CLoF:
A Compositional Lock Framework for Multi-level NUMA Systems

Rafael Chehab **Antonio Paolillo** Diogo Behrens Ming Fu Hermann Härtig Haibo Chen






HUAWEI

TECHNISCHE UNIVERSITÄT DRESDEN

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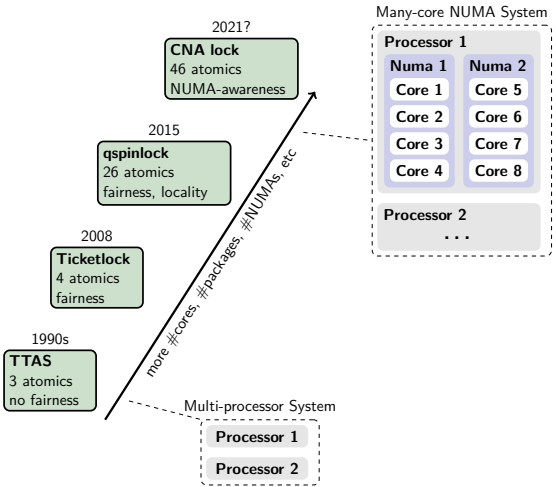
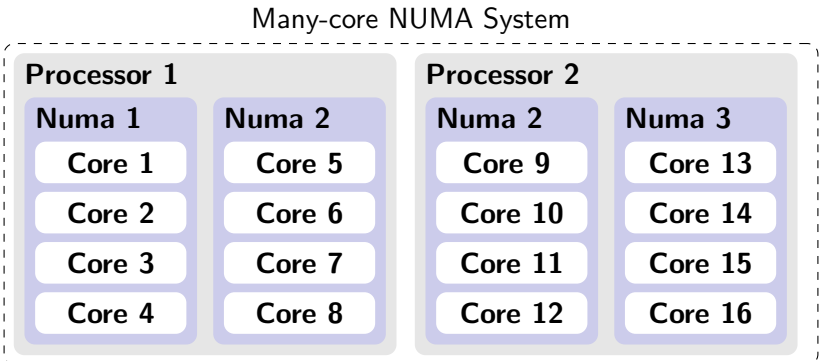
Linux spinlock evolution



Challenge: exploiting the deep hierarchy of large NUMA machines

Core distance affects shared-memory communication performance



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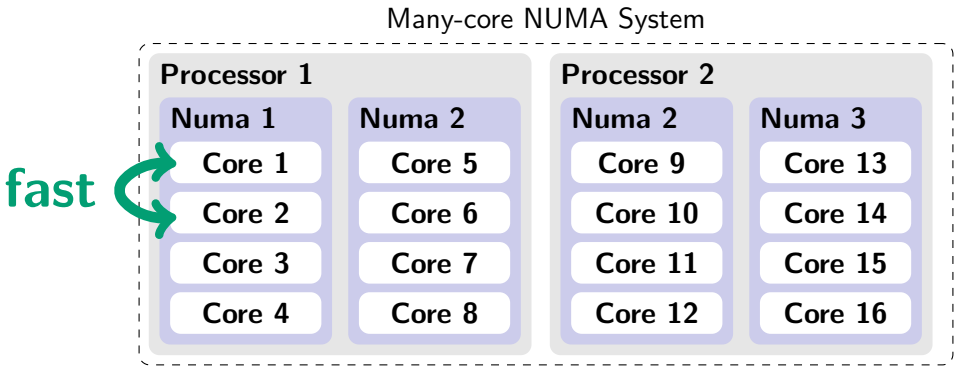

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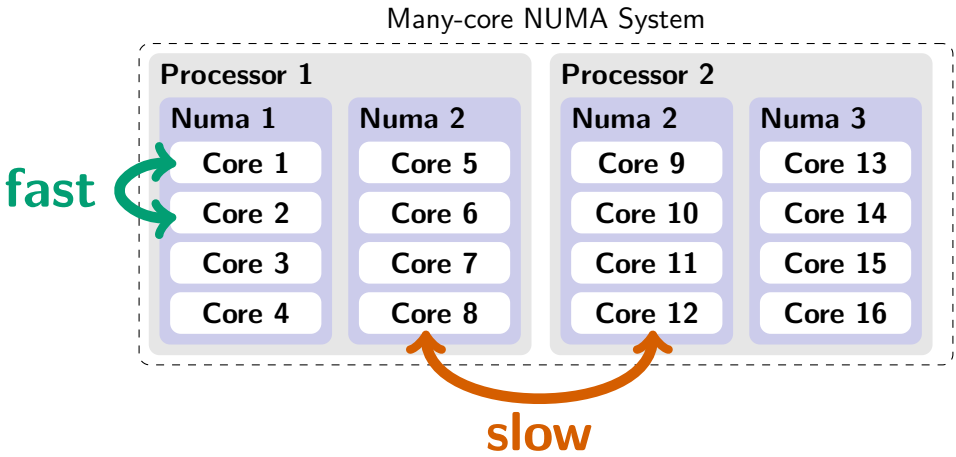

