Model Checking for Weakly Consistent Libraries

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Max Planck Institute for Software Systems (MPI-SWS)

How Do We Verify Concurrent Programs?

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Stateless Model Checking (SMC): enumerates all executions

- without explicitly *storing* the visited states

Challenges:

- State space explosion
- Weak memory

Challenge #1: State Space Explosion

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$[x = y = 0]$
$x := 1 \parallel x := 2 \parallel y := 42$

Executions:

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SMC+POR$^{\texttt{porf}}$: 1

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$\Rightarrow$ with the exception of `herd`

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What memory model **properties** are sufficient for efficient SMC?

Our contribution

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  - parametric in the choice of the memory model

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- **GenMC:** an SMC procedure
    - parametric in the choice of the memory model (+ libraries!)
    - sound, complete, optimal, and efficient

Generic Model Checking

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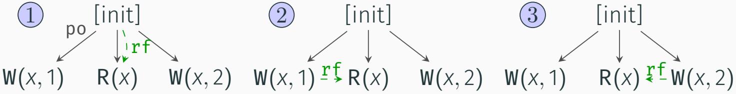

Systematically Enumerate All Graphs

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Can the reads of this program read 42?

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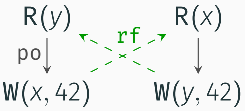

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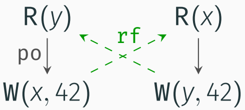

Can the reads of this program read 42?

The number of executions may be infinite!

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- po $\cup$ `rf` is acyclic

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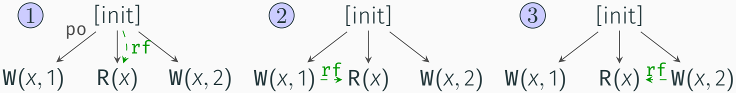

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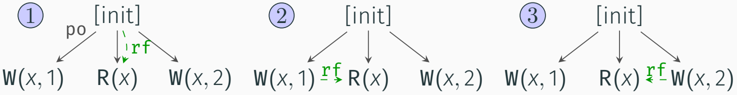

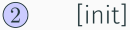

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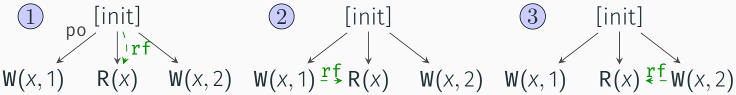

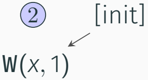

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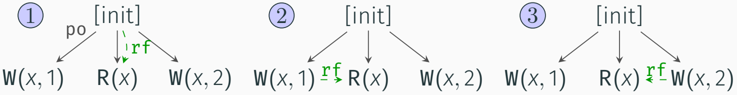

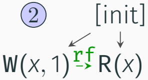

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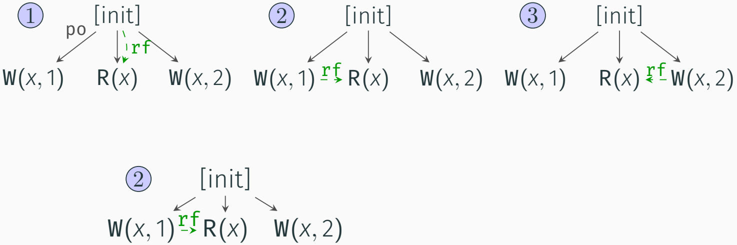

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[init]

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$$\texttt{W}(x, 1) \xleftarrow{} \text{[init]}$$

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$$\begin{array}{c} \phantom{\mathtt{W}(x,1) \xrightarrow{\mathtt{rf}}} \text{[init]} \\ \mathtt{W}(x, 1) \xrightarrow{\mathtt{rf}} \mathtt{R}(x) \end{array}$$

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$$
\begin{array}{ccc}
 & [\text{init}] & \\
\swarrow & \downarrow & \searrow \\
\mathtt{W}(x,1) \xrightarrow{\mathtt{rf}} & \mathtt{R}(x) & \mathtt{W}(x,2)
\end{array}
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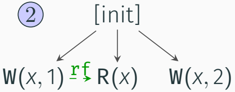

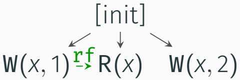

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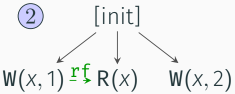

