

# Relational Product of BDDs in External Memory

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**Steffan Christ Sølvesten**, Jaco van de Pol

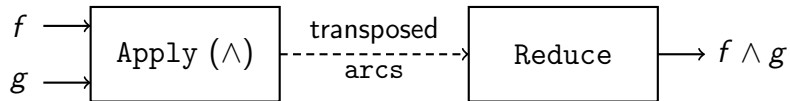
SPIN 2025

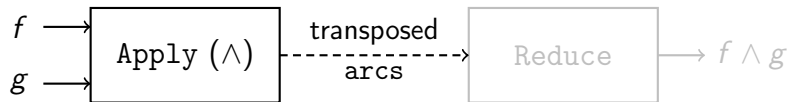


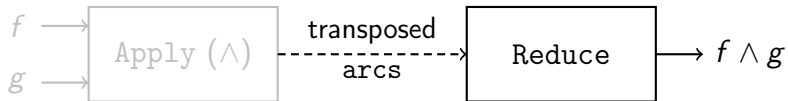
$$Next(S_{\vec{x}}, T_{\vec{x}, \vec{x}'}) \equiv ( \exists \vec{x}. S_{\vec{x}} \wedge T_{\vec{x}, \vec{x}'} )[\vec{x}' / \vec{x}]$$

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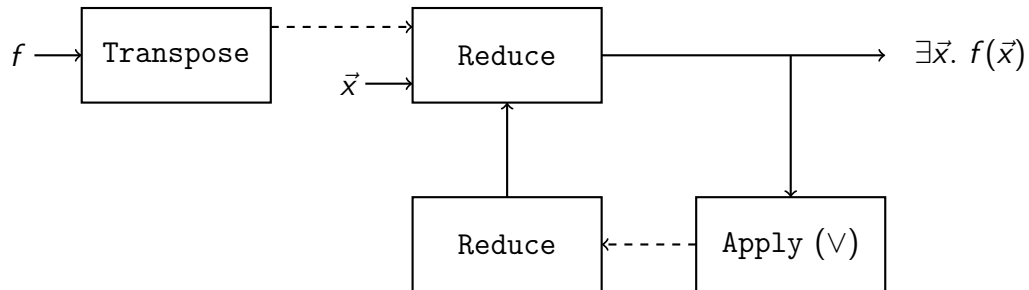




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[TACAS 25]

$$\begin{array}{c}
\text{[TACAS 22]} \\
| \\
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\end{array}$$

# Replace

## Definition

A relabelling  $\pi$  is monotonic if  $x_i < x_j \implies \pi(x_i) < \pi(x_j)$

## Lemma

*If  $\pi$  is monotonic, then the BDD  $f(\vec{x})$  is isomorphic to  $f(\pi(\vec{x}))$ .*

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$\mathcal{O}(N)$  time,  $2 \cdot \text{scan}(N)$  I/Os, and  $N$  external space.

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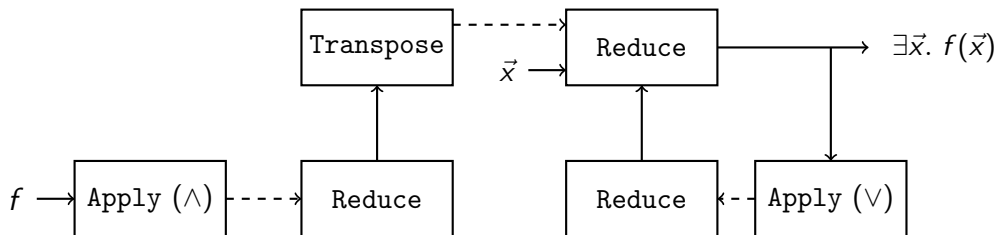
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- **One can apply  $\pi$  in a single linear scan.**  
 $\mathcal{O}(N)$  time,  $2 \cdot \text{scan}(N)$  I/Os, and  $N$  external space.
- **One can incorporate  $\pi$  into a (succeeding) top-down Apply sweep.**  
 $\mathcal{O}(N)$  time, 0 I/Os, and 0 external space.
- **One can incorporate  $\pi$  into a (preceeding) bottom-up Reduce sweep.**  
 $\mathcal{O}(n)$  time, 0 I/Os, and 0 external space.

