event-Driven

- ➡ on job release
- ➡ on job completion
- ➡ preemptions occur immediately



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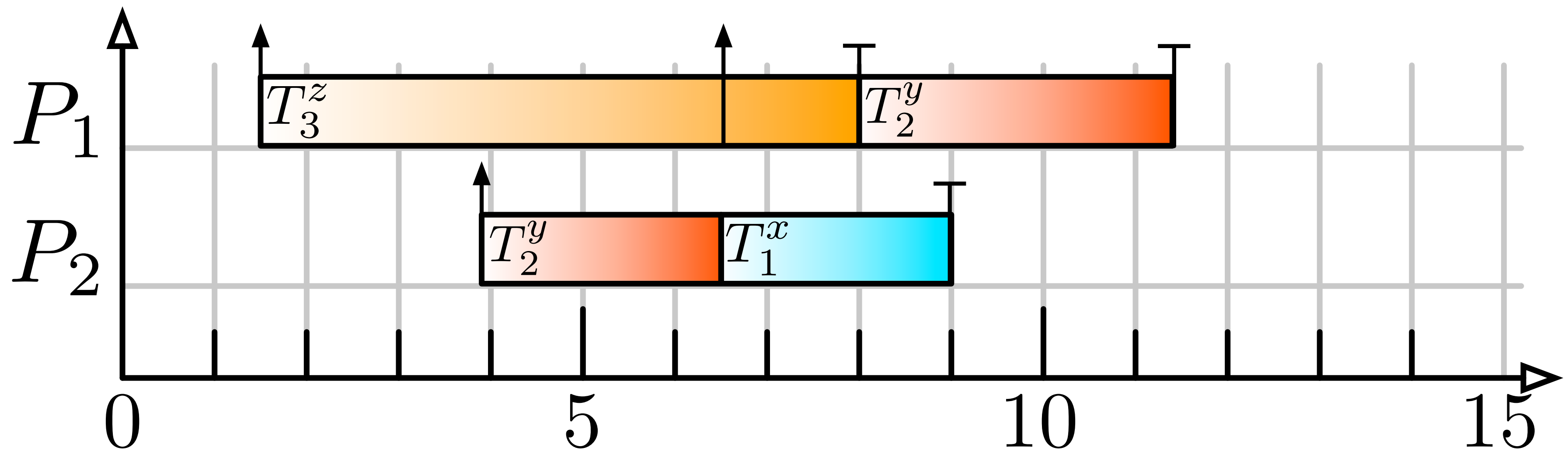
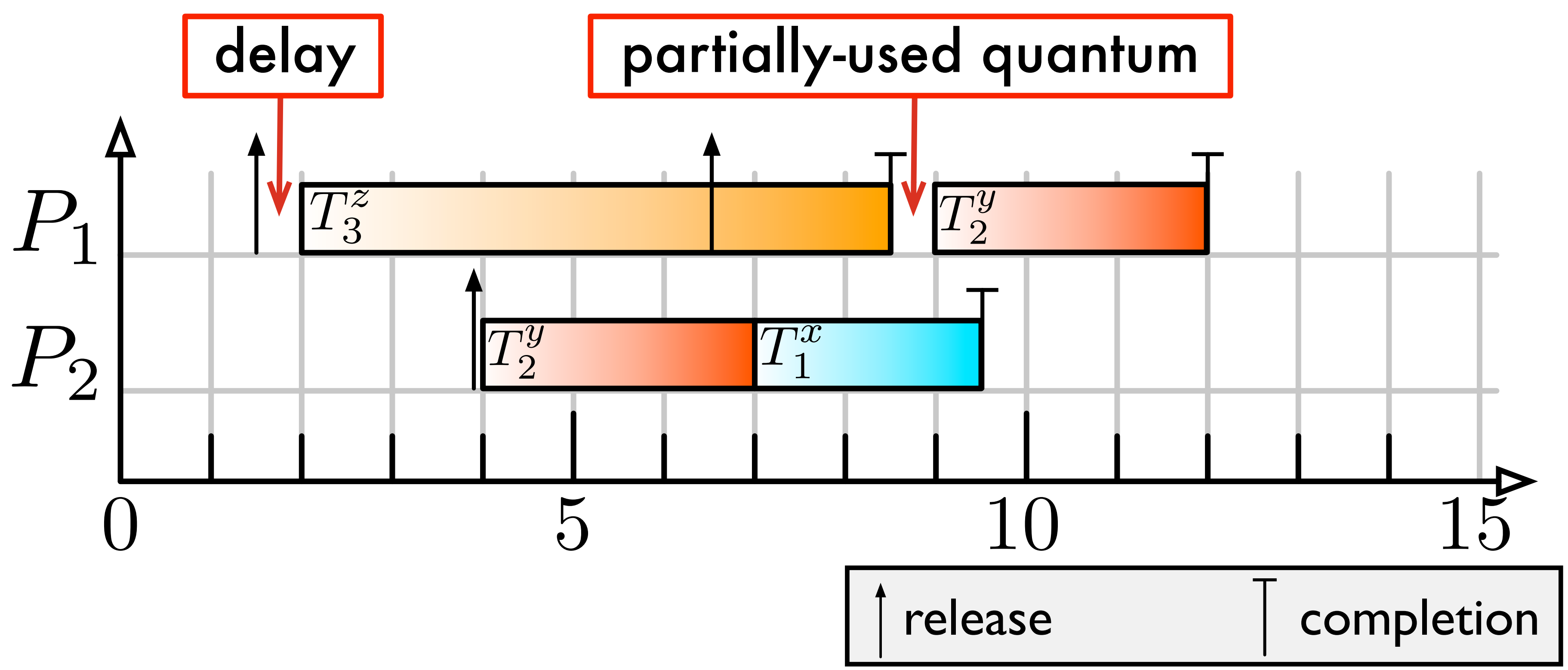


Quantum-Driven

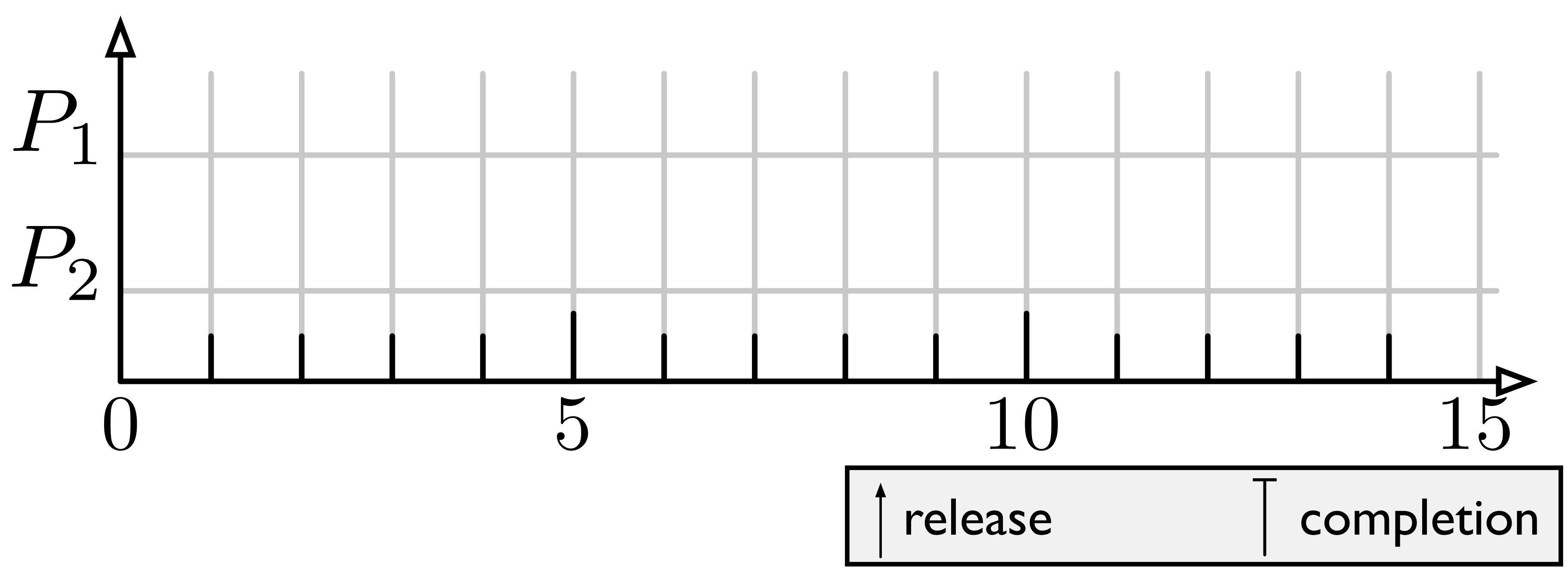
- ➡ on every timer tick
- ➡ easier to implement
- ➡ on release a job is just enqueued; scheduler is invoked at next tick



Quantum Alignment

Aligned

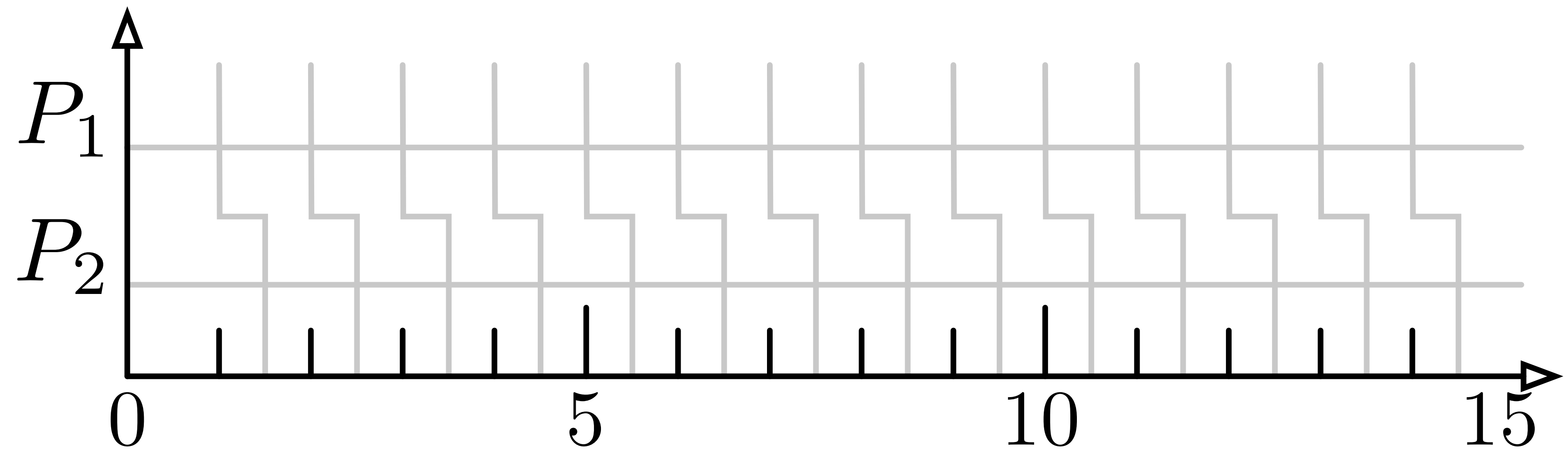
- ➡ Tick **synchronized** across processors.
- ➡ **Contention** at quantum boundary!



Quantum Alignment

Staggered

- ➡ Ticks spread out across quantum.
- ➡ **Reduced** bus and lock contention.
- ➡ Additional **latency**.



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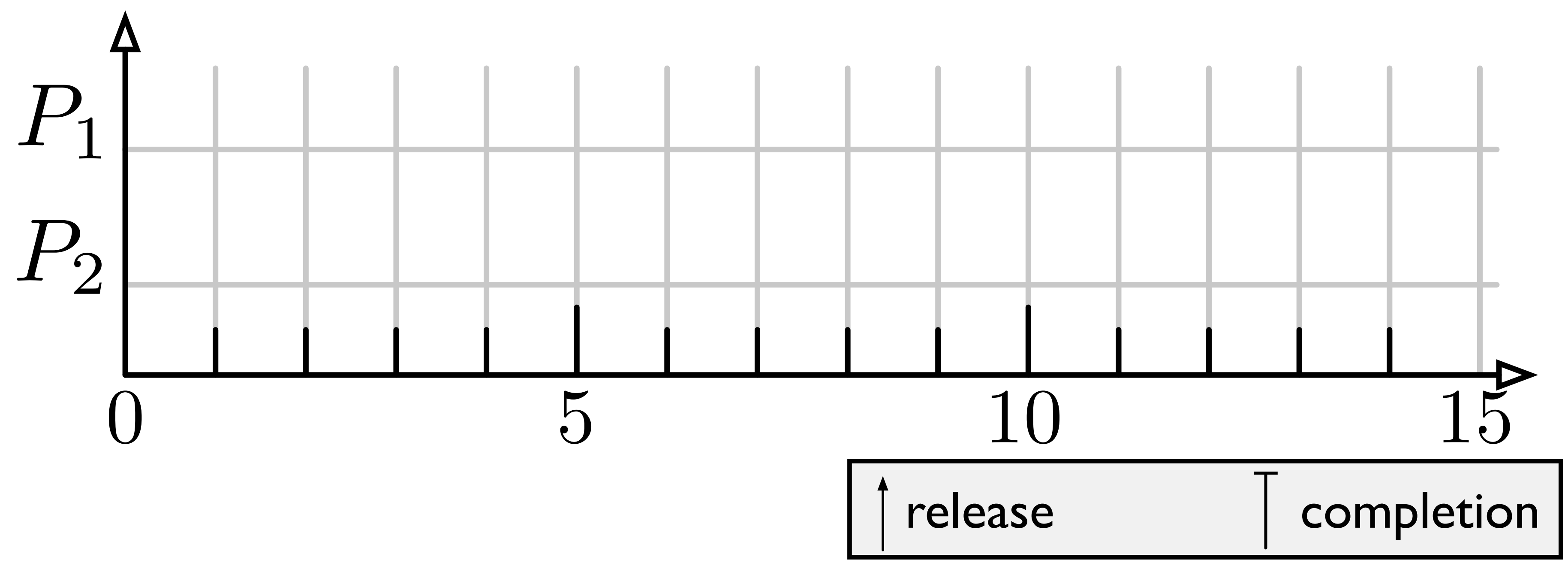