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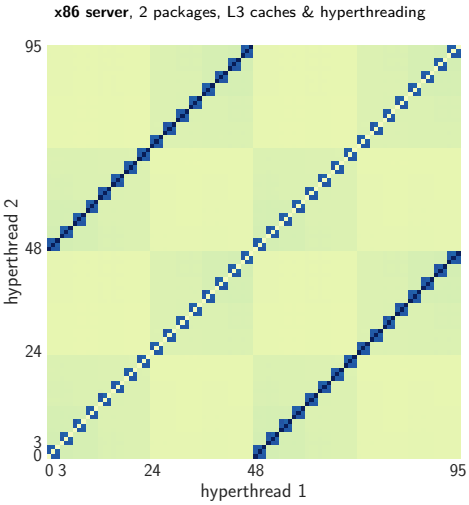
Discovering the hierarchy with a pair of threads incrementing a shared counter



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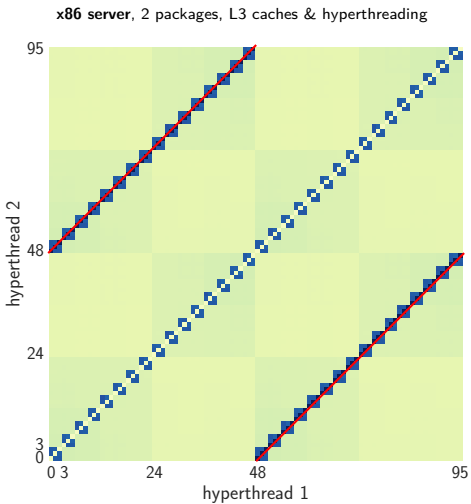

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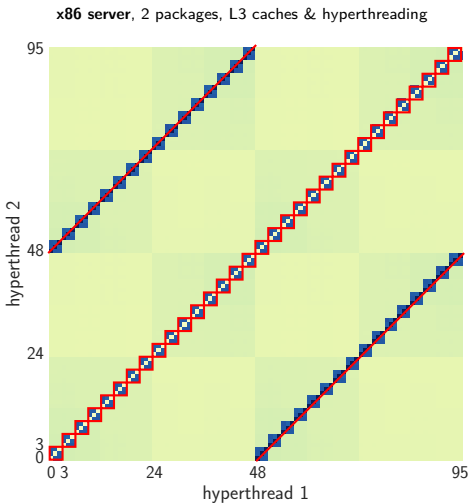

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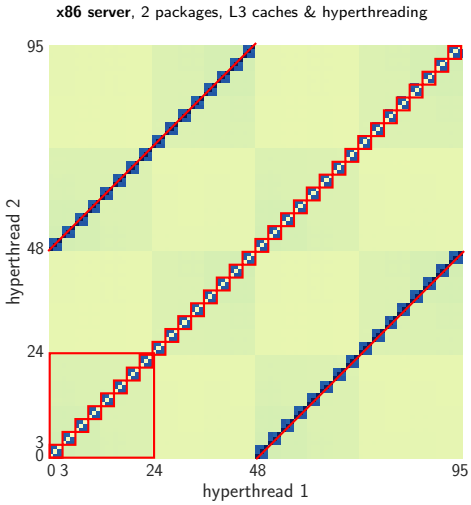

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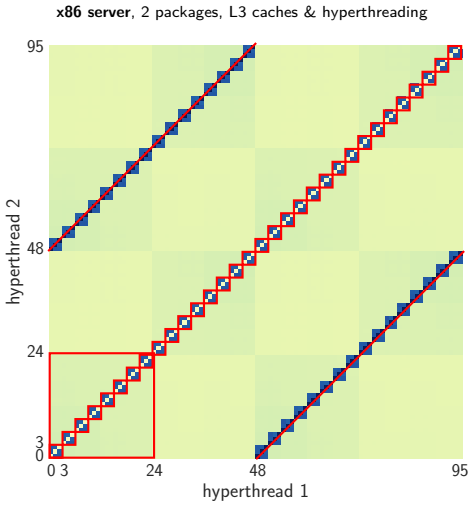
HMCS performs better when it sees the deep hierarchy



- The full hierarchy
  - hyperthreading – secondary diagonals
  - L3 cache partitions – 3×3 squares
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- HMCS lock can exploit the hierarchy
  - HMCS⟨2⟩, HMCS⟨3⟩: partial hierarchy
  - HMCS⟨4⟩: **full hierarchy**