# AndExists

## Observation

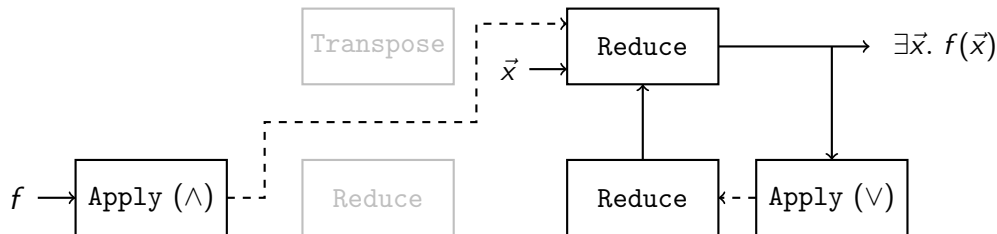
The I/O-efficient And [TACAS 22] and Exists [TACAS 25] operations can be merged:



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This saves  $\Theta(\text{sort}(N))$  time and I/Os.



# AndExists

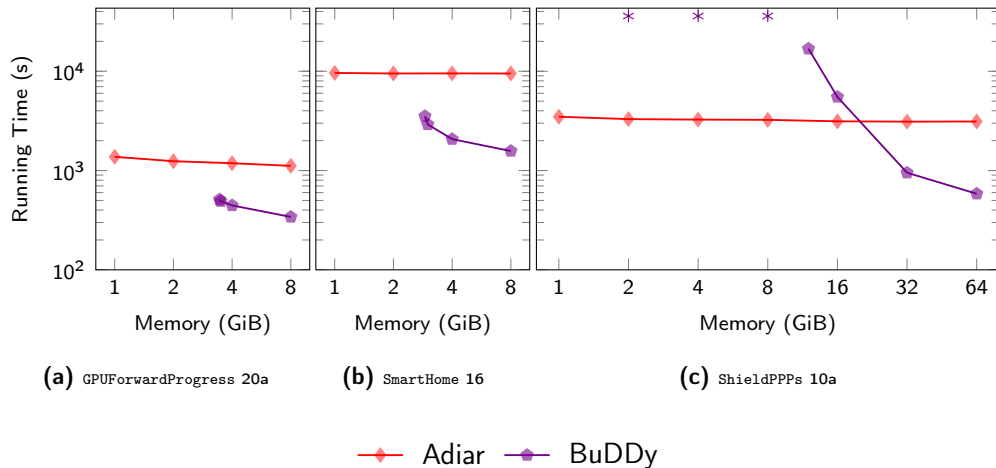
## Observation

The I/O-efficient And [TACAS 22] and Exists [TACAS 25] operations can be merged:

- **The outer accumulating Reduce sweep of the Exists can do double-duty as the Reduce sweep of the preceeding And operation.**  
This saves  $\Theta(\text{sort}(N))$  time and I/Os.
- **The And operation can prune subtrees that trivially will become redundant during the succeeding Exists.**  
This can save up to  $\mathcal{O}(\text{sort}(N^{2^{n-1}}))$  time and I/Os.  
In practice, this only saves up to  $\mathcal{O}(\text{sort}(N))$  time and I/Os.