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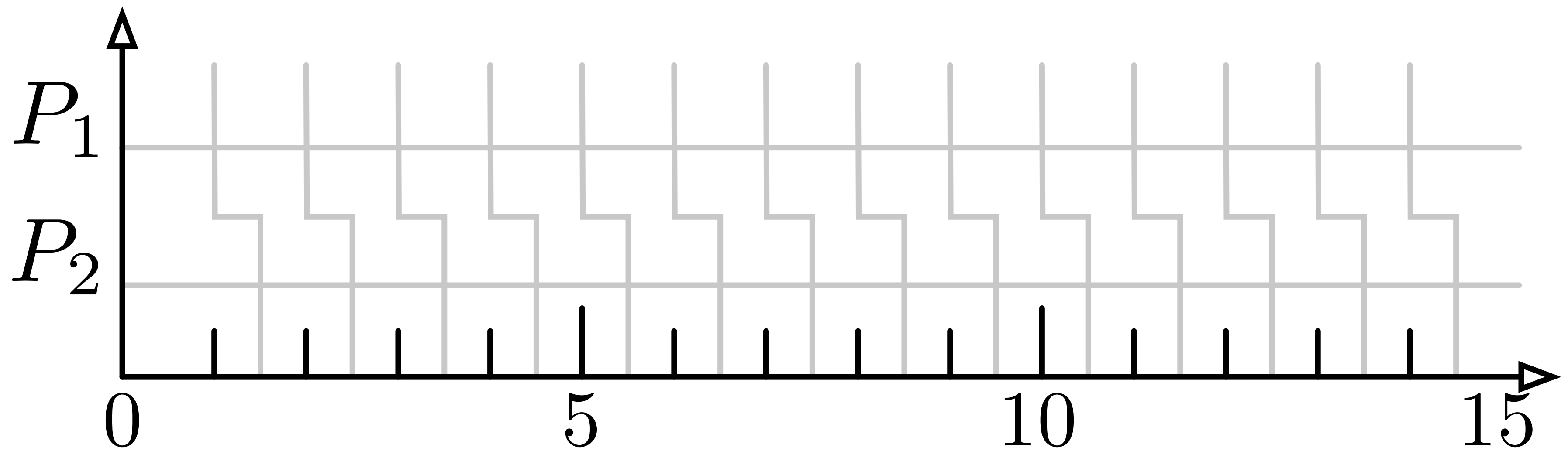

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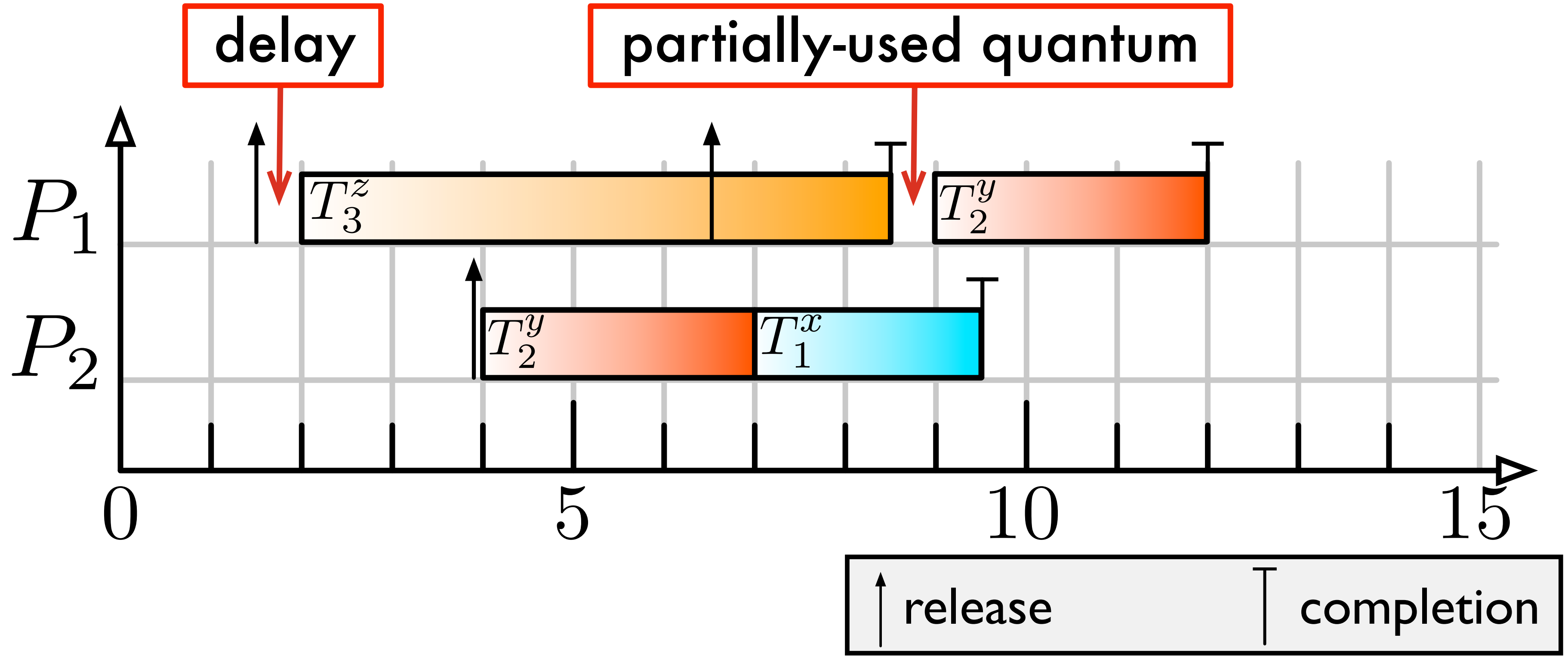

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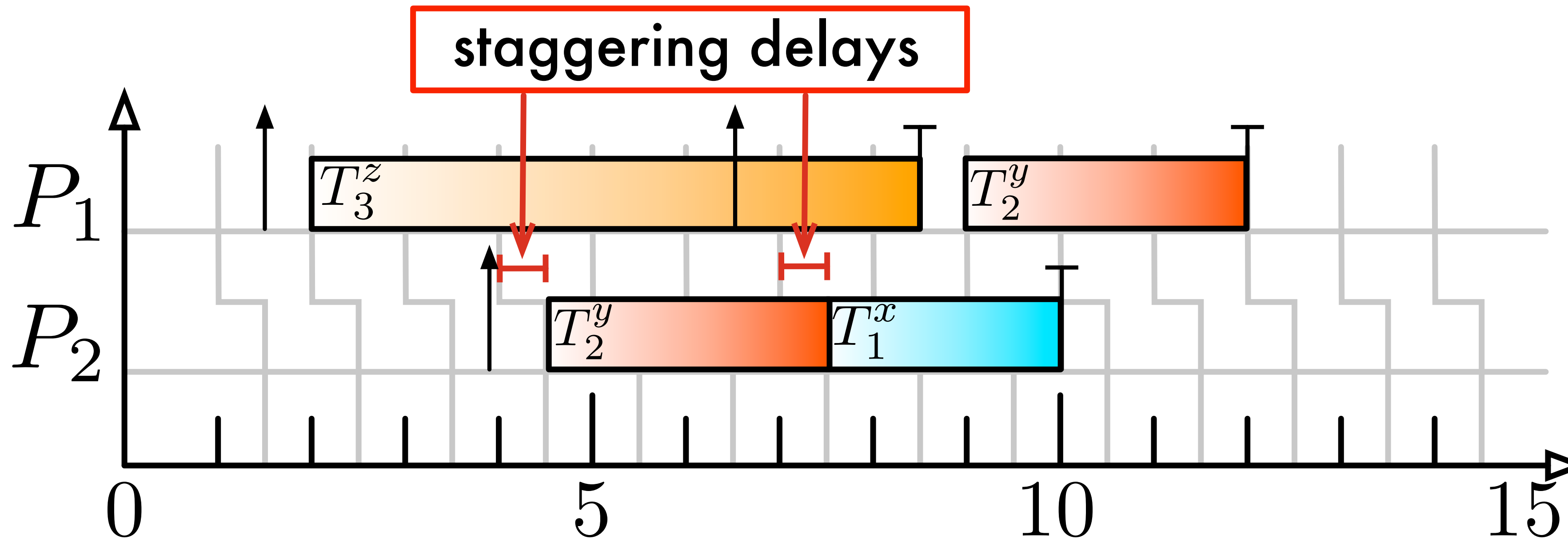

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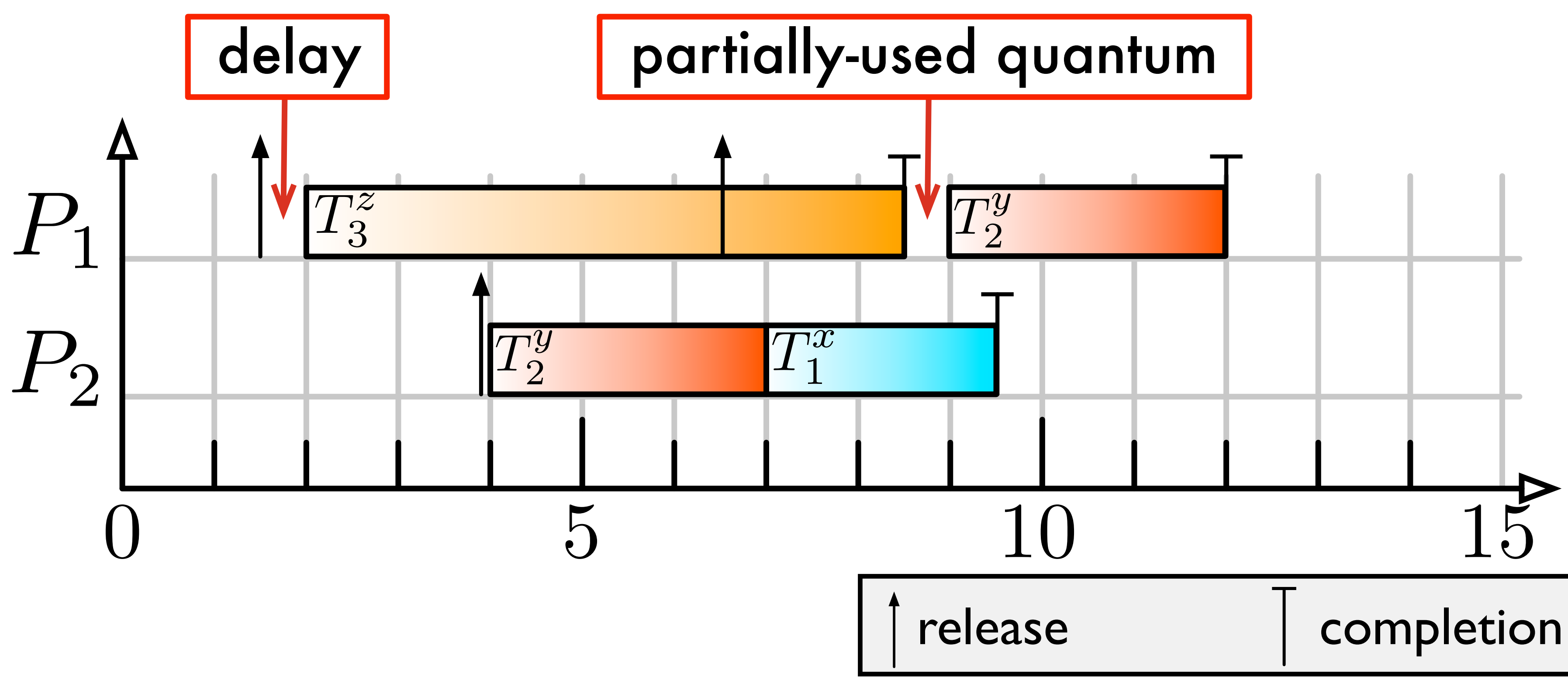

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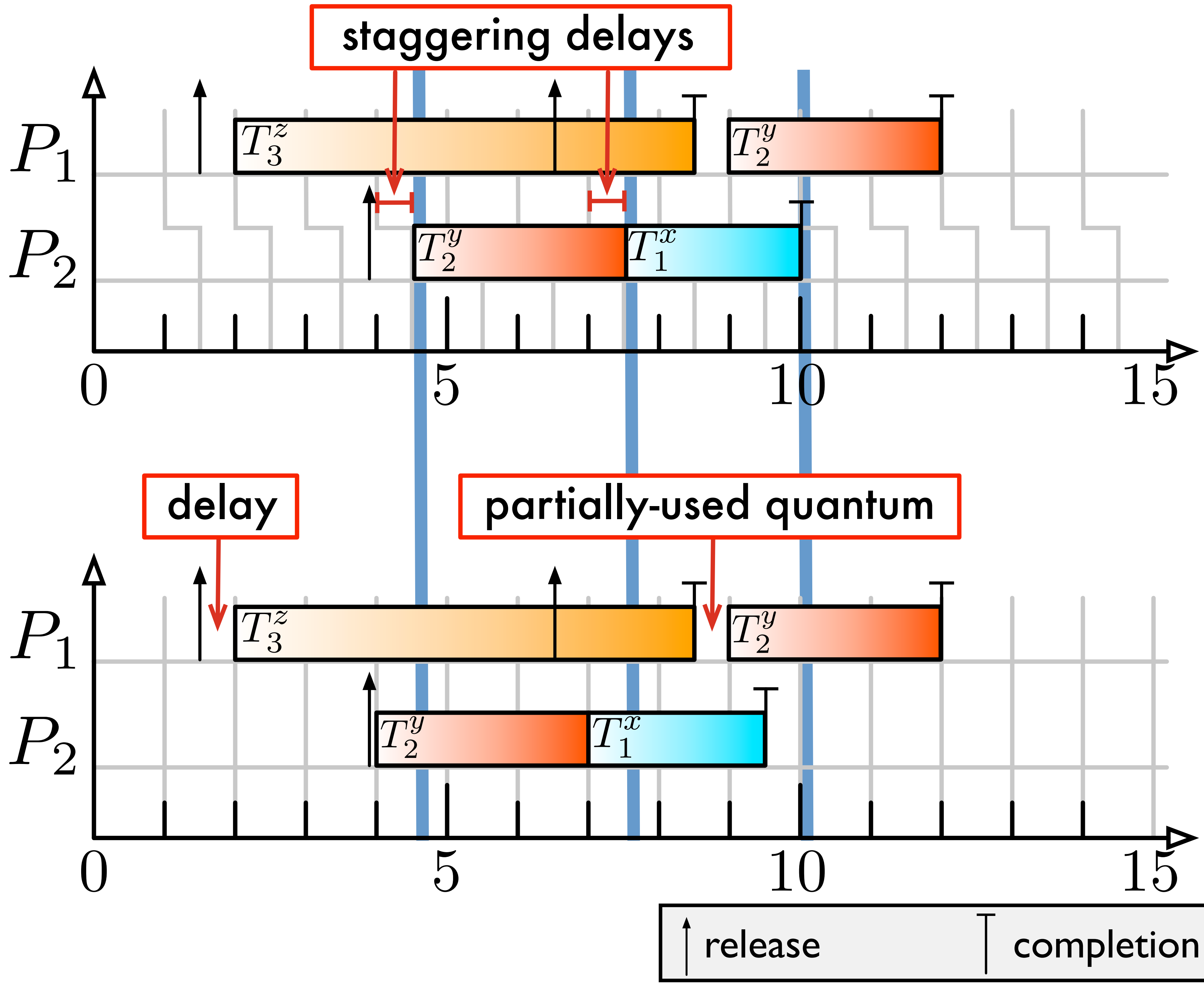

Interrupt Handling

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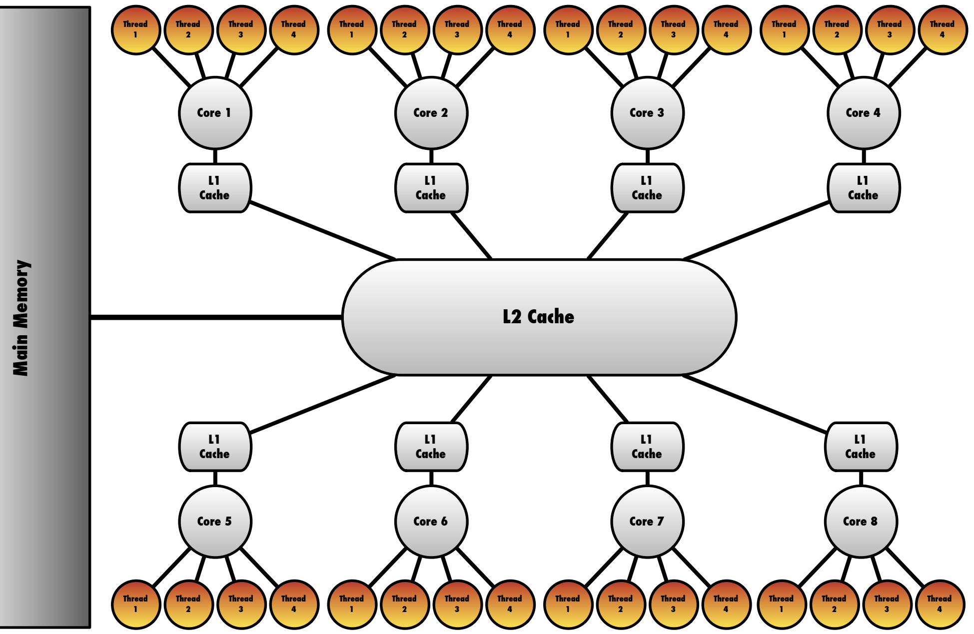

Global interrupt handling.