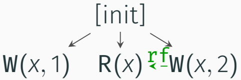

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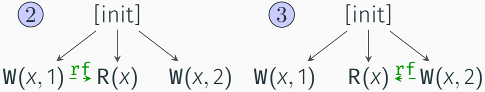

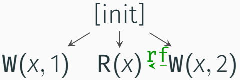

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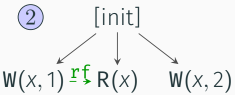

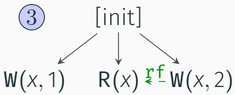

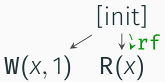

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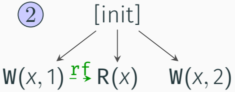

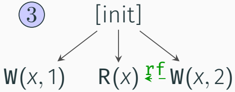

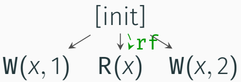

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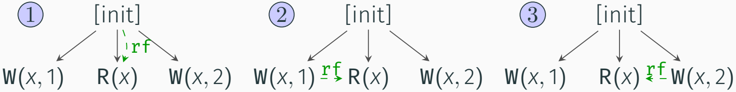

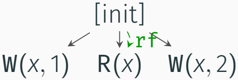

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but not by POWER and ARM

Handling Locks

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$[init(l)]$	
$lock(l)$ $unlock(l)$	$lock(l)$ $unlock(l)$

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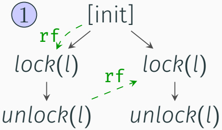

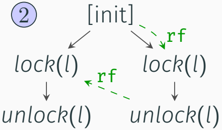

Results

An Interesting Example

	Nidhugg		RCMC	GenMC	
	SC	SC^{o}	$RC11^{\texttt{mo}}$	$RC11^{\texttt{mo}}$	$RC11^{\texttt{porf}}$
lamport(2)	.13	.10	.04	.03	.03
lamport(3)	7.53	4.49	5.40	6.87	1.36
lamport(4)	🕒	🕒	🕒	🕒	🕒

🕒 = tool did not finish within 2 days

All times are in seconds

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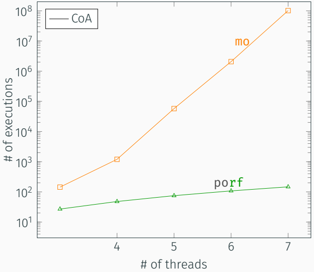
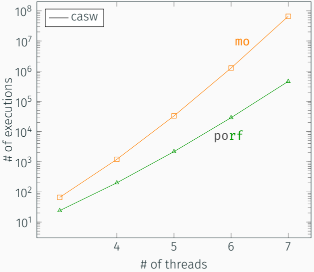
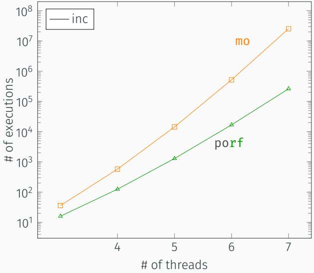
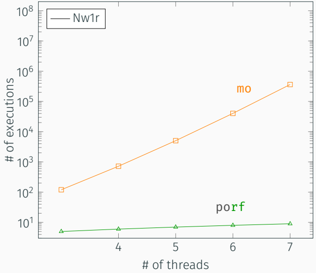
Equivalence Partitionings

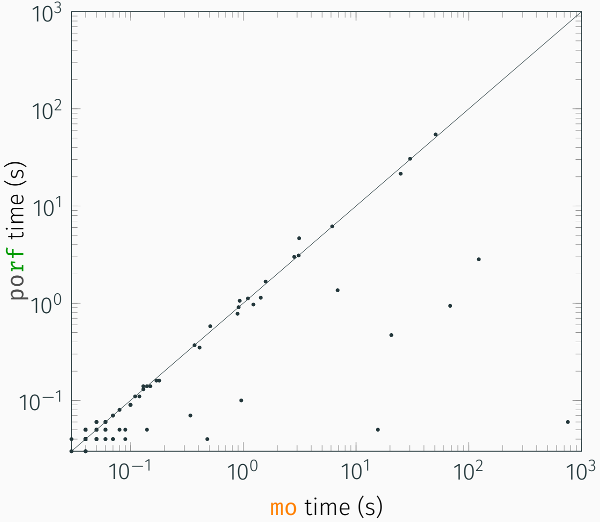








Equivalence Partitionings (202 benchmarks)



More in the paper

- Detailed description of the algorithm
- Formalization of memory model assumptions
- More benchmarks and evaluation

Conclusions

Summary

- Sound, complete, and optimal SMC procedure for memory models that are:
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  - prefix-closed
  - extensible
- GenMC can be exponentially faster than existing tools
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Future work

- Can we relax the memory-model assumptions?