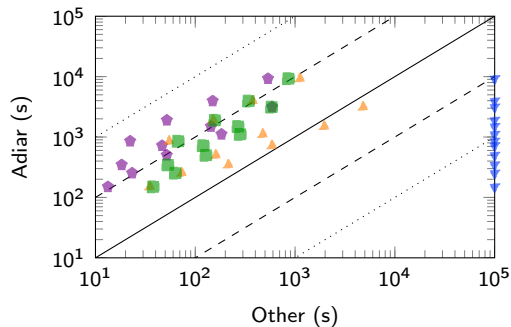


## Experiment: $\text{Next}(S_{\vec{x}}, T_{\vec{x}, \vec{x}'})$

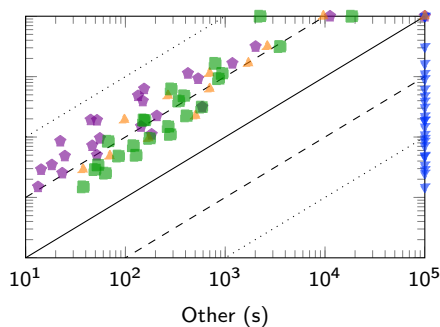


Relational Product for MCC models with a  $2^{25}$  state space BDD. Timeouts are marked as stars.

## Experiment: $\text{Next}(S_{\vec{x}}, T_{\vec{x}, \vec{x}'})$ & $\text{Prev}(S_{\vec{x}}, T_{\vec{x}, \vec{x}'})$



(a)  $\text{Next}(S_{\vec{x}}, T_{\vec{x}, \vec{x}'})$

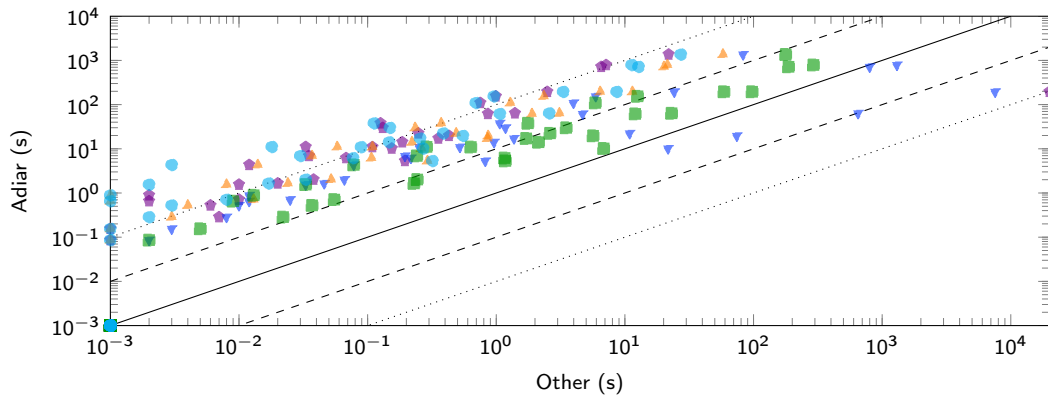


(b)  $\text{Prev}(S_{\vec{x}}, T_{\vec{x}, \vec{x}'})$

◆ BuDDy ▼ CAL ▲ CUDD ■ LibBDD

Relational Product for MCC models, 384 GiB of memory, and  $2^{22}, \dots, 2^{25}$  state space BDDs.