- ➡ Job releases triggered by **interrupts**.
- ➡ Interrupts may fire **on any processor**.
- ➡ Jobs may execute **on any processor**.
- ➡ Thus, in the worst case, a job may be **delayed by each interrupt**.

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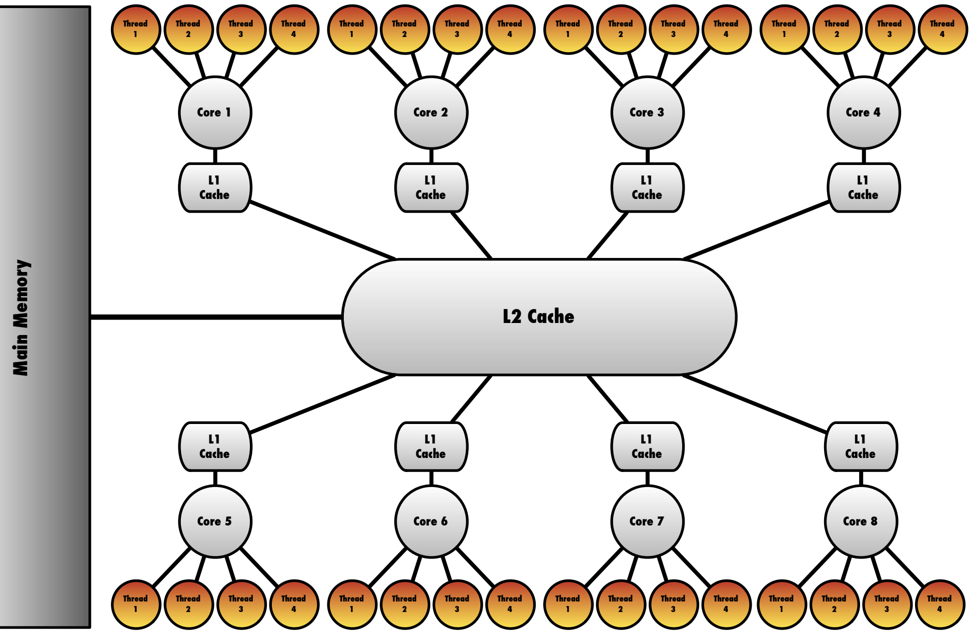

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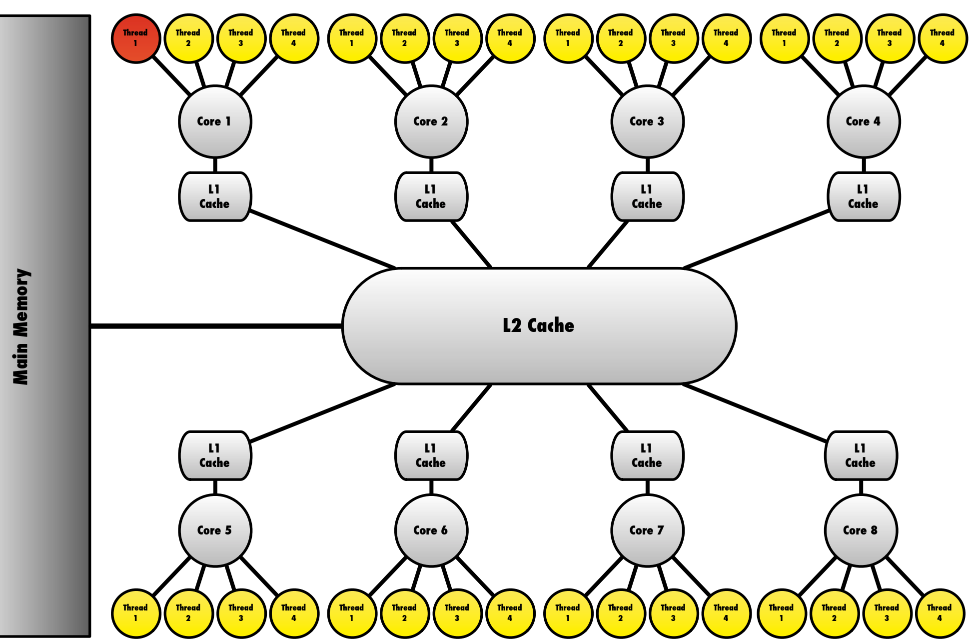
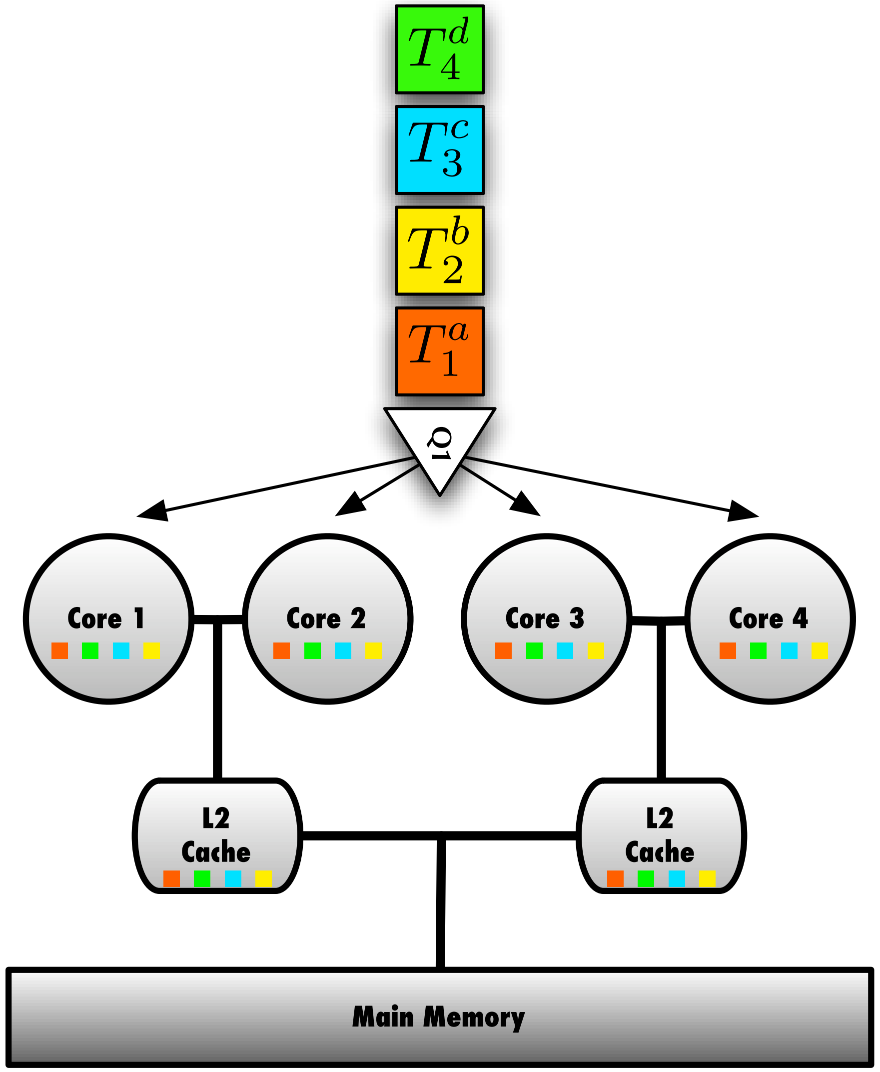


Dedicated interrupt handling.

- ➡ **Only one processor** services interrupts.
- ➡ Jobs may execute **on other processors**.
- ➡ Jobs are not delayed by release interrupts.
- ➡ Well-known technique; used in the **Spring** kernel (Stankovic and Ramamritham, 1991).
- ➡ How does it affect **schedulability**?

J.A. Stankovic and K. Ramamritham (1991), The Spring kernel: A new paradigm for real-time systems. *IEEE Software*, 8(3):62–72.

Ready Queue


T_4^d
T_3^c
T_2^b
T_1^a
Q1
Core 1
Core 2
Core 3
Core 4
L2 Cache
L2 Cache
Main Memory

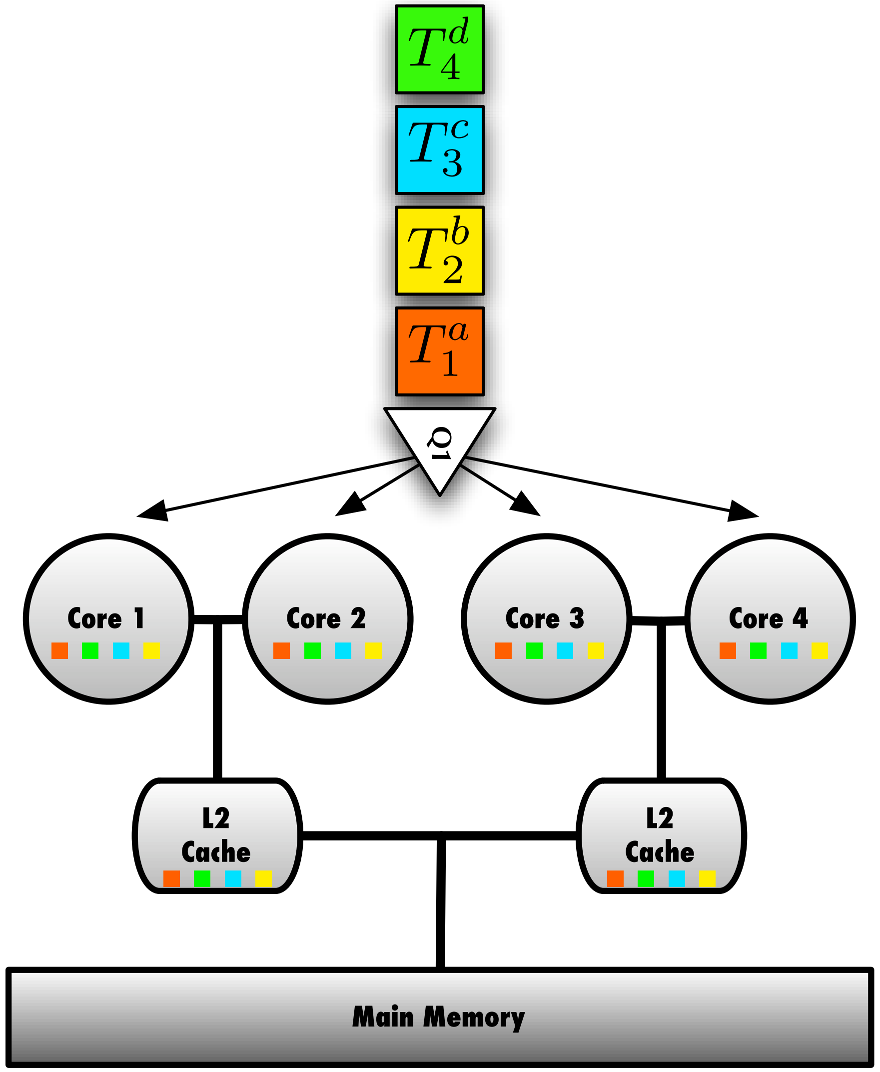
Ready Queue

Globally-shared priority queue.

➡ Problem: **hyper-period boundaries**.

➡ Problem: **lock contention**.

➡ Problem: **bus contention**.



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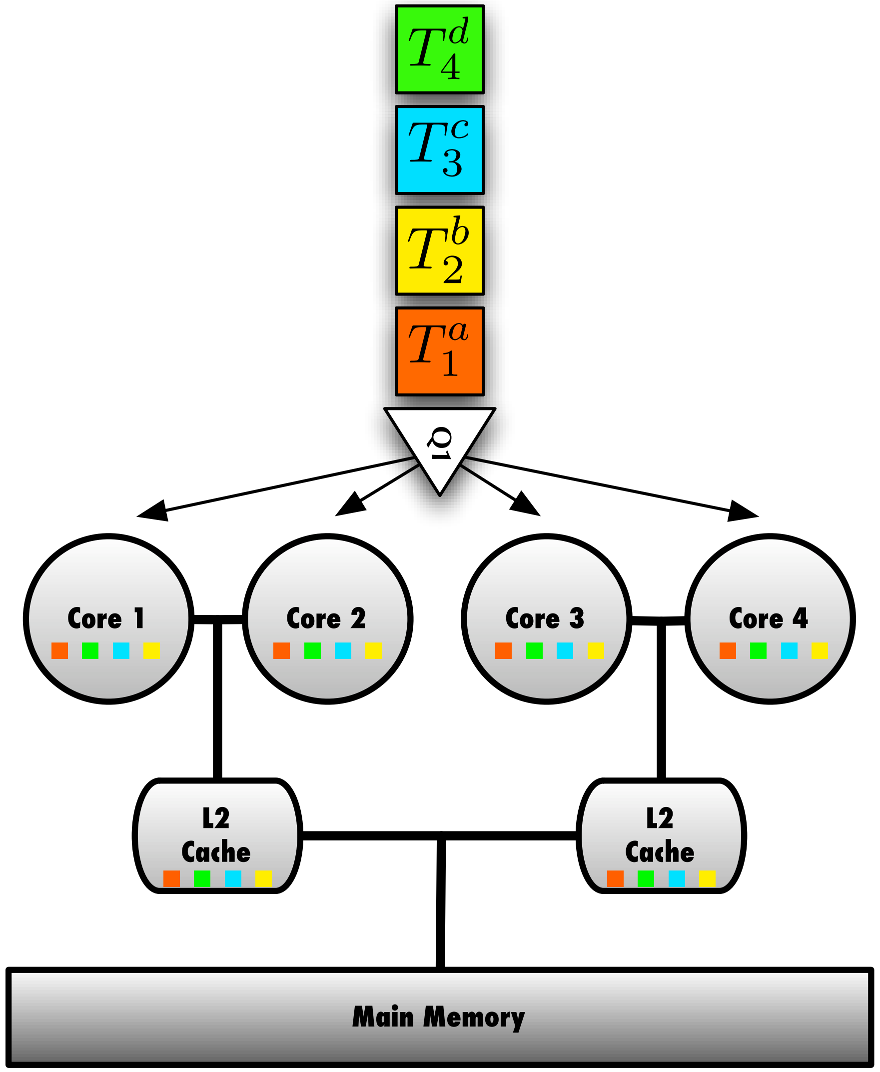
Requirements.