Thank You!

Backup Slides

Why Extensibility Is Necessary

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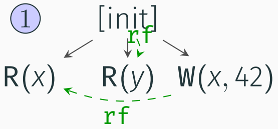

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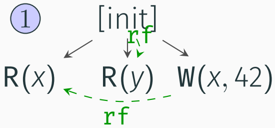

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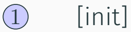

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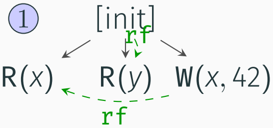

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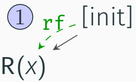

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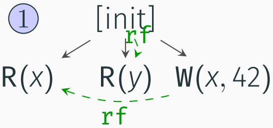

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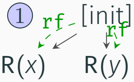

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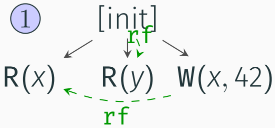

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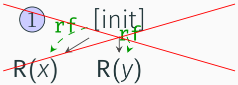

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[$init(l)$]	
$a : lock(l)$	$b : lock(l)$
$a' : unlock(l)$	$b' : unlock(l)$

$$
\begin{tikzcd}
init(l) \arrow[d, "\mathtt{rf}"', dashed] \arrow[d] \\
a : lock(l)
\end{tikzcd}
\rightsquigarrow
\begin{tikzcd}
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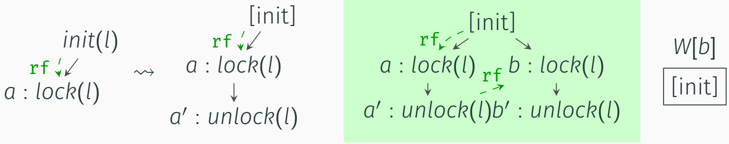

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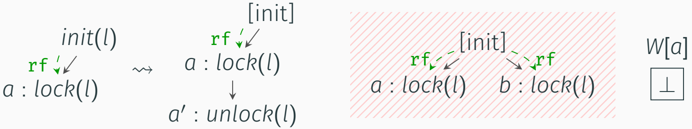
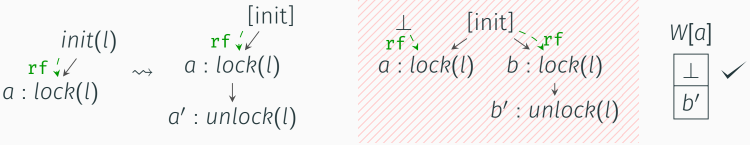
$[init(l)]$	
$a : lock(l)$ $a' : unlock(l)$	$b : lock(l)$ $b' : unlock(l)$



Handling Locks

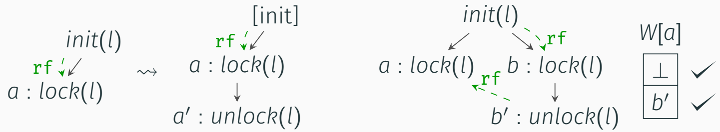
$[init(l)]$	
$a : lock(l)$	$b : lock(l)$
$a' : unlock(l)$	$b' : unlock(l)$



Handling Locks

$$[\mathit{init}(l)]$$

$a : \mathit{lock}(l)$	$\Vert$	$b : \mathit{lock}(l)$
$a' : \mathit{unlock}(l)$	$\Vert$	$b' : \mathit{unlock}(l)$



Linux-Kernel Benchmarks

	Nidhugg SC	Nidhugg TSO	Nidhugg PSO	RCMC RC11	RCMC WRC11	GENMC MO	GENMC WB
mcs_spinlock(2)	.12	.09	.10	.05	.05	.05	.05
mcs_spinlock(3)	2.98	6.84	12.54	.84	.67	.89	.78
mcs_spinlock(4)	0.68h	1.51h	3.32h	0.16h	0.15h	0.42h	0.26h
qspinlock(2)	.17	.11	.11	.04	.04	.04	.04
qspinlock(3)	10.93	18.20	23.43	2.13	2.08	1.10	1.12
seqlock(2)	.10	.09	.10	.04	.04	.04	.04
seqlock(3)	1.64	3.07	11.00	.49	.51	.37	.37