Dynamic Reductions for Model Checking Concurrent Software

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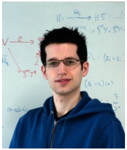

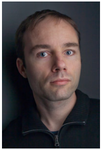

Formal Methods in Systems Engineering
Vienna University of Technology

March 21, 2017

Reductions

Model Checking of Concurrent Software

1. Explosion of interleavings
2. Partial-order reduction vs Lipton reduction
3. Symbolic is a challenge
4. *Global* commutativity is needed, but a severe bottleneck

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b = 2;                  x += 2;
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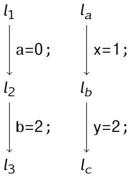

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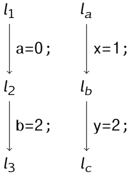

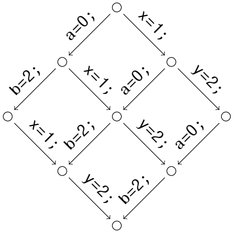

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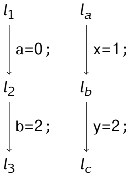

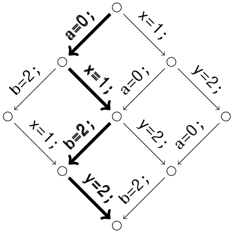

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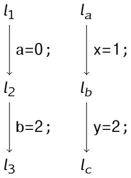

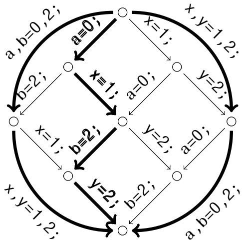

Transactions in databases

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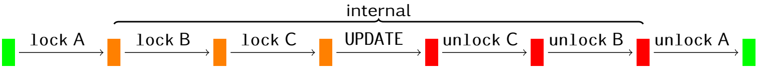

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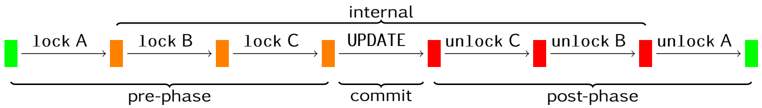

Commutativity

Action α right commutes with β, iff α can always be delayed after β:

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Definition (Right commutativity ($\overrightarrow{\bowtie}$))

$$\alpha \mathrel{\overrightarrow{\bowtie}} \beta \quad \text{iff} \quad \forall \sigma_1,\sigma_2,\sigma_3 : \begin{array}{ccc} \sigma_1 & & \\ \downarrow{\scriptstyle\alpha} & & \\ \sigma_2 & \xrightarrow{\beta} & \sigma_3 \end{array} \quad \Rightarrow \exists \sigma_4 : \begin{array}{ccc} \sigma_1 & \xrightarrow{\beta} & \sigma_4 \\ \downarrow{\scriptstyle\alpha} & & \downarrow{\scriptstyle\alpha} \\ \sigma_2 & \xrightarrow{\beta} & \sigma_3 \end{array}$$

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- An action both-commutes with all actions that access a disjoint set of variables.
- A lock(/unlock) right(/right)-commutes with other lock and unlock operations.

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Definition (Right-Movability)

The action α of thread i is a right-mover, iff for all $j \neq i$: $\xrightarrow{\alpha}_i \overrightarrow{\bowtie} \rightarrow_j$

Lipton Reduction

[Lipton '77, Lamport et al. '89]

Example (A statement sequence, where x is the only global variable)

```
a = 1; x = 2; b = 3; c = 4;
```

Lipton Reduction

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a = 1; x = 2; b = 3; c = 4;    ⇝    a, x, b, c = 1, 2, 3, 4;
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Lipton Reduction

A statement $\alpha_1;\ldots;\alpha_n$ of thread i can be reduced to $\alpha_1 \circ \cdots \circ \alpha_n$, if for some $1 \leq k < n$, and all $j \neq i$:

1. $\alpha_1,\ldots,\alpha_{k-1} \overset{\rightarrow}{\bowtie} \rightarrow_j$ (*pre-phase* statements (before α_k) are *right movers*)
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$\xrightarrow{x\ =\ 6}$ $\xrightarrow{a\ =\ 1}$ $\xrightarrow{x\ =\ 7}$ $\xrightarrow{x\ =\ 8}$ $\xrightarrow{x\ =\ 2}$ $\xrightarrow{b\ =\ 3}$ $\xrightarrow{x\ =\ 9}$ $\xrightarrow{c\ =\ 4}$

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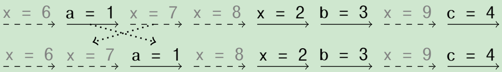

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