➡ **Mergeable** priority queue: release *n* jobs in O(log *n*) time.

➡ **Parallel** enqueue / dequeue operations.

➡ Mostly **cache-local** data structures.



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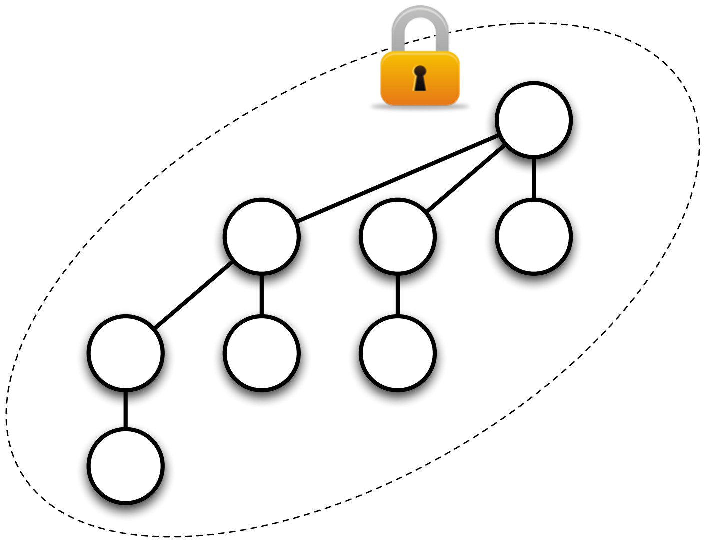
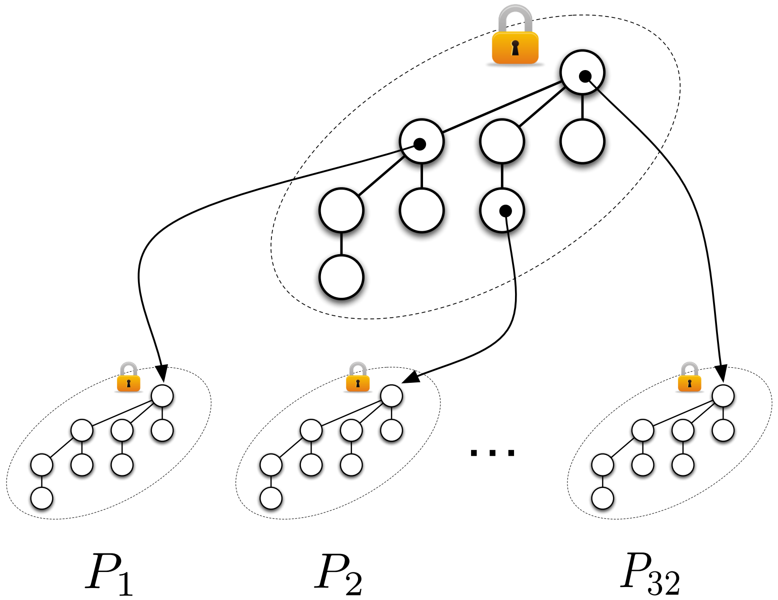
In this study, we consider three queue implementations.

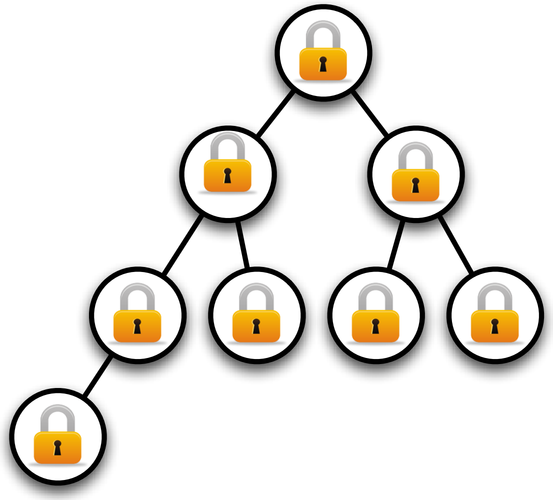
Coarse-Grained Heap



Hierarchical Heaps



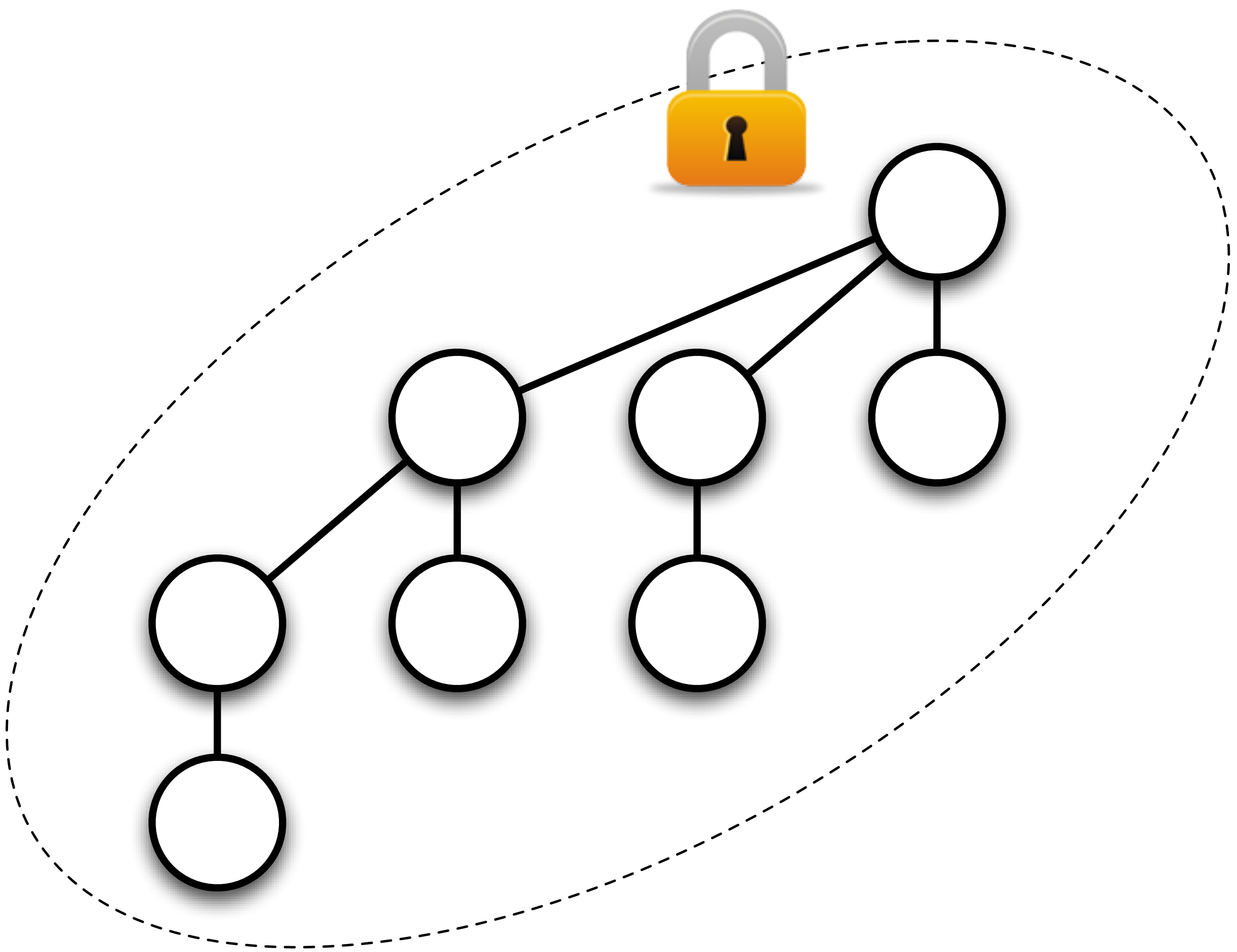
Fine-Grained Heap



Ready Queue: Coarse-Grained Heap

Binomial heap + single lock.

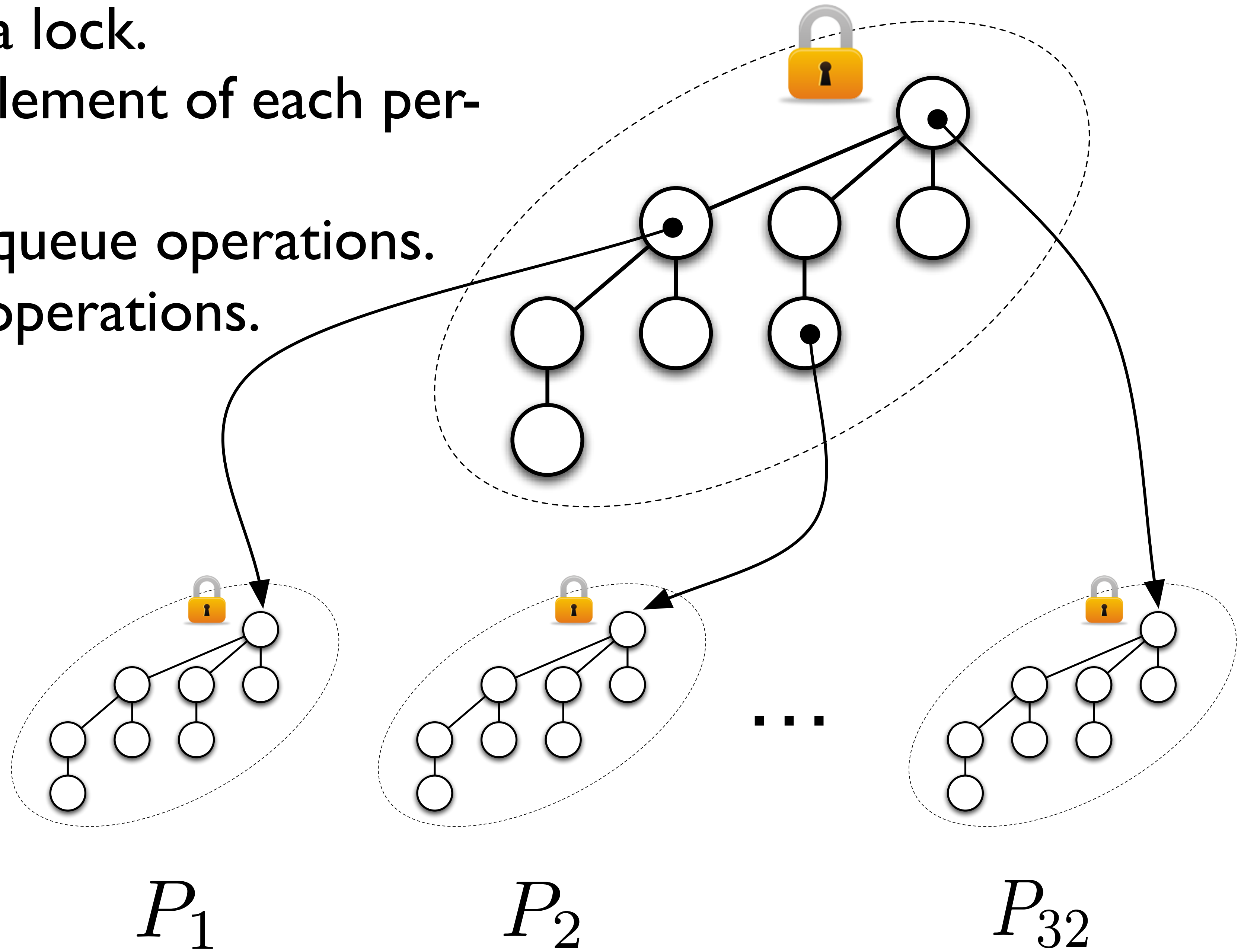
- ➡ Lock used to synchronize all G-EDF state.
- ➡ **Mergeable** queue.
- ➡ No parallel updates.
- ➡ No cache-local updates.
- ➡ Low locking overhead (only single lock acquisition).



Ready Queue: Hierarchical Heaps

Per-processor queues + master queue.

- ➡ Each queue protected by a lock.
- ➡ Master queue holds min element of each per-processor queue.
- ➡ **Global, sequential** dequeue operations.
- ➡ **Mostly-local** enqueue operations.



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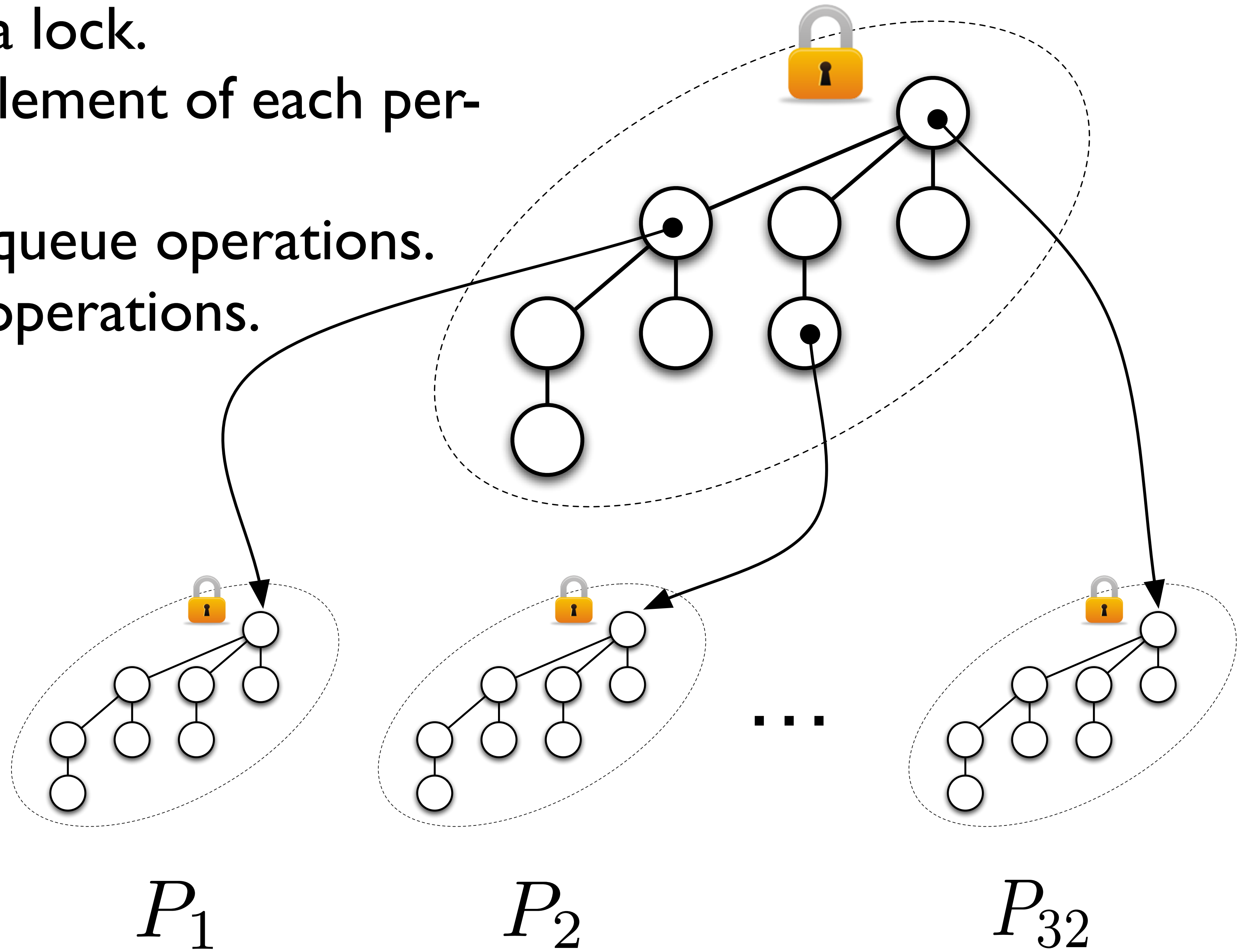
Locking.