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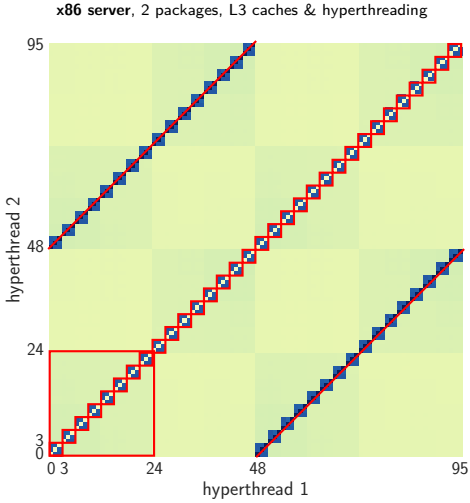

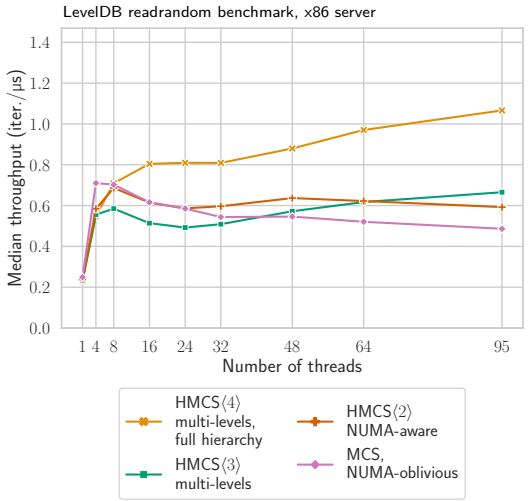

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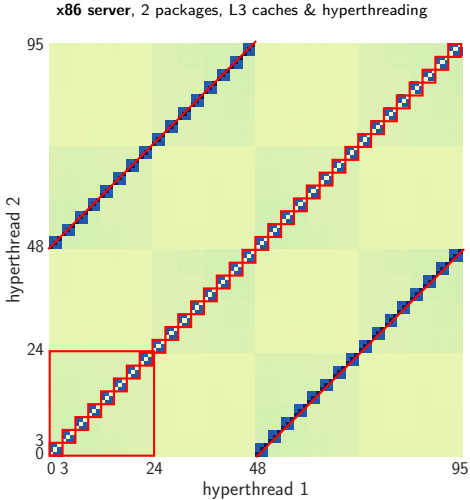
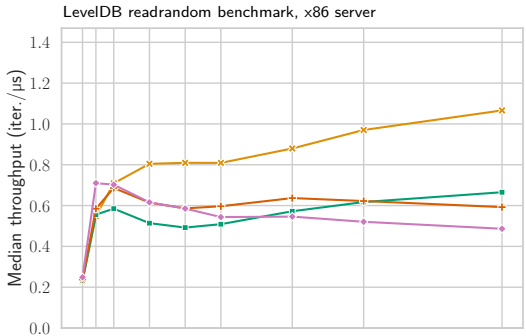


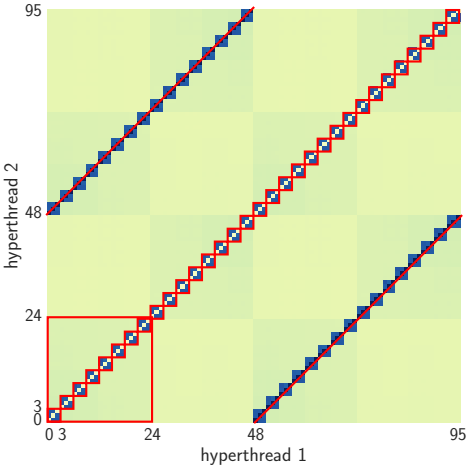


Multi-Level:
Encoding the actual deep hierarchy in a multi-level lock maximizes locality, thus improves performance.

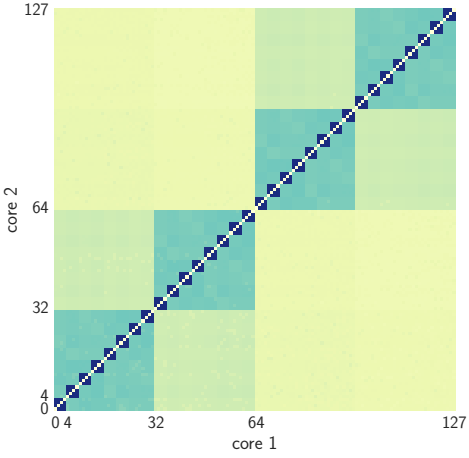
Challenge: exploiting the deep hierarchy of large NUMA machines