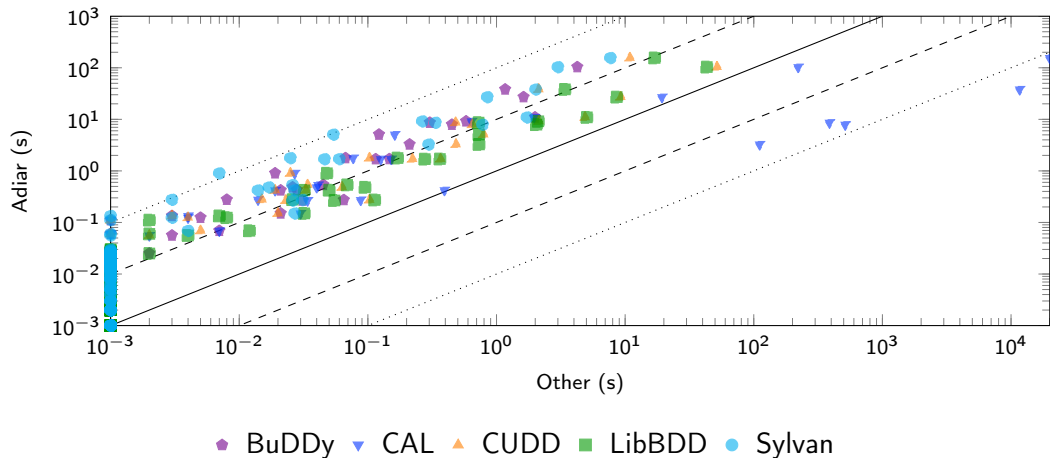
## Experiment: Reachability



◆ BuDDy ▼ CAL ▲ CUDD ■ LibBDD ● Sylvan

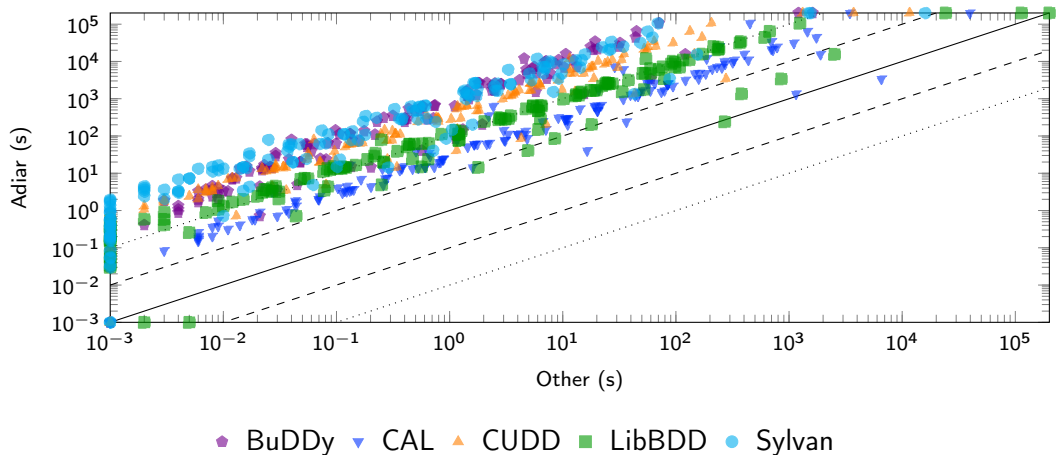
16 Petri Nets [MCC 21–23] with 384 GiB of memory.

## Experiment: Deadlock Detection



16 Petri Nets [MCC 21–23] and 59 Boolean Networks [AEON, PyBoolNet] with 384 GiB RAM.

## Experiment: SCC Decomposition



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# Conclusions and Future Work

- To improve the I/O-efficient  $Next(S_{\vec{x}}, T_{\vec{x}, \vec{x}'})$ , focus on *AndExists*.
  - Factor of  $\sim 2\times$  by using a *AndExists* instead of *And* and *Exists* for conventional depth-first implementations [1]. This may explain the sudden performance gap.
  - For larger instances, less than  $\frac{1}{10}$ th of the time is spent on the *And*.

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- [1] Van Dijk et al.: *A Comparative Study of BDD packages for Probabilistic Symbolic Model Checking*. (2015)
  - [2] Van Dijk: *Sylvan – Multi-core Decision Diagrams*. (2016)
  - [3] Van Dijk et al.: *Multi-core on-the-fly saturation*. (2019)
  - [4] Brand et al.: *A Decision Diagram Operation for Reachability*. (2023).
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- Design a  $Replace(\pi)$  for Non-monotone Variable Substitutions.

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🌐 [ssoelvsten.github.io](https://ssoelvsten.github.io)

## Adiar

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🔗 [github.com/ssoelvsten/adiar](https://github.com/ssoelvsten/adiar)

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