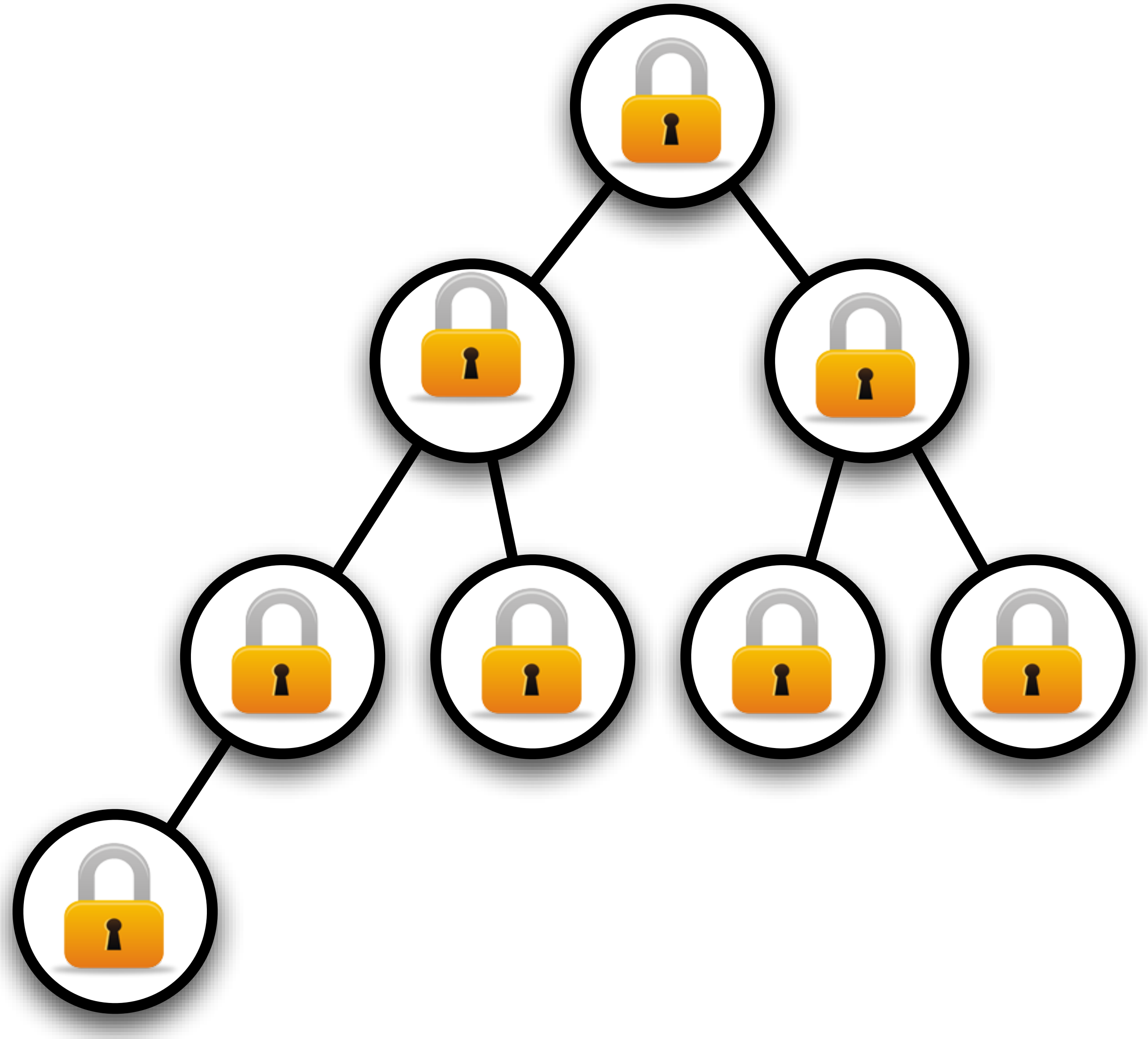
- Dequeue: top-down.
- Enqueue: bottom-up.
- Enqueue may have to drop lock, retry.
- Additional complexity wrt. dequeue (see paper).
- Bottom line: **expensive**.



Ready Queue: Fine-Grained Heap

Parallel binary heap.

- ➡ One lock per heap node.
- ➡ Proposed by Hunt et al. (1996).
- ➡ **Not mergeable**.
- ➡ **Parallel enqueue / dequeue**.
- ➡ **No cache-local data**.



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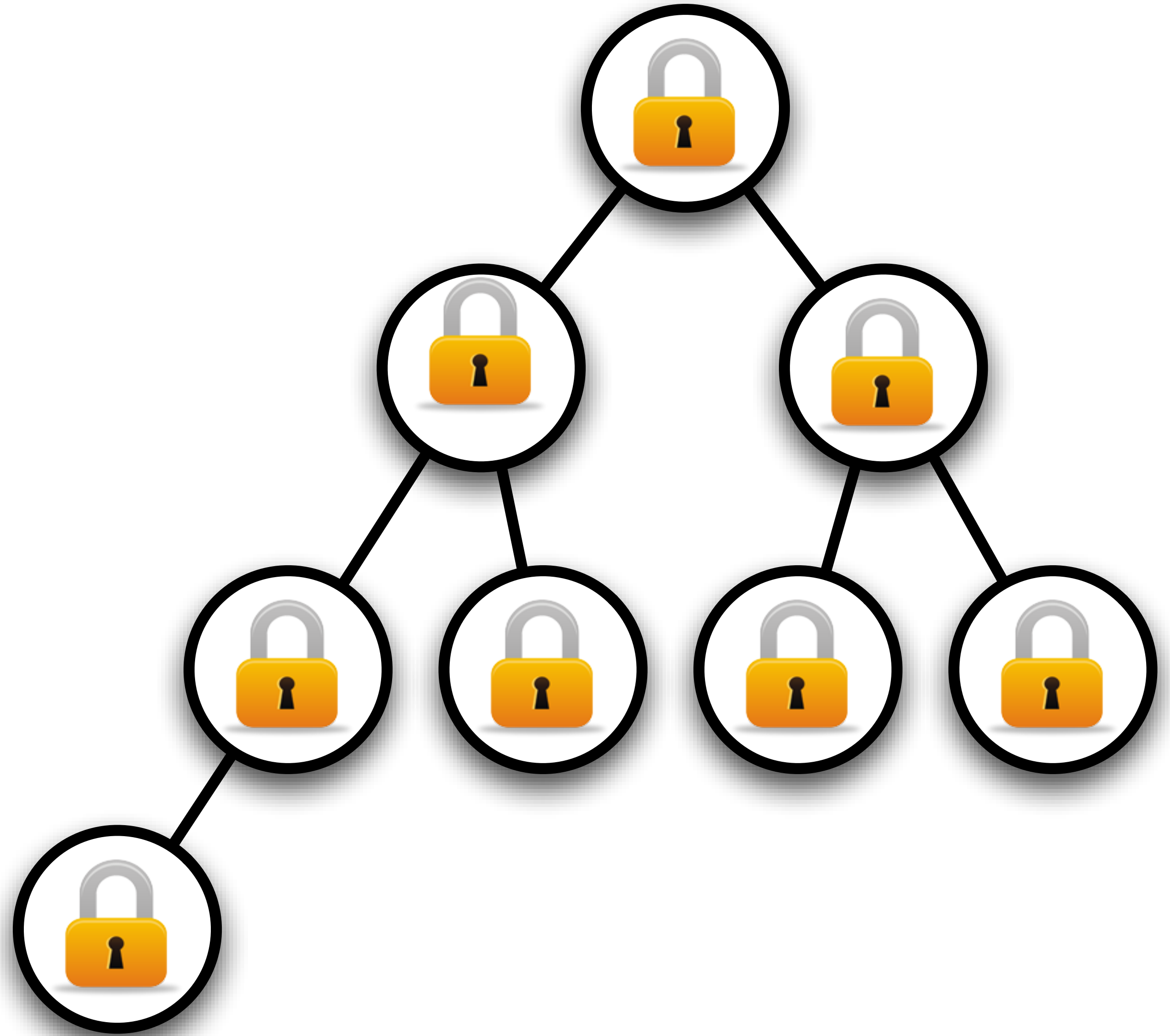
Locking.

- ➡ Many lock acquisitions.
- ➡ Atomic **peek+dequeue** operation needed to check for preemptions.



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Additional Components

Release queue.

➡ Support mergeable queues.
➡ Support dedicated interrupt handling.

Job-to-processor mapping.

➡ Quickly determine whether preemption is required.
➡ Avoid unnecessary preemptions.
➡ Used to linearize concurrent scheduling decisions.

(Details in the paper.)

Implementation in *LITMUS*[RT]

LITMUS^{RT}

Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

Linux Testbed for Multiprocessor Scheduling in Real-Time systems

LITMUS RT

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UNC's Linux patch.

➡ Used in several previous studies.

➡ On-going development.

➡ Currently, based off of Linux 2.6.24.

LITMUS^RT

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Scheduler Plugin API.

- ➡ `scheduler_tick()`
- ➡ `schedule()`
- ➡ `release_jobs()`

Considered G-EDF Variants

Name	Ready Q	Scheduling	Interrupts

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Name	Ready Q	Scheduling	Interrupts
CEm	coarse-grained	event-driven	global
CQm	coarse-grained	quantum (aligned)	global
S-CQm	coarse-grained	quantum (staggered)	global
HEm	hierarchical	event-driven	global
FEm	fine-grained	event-driven	global

Co... ...nts

Baseline from
(Brandenburg et al., 2008)

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FEm	fine-grained	event-driven	global

No fine-grained heaps + quantum-driven scheduling.
(Parallel updates not beneficial due to quantum barrier.)

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FEm	fine-grained	event-driven	global
CE1	coarse-grained	event-driven	dedicated
CQ1	coarse-grained	quantum (aligned)	dedicated
S-CQ1	coarse-grained	quantum (staggered)	dedicated
FE1	fine-grained	event-driven	dedicated

No hierarchical heaps + dedicated interrupt handling.
(Hierarchical heaps not beneficial if only one proc. enqueues.)

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Schedulability Study

Objective

Compare the discussed implementations in terms of the ratio of randomly-generated task sets that can be shown to be schedulable ***under consideration of system overheads****.*

Scheduling Overheads

Scheduling Overheads

Release overhead.

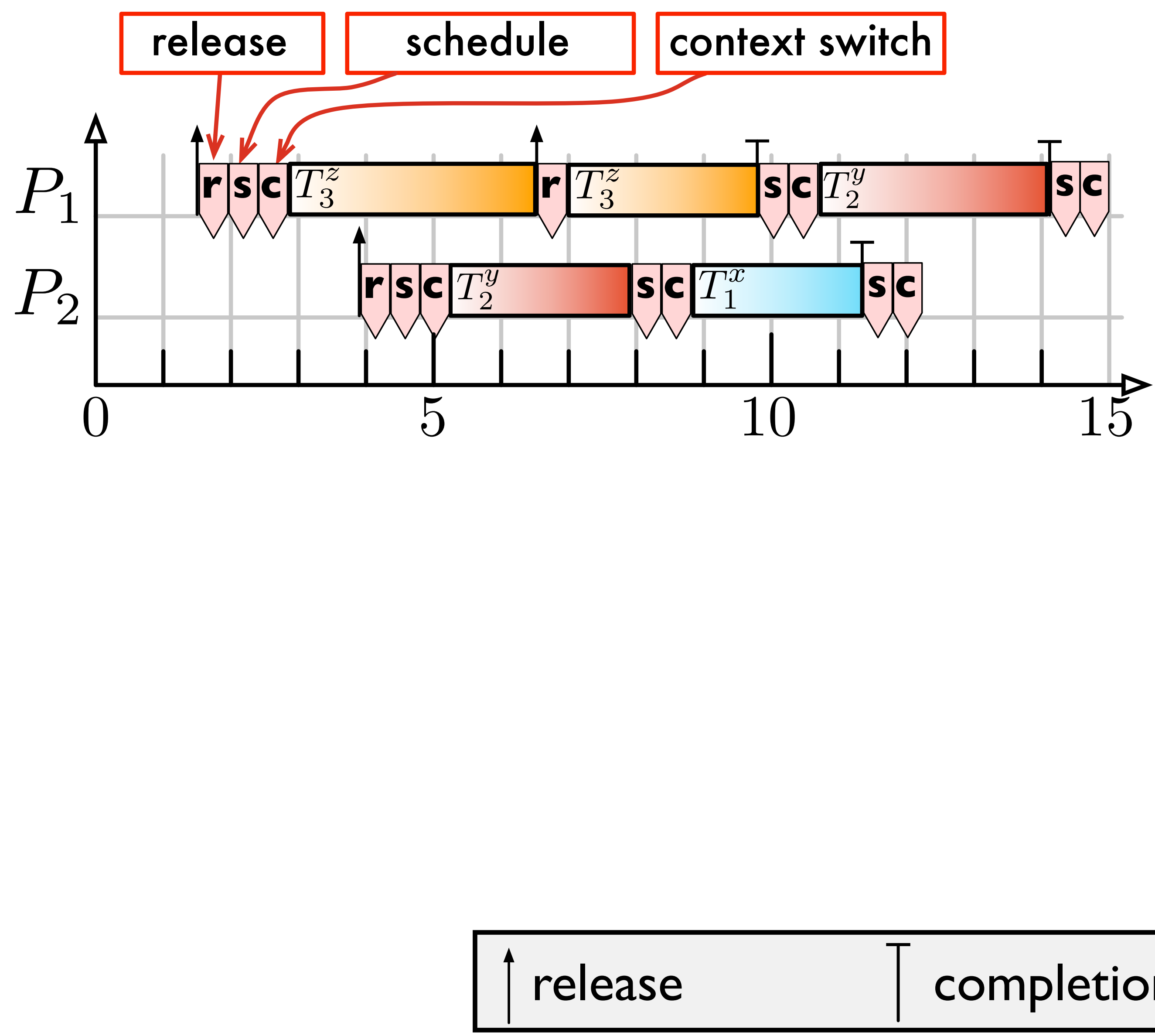
➡ The cost of a one-shot timer interrupt.