Different platforms may have different deep hierarchies

x86 server, 2 packages, L3 caches & hyperthreading

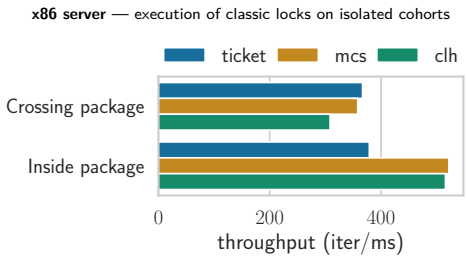


Arm server, 2 packages, 4 NUMA nodes, cache tagging



Challenge: locks perform differently according to scheduling & architecture

Comparing locks across different cohorts



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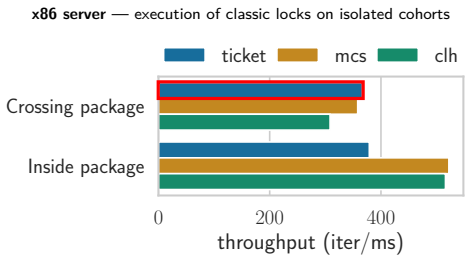

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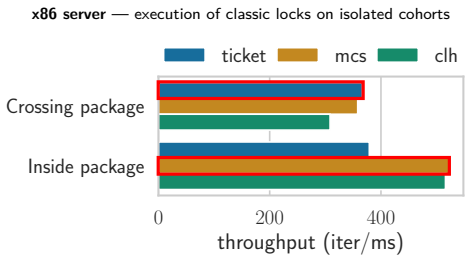

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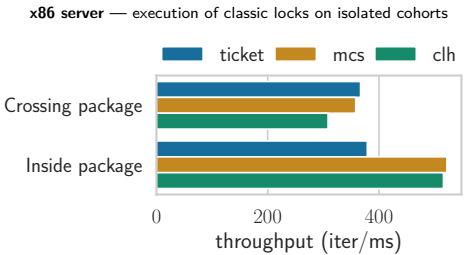

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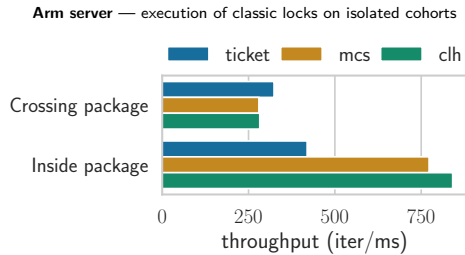

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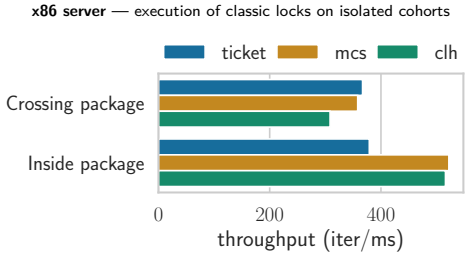

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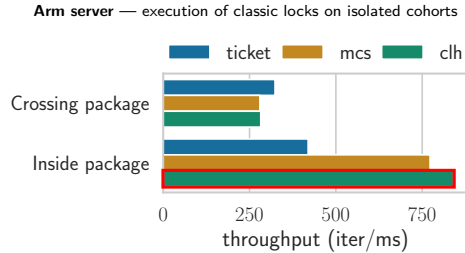

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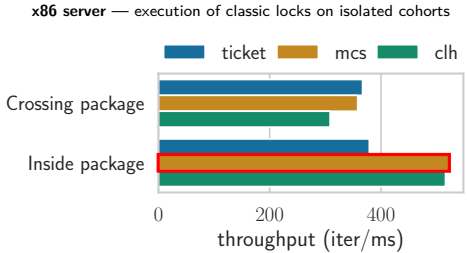

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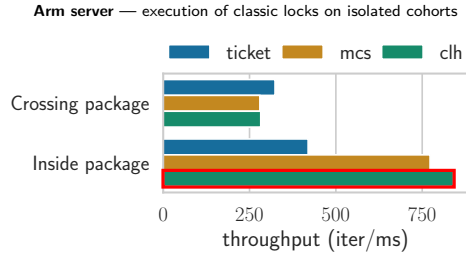

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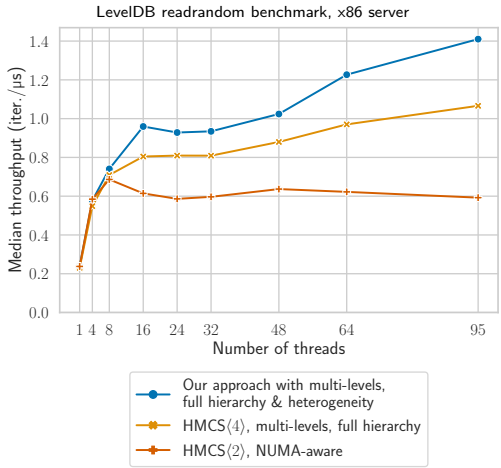
Challenge: locks perform differently according to scheduling & architecture

Potential performance benefits of heterogeneity

Heterogeneity:
Locks perform differently according to levels, architectures & platforms.