Scheduling overhead.

➡ Selecting the next job to run.

Context switch overhead.

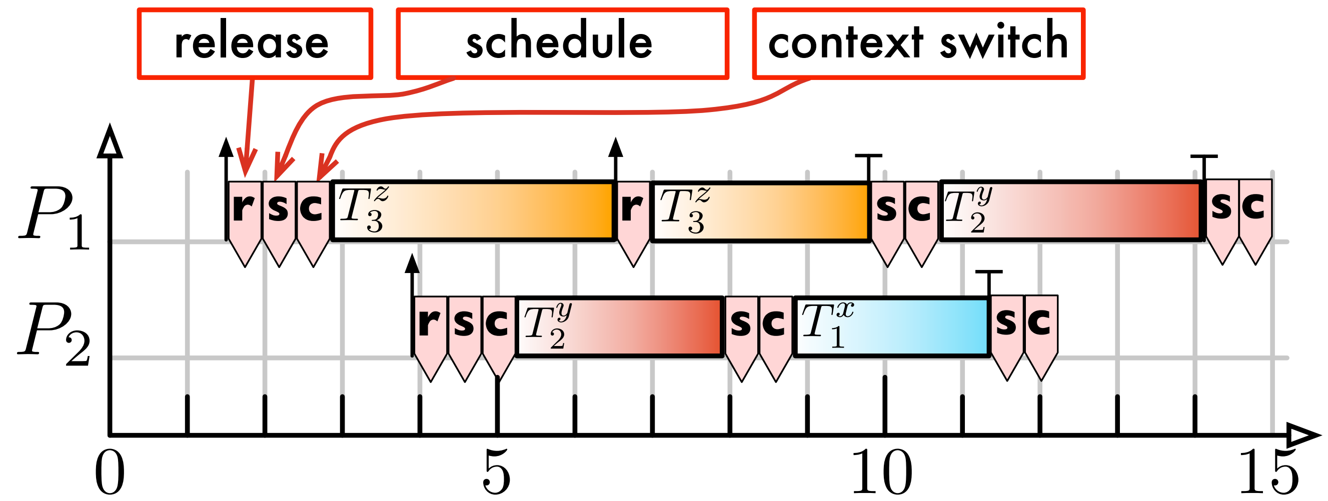
➡ Changing address space.



Scheduling Overheads

Release overhead.
➡ The cost of a one-shot timer interrupt.

Scheduling overhead.
➡ Selecting the next job to run.



Context switch overhead.
➡ Changing address space.

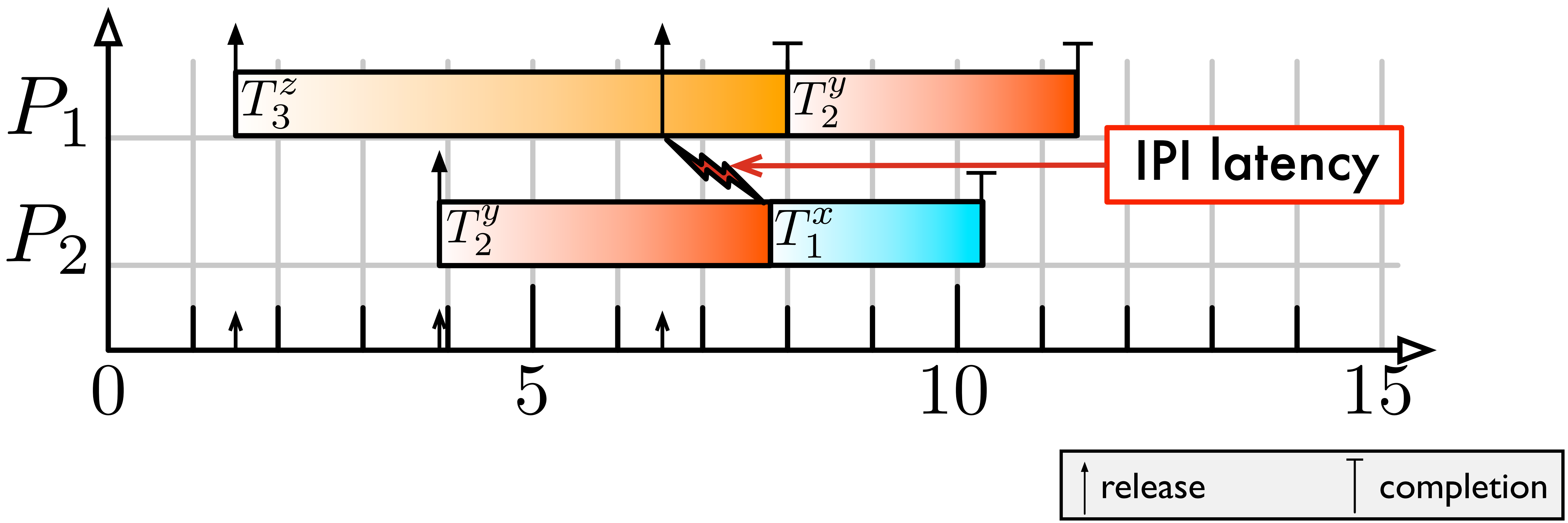
Tick overhead.
➡ Cost of a periodic timer interrupt.
➡ Beginning of a new quantum.

Preemption and migration overhead.
➡ Loss of cache affinity.
➡ Known from (Brandenburg et al., 2008).

IPI Latency

Inter-processor interrupts (IPIs).

- ➡ Interrupt may be processed by a processor different from the one that will schedule a newly-arrived job.
- ➡ Requires notification of remote processor.
- ➡ **Event-based scheduling incurs added latency**.



Test Platform

LITMUS^{RT}

➡ UNC's Linux-based Real-Time Testbed

Sun UltraSPARC T1 "Niagara"

➡ 8 cores, 4 HW threads per core = 32 logical processors.

➡ 3 MB shared L2 cache

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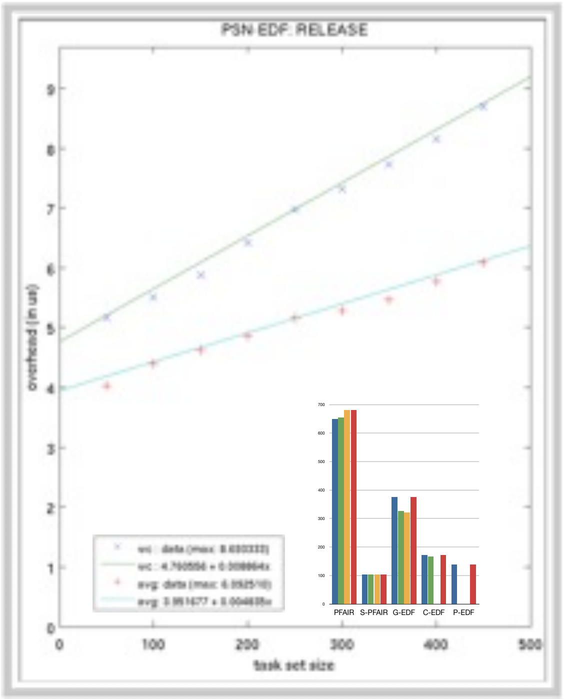


Overheads

➡ Traced overheads under each of the plugins.

➡ Collected more than 640,000,000 samples (total).

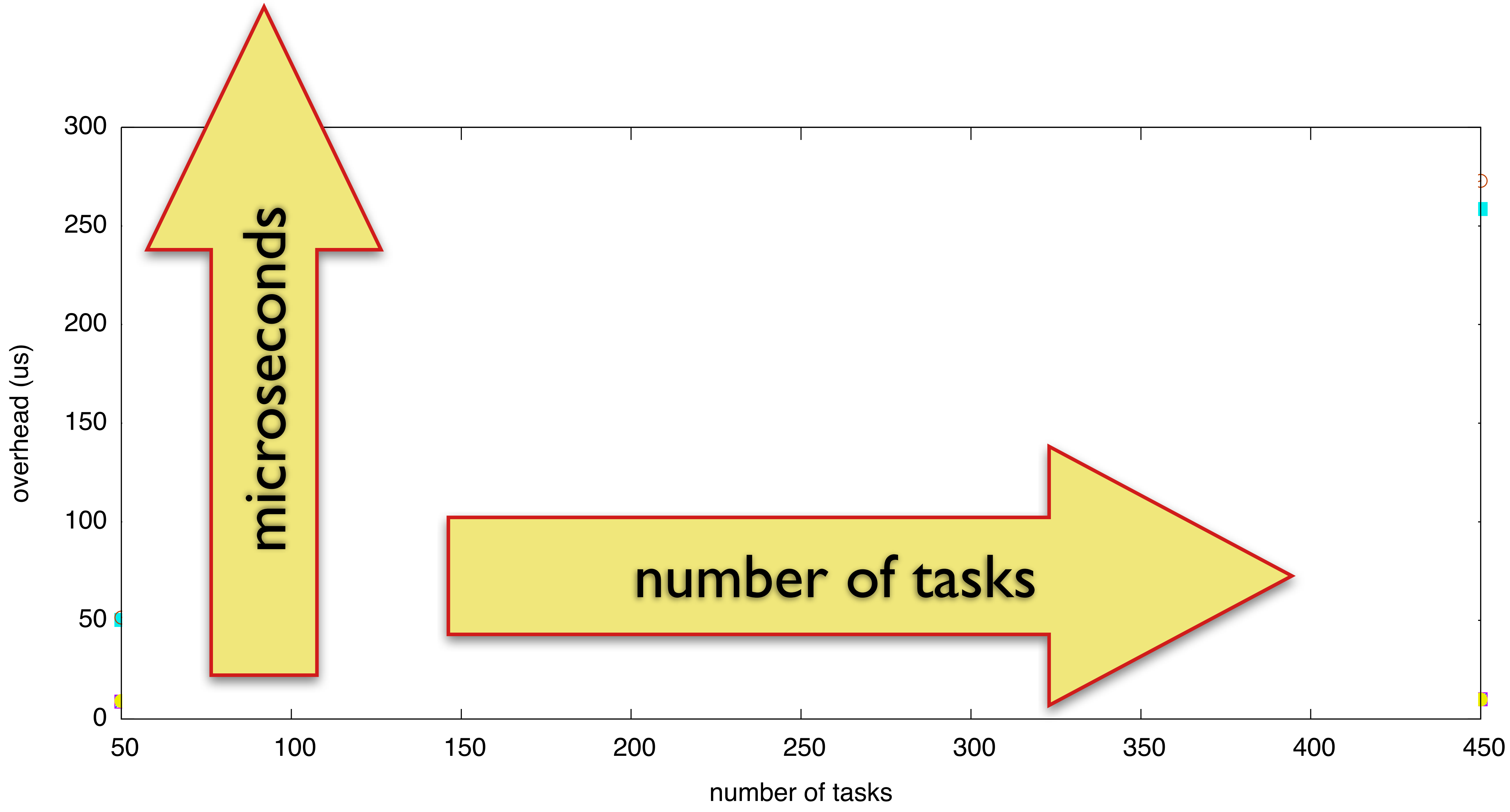
➡ Computed worst-case and average-case overheads.

➡ Over 20 graphs; see online version.

Outliers

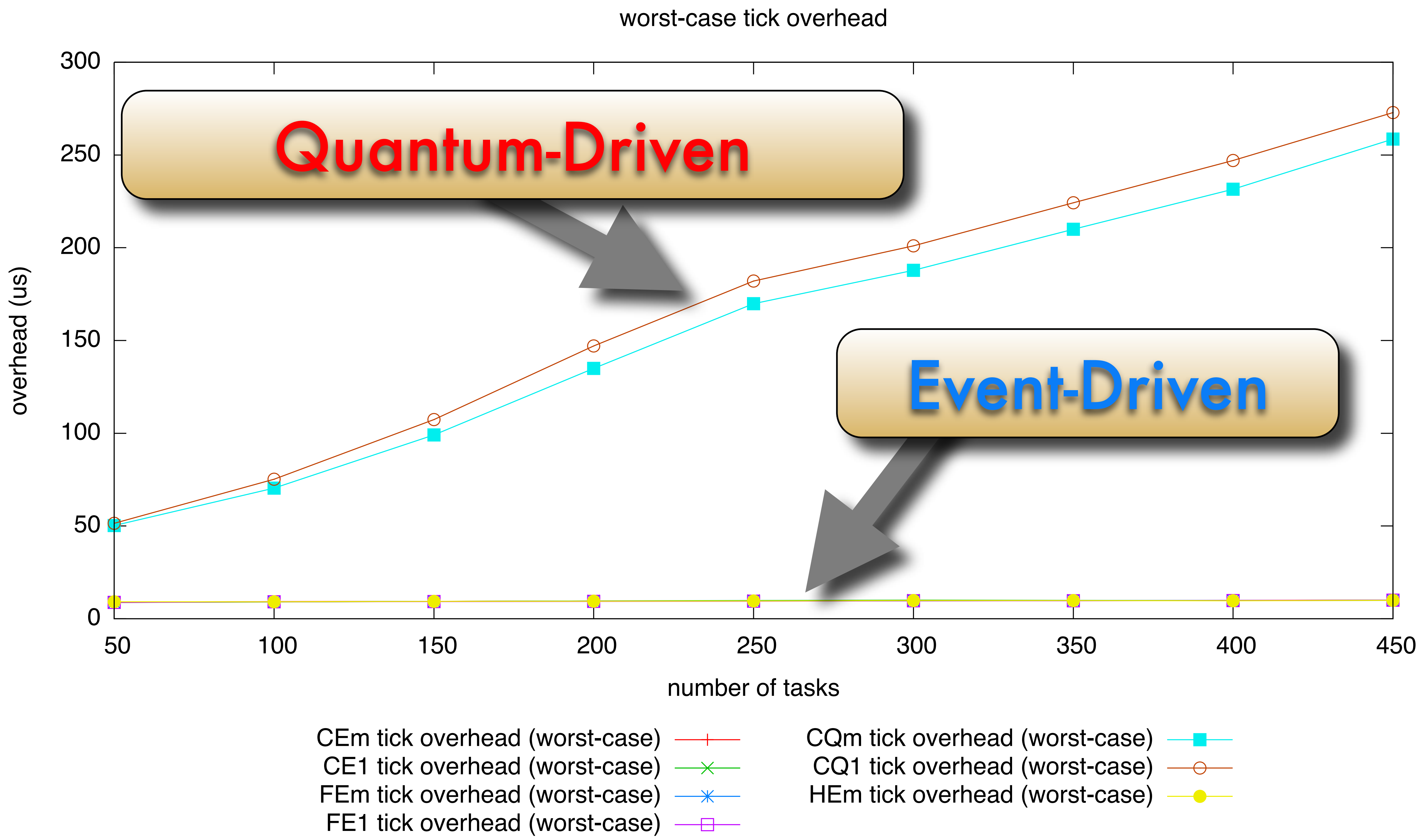
➡ Removed top 1% of samples to discard outliers.