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Correctness on WMMs:
Lock correctness is critical but verifying it is very expensive.

Our contributions: CLoF

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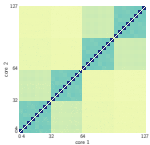
NUMA-aware locks		Correctness on WMMs	Heterogeneity	Multi-Level
lock cohorting	PPoPP'12	✗	✓	✗
HMCS	PPoPP'15	✗[1]	✗	✓
CNA lock	EuroSys'19	✗	✗	✗
ShflLock	SOSP'19	✗	✗	✗
CLoF	SOSP'21	✓	✓	✓

[1] Insufficient barriers, fixed in Oberhauser *et al.*, Verifying and Optimizing the HMCS Lock for Arm Servers, NETYS'2021.

The CLoF workflow

A user's perspective

Discover memory hierarchy



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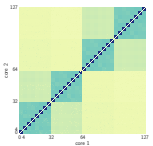

Verify correctness on WMMs with VSync

tkt clh mcs

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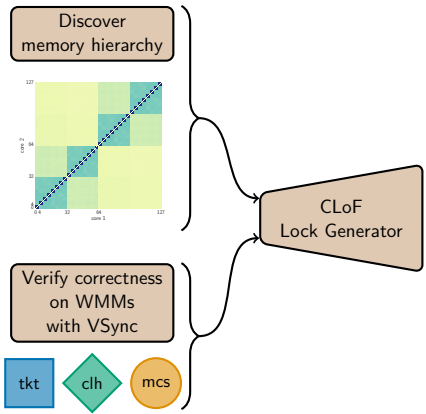

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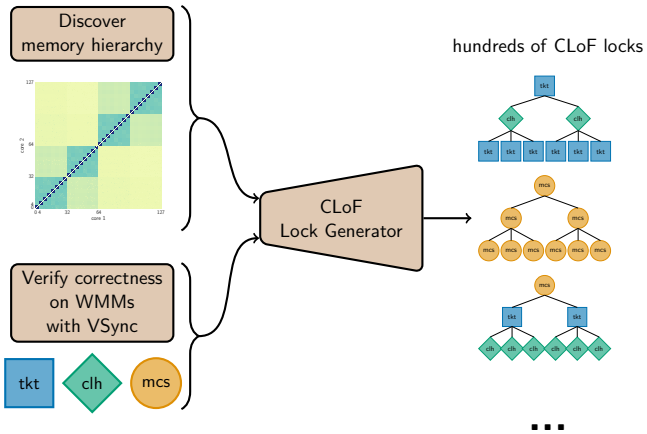

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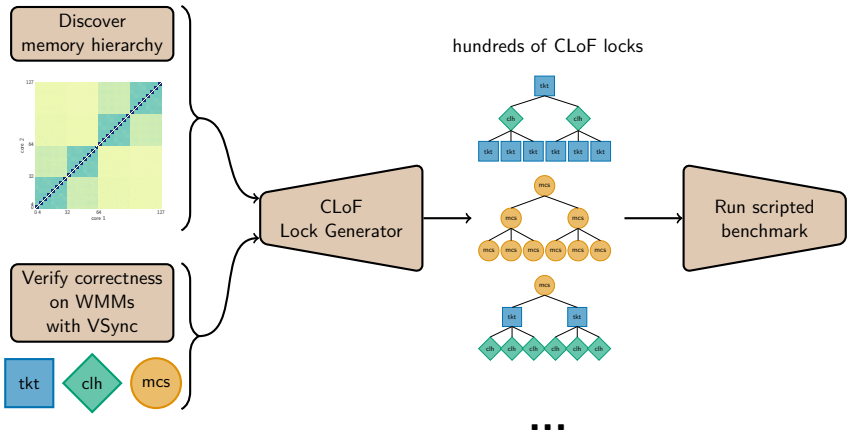

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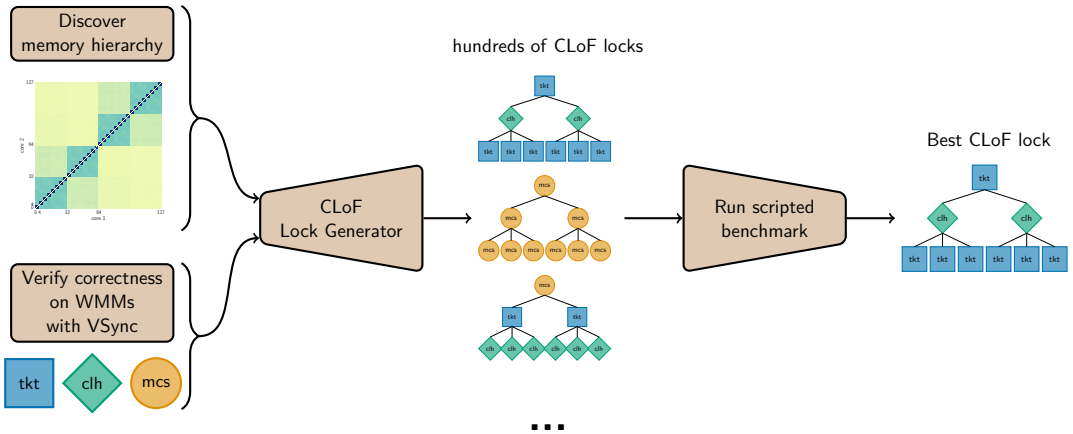

Composing CLoF locks

Two NUMA-node example

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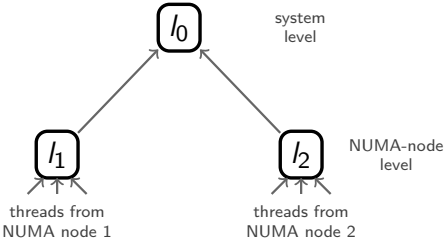

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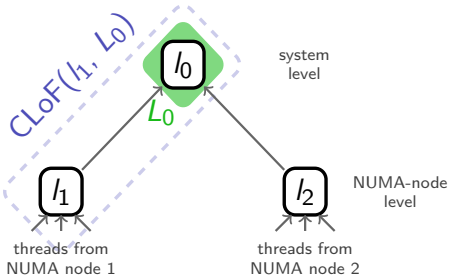

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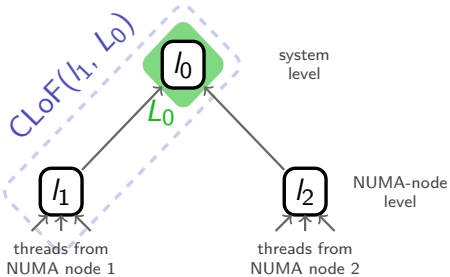

Simplified algorithm

CLoF(l, L)::acquire =
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    if (¬already has L)
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CLoF(l, L)::release =
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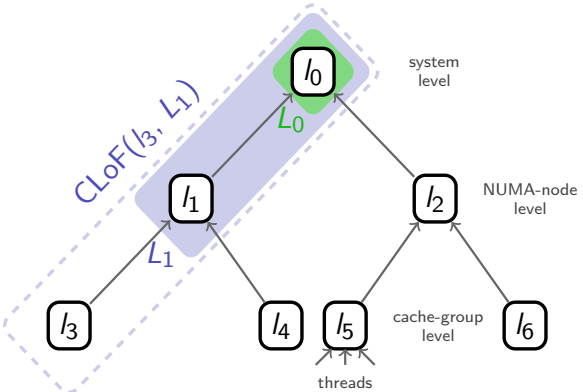

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CLoF correctness

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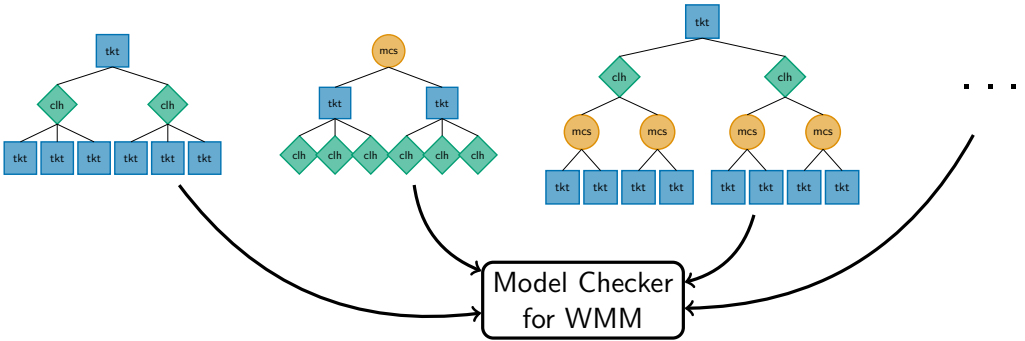

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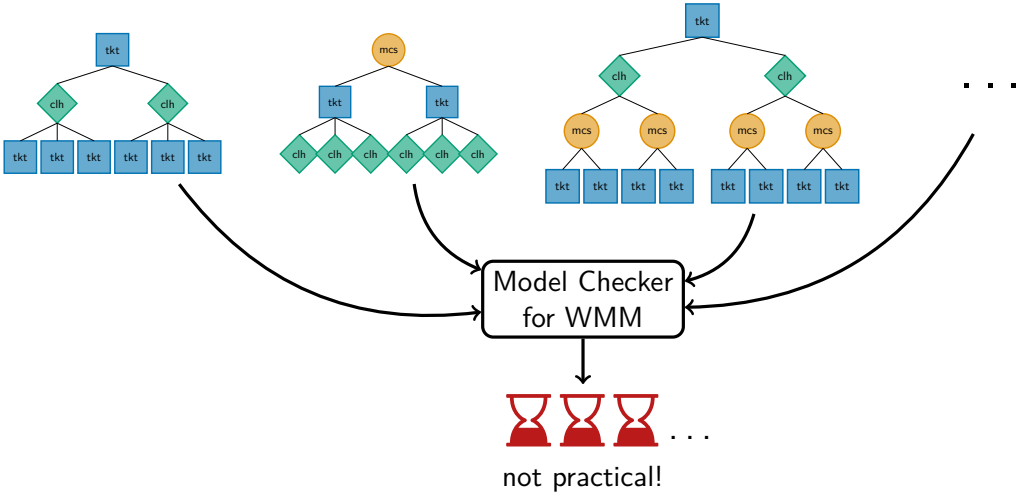

CLoF correctness

Combining induction argument with model checking

Base Step

Induction Step

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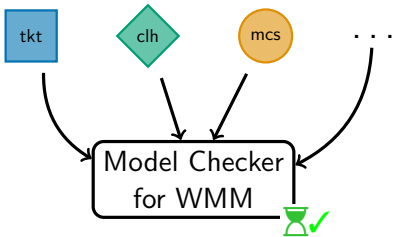

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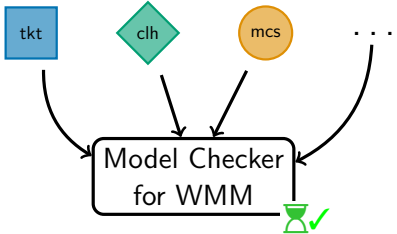

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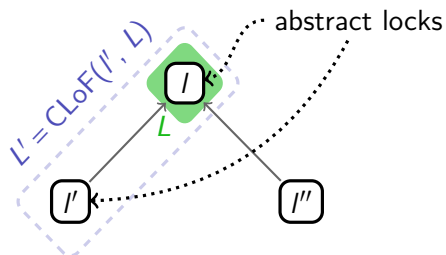

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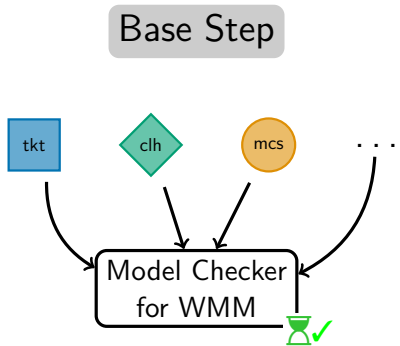

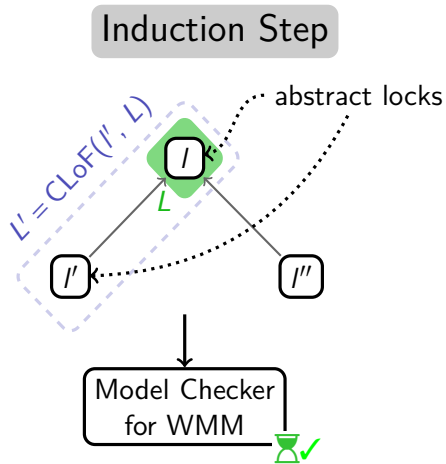

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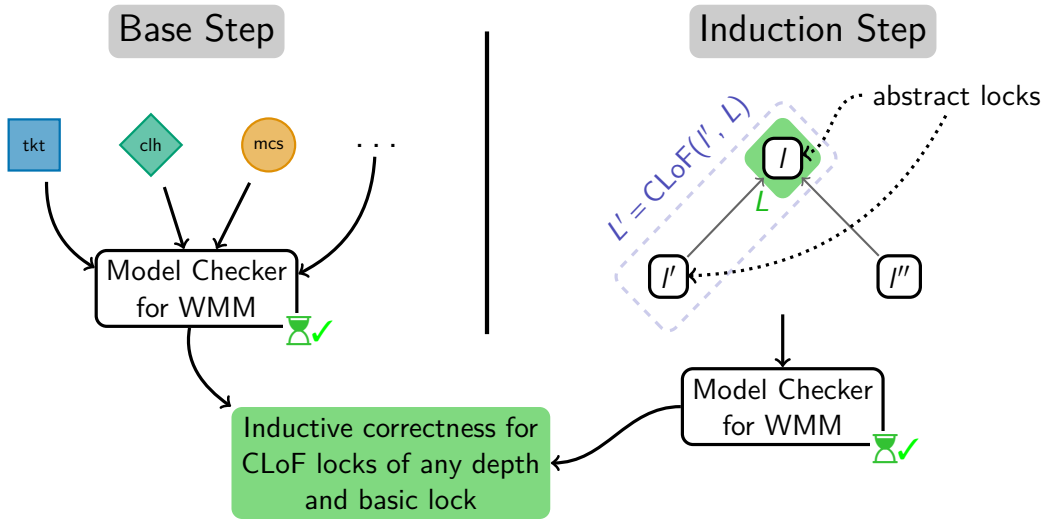
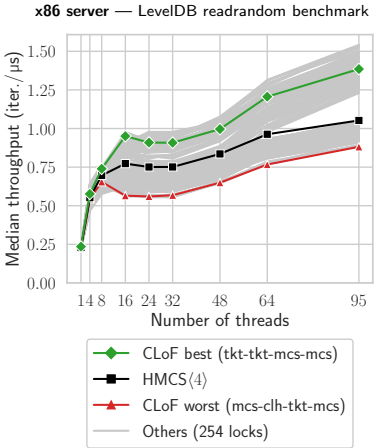
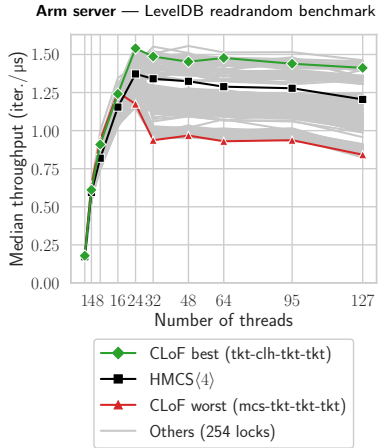


Select the best CLoF⟨4⟩ lock

Generating/evaluating 256 CLoF locks and selecting the best





Select the best CLoF⟨4⟩ lock

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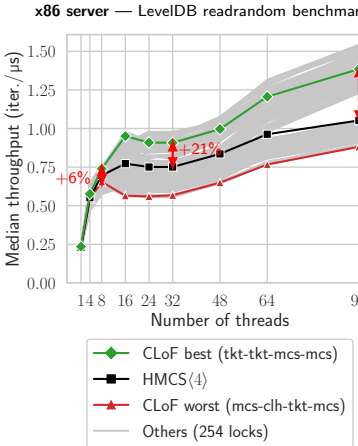

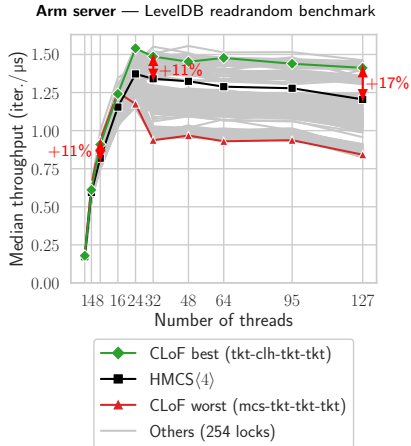

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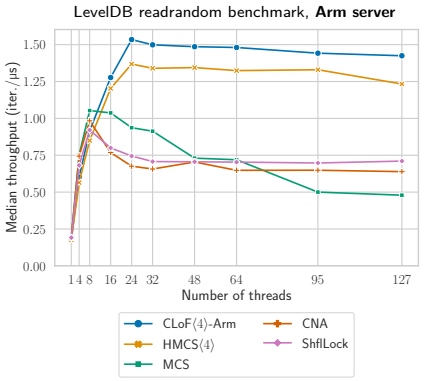

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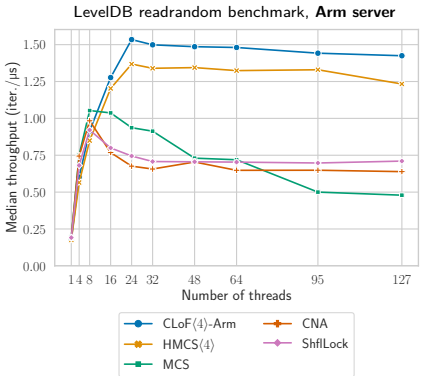

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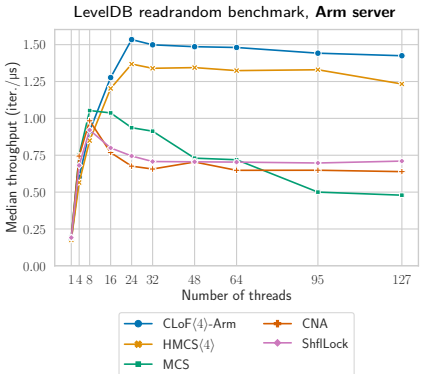
- **Future work**
  - CLoF in the Linux kernel
  - big.LITTLE platforms



Thank you

antonio.paolillo@huawei.com