Example: Tick Overhead

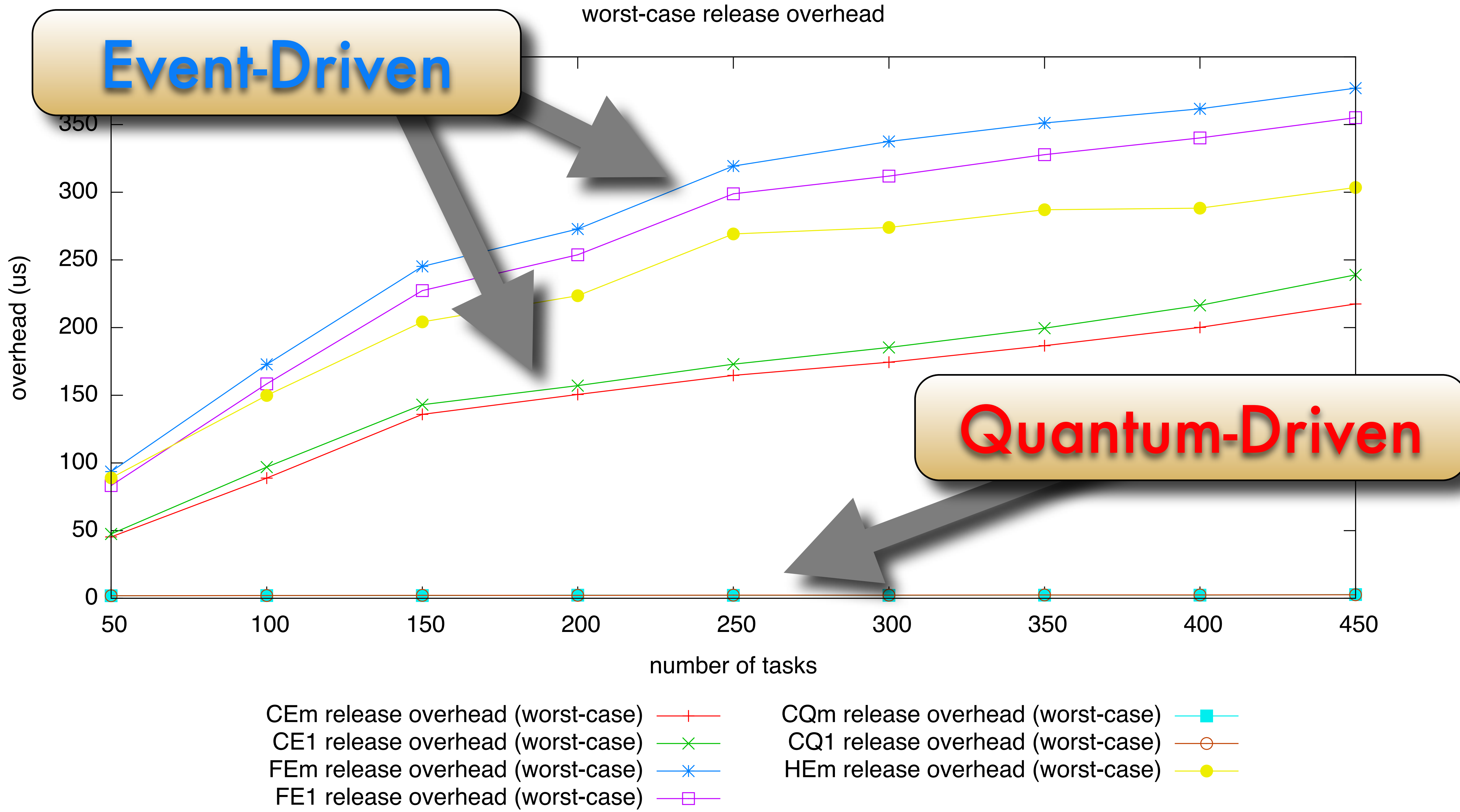


"Higher is worse."

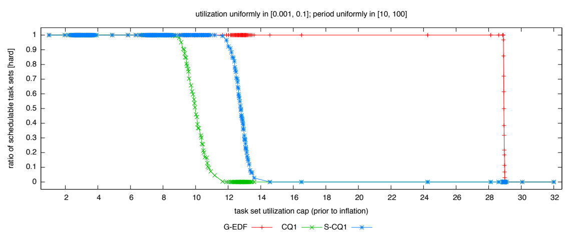
Example: Tick Overhead

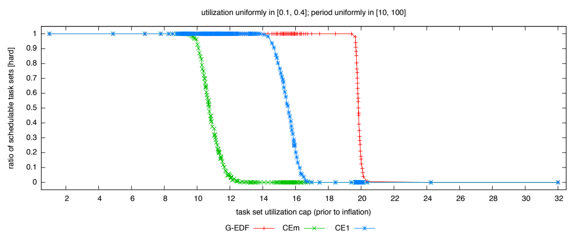


Example: Release Overhead



Study Setup

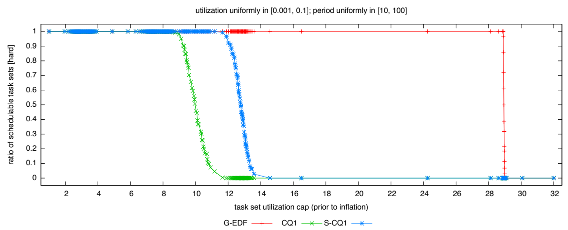


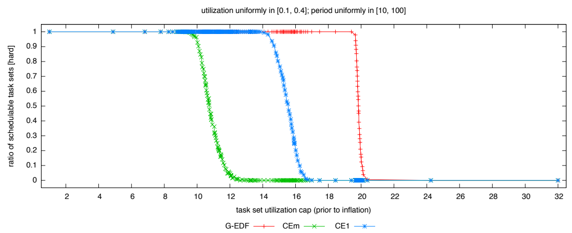


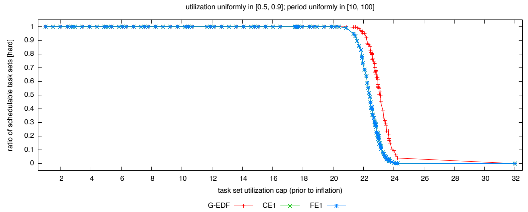
Methodology.

- ➡ Randomly generate task set.
- ➡ Apply overheads (for each G-EDF implementation).
- ➡ Test whether task set can be claimed schedulable (for each G-EDF implementation).

Study Setup







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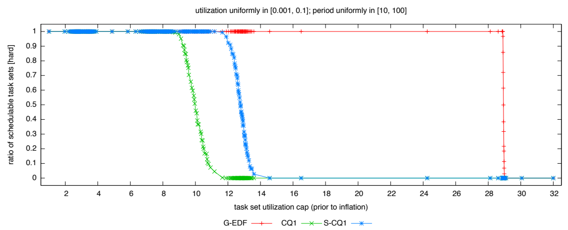
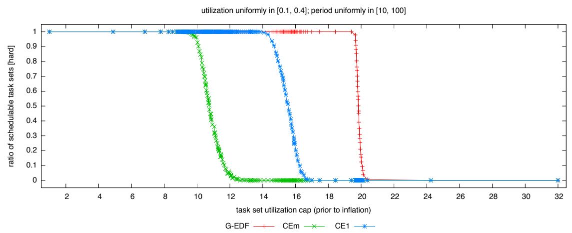
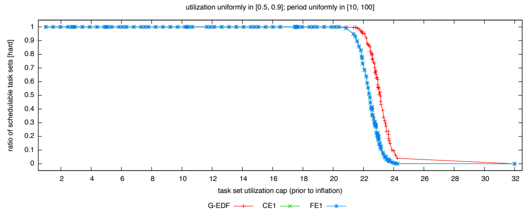
Schedulability.

- ➡ Hard real-time: worst-case overheads, no tardiness.
- ➡ Soft real-time: average-case overheads, bounded tardiness.

Study Setup







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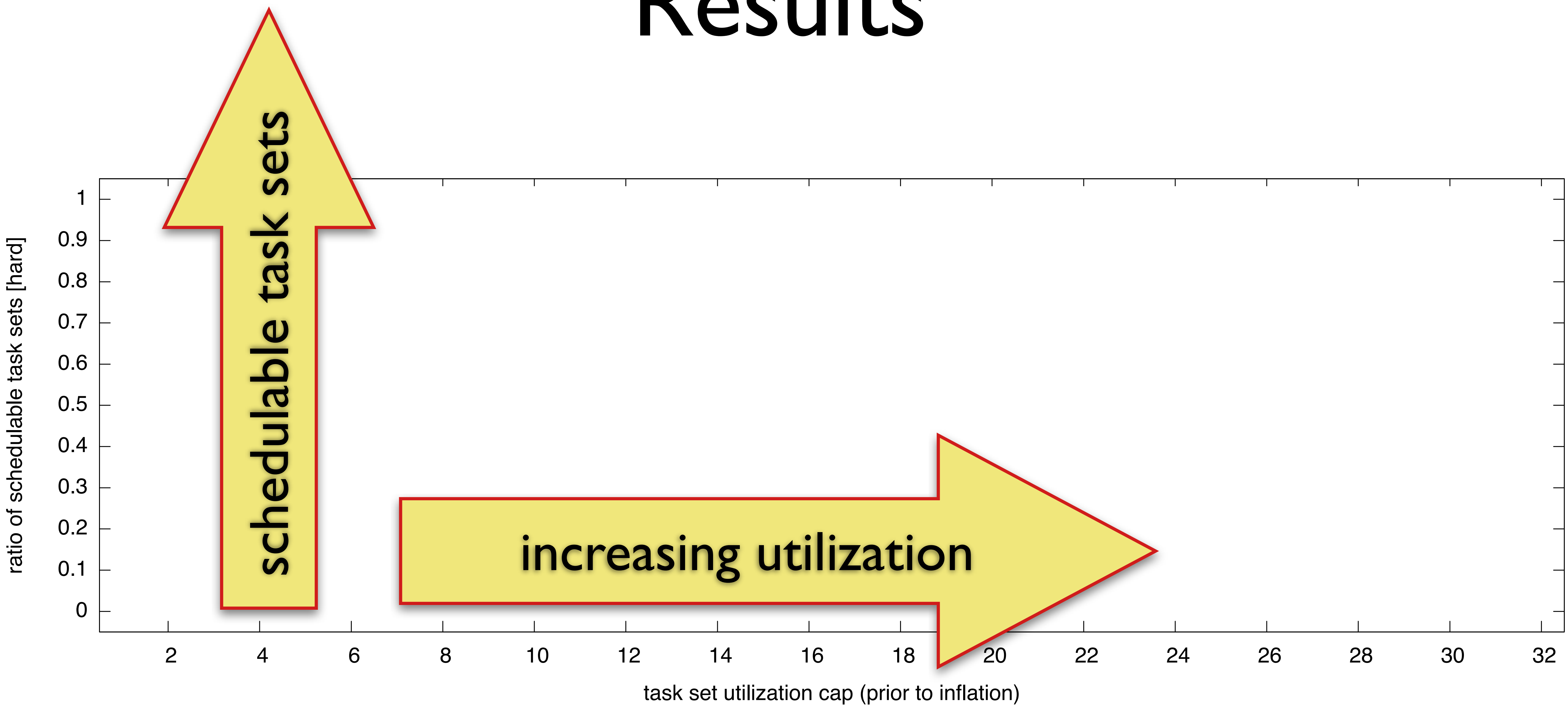
Task set generation.

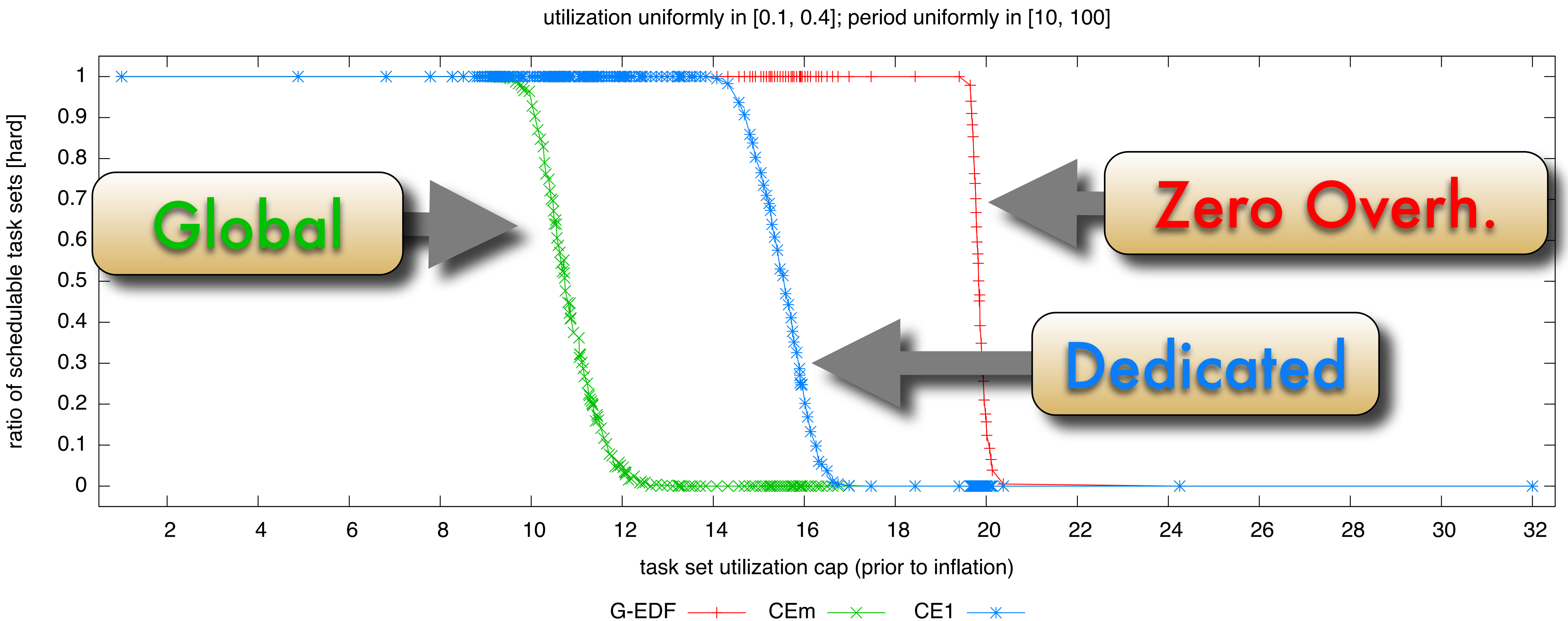
- ➡ Six utilization distributions (uniform and bimodal).
- ➡ Three period distributions (uniform).
- ➡ Over 300 graphs; see online version.

Results



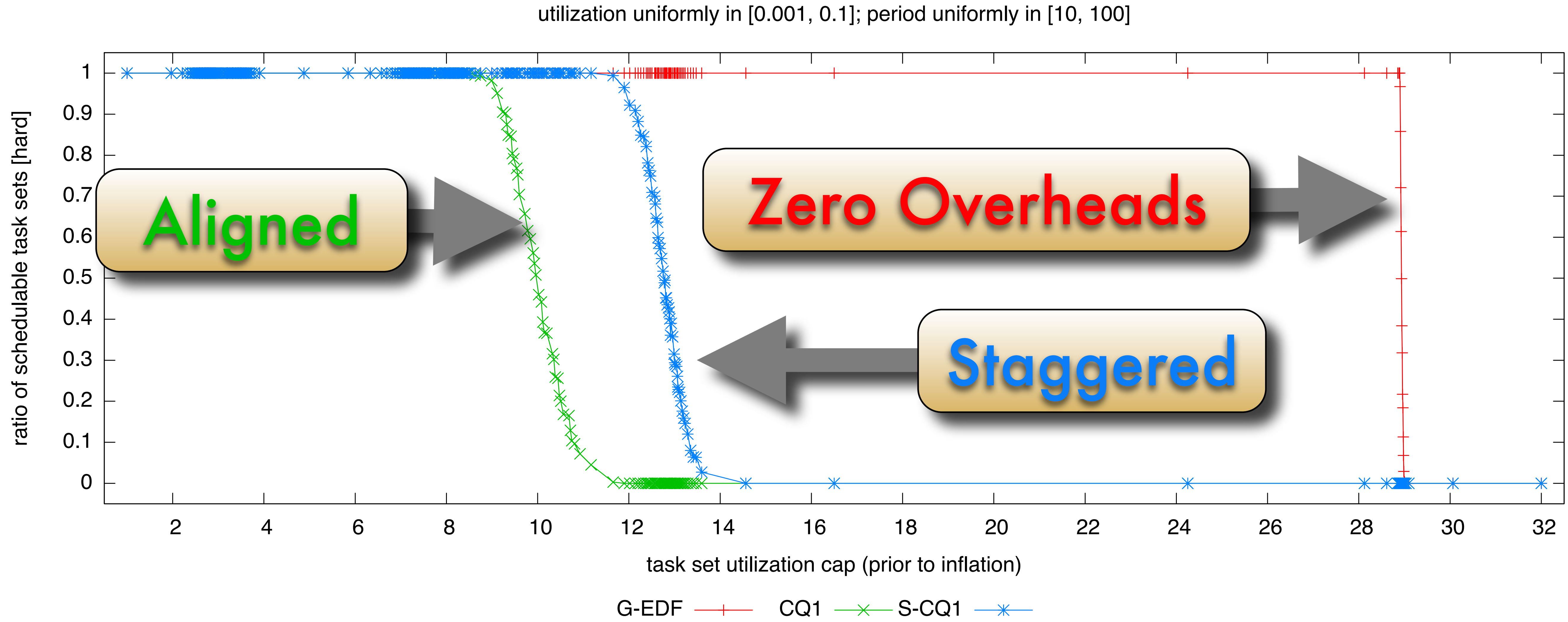
"Higher is better."

Interrupt Handling



Dedicated interrupt handling was generally preferable (or no worse).

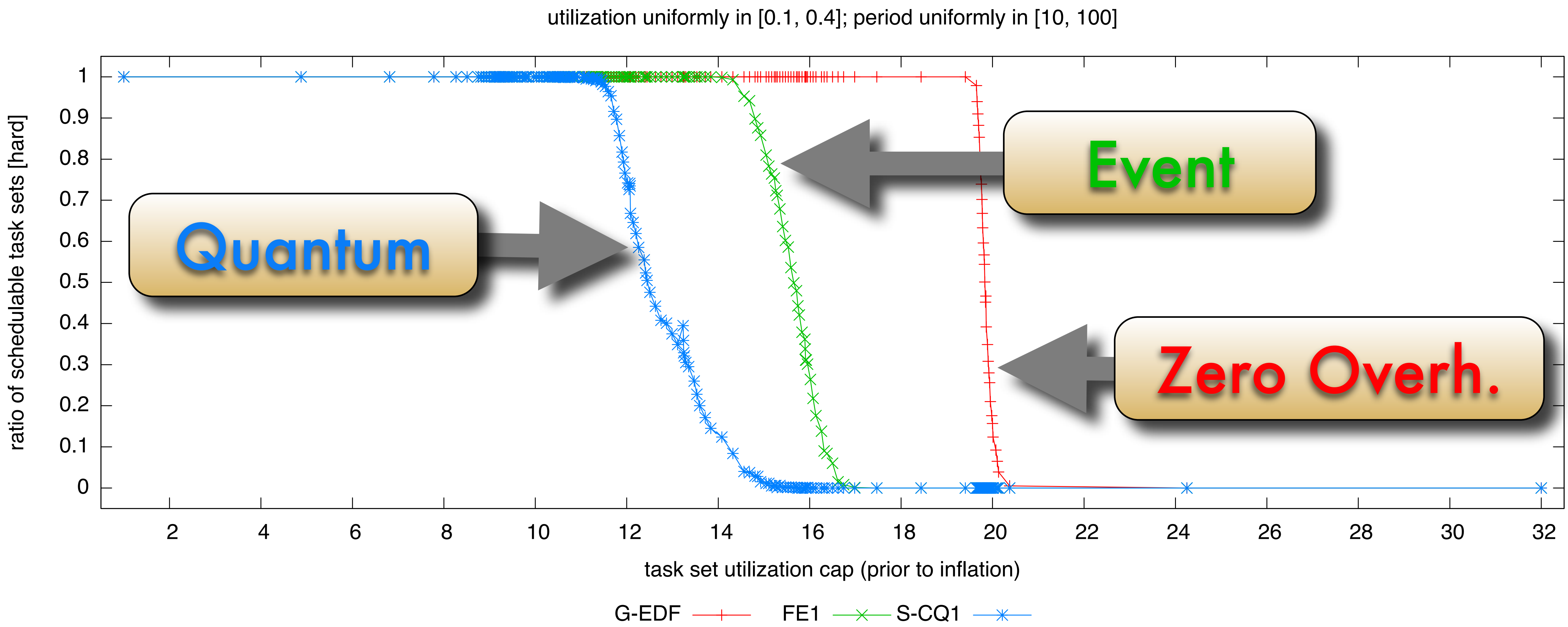
Quantum Staggering



Staggered quanta

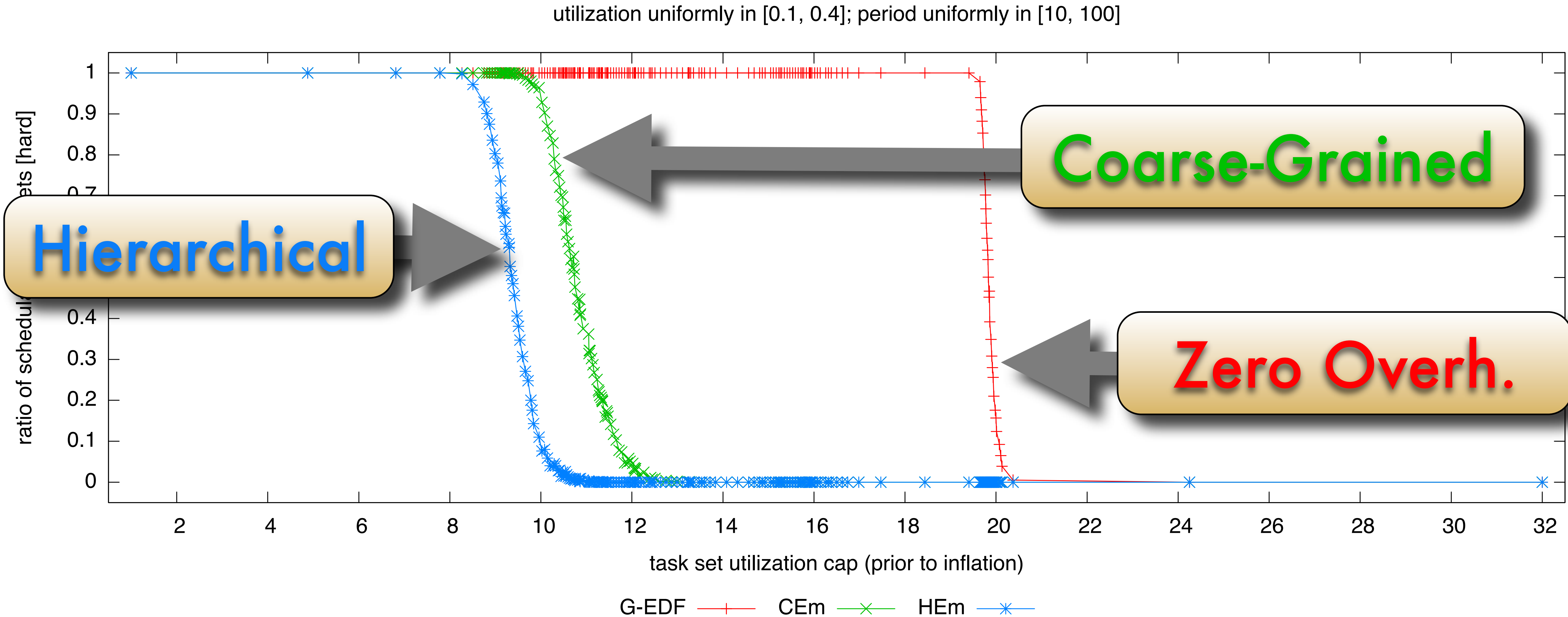
were generally preferable (or no worse).

Quantum- vs. Event-Driven



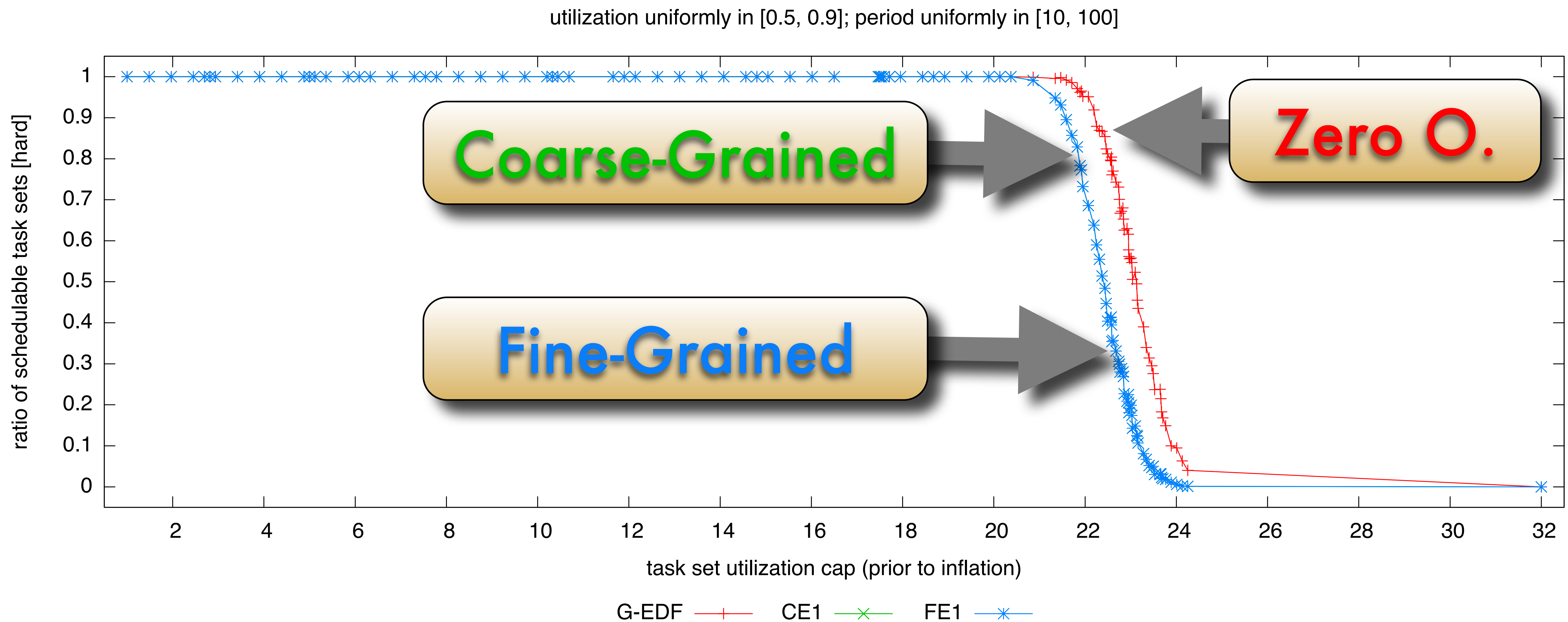
Event-driven scheduling
was preferable in most cases.

Choice of Ready Queue (1)



The **coarse-grained ready queue** performed better than the hierarchical queue.

Choice of Ready Queue (II)



The fine-grained ready queue
performed marginally better than the coarse-grained queue
if used together with **dedicated interrupt handling**.

Conclusion

Summary of Results

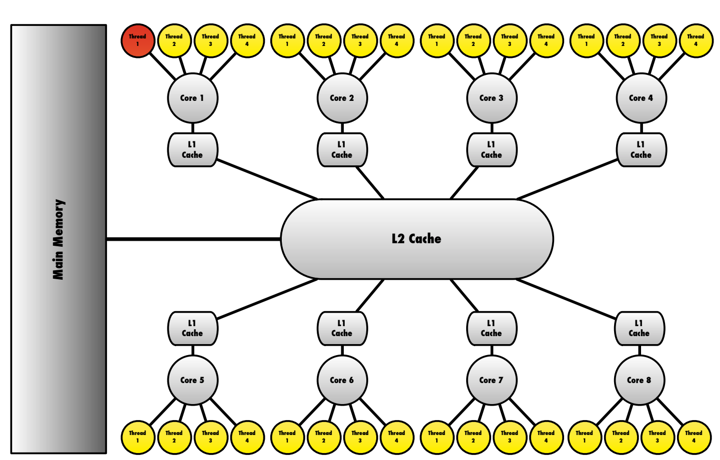
Implementation choices
can impact schedulability as much as
scheduling-theoretic tradeoffs.

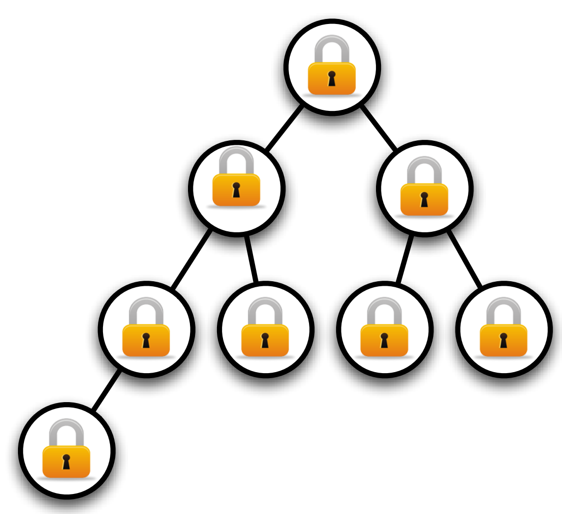
Unless task counts are very high
or periods very short,
G-EDF **can scale** to 32 processors.

Recommendation

Best results obtained with combination of:

fine-grained heap
event-driven scheduling
dedicated interrupt handling





Future Work

Platform.

➡ Repeat study on embedded hardware platform.

Implementation.

➡ Simplify locking requirements.

➡ Parallel mergeable heaps?

Analysis.

➡ Less pessimistic hard real-time G-EDF schedulability tests.

➡ Less pessimistic interrupt accounting.

Thank you!

LITMUS RT

Linux Testbed for Multiprocessor Scheduling in Real-Time Systems

available at

http://www.cs.unc.edu/~anderson/litmus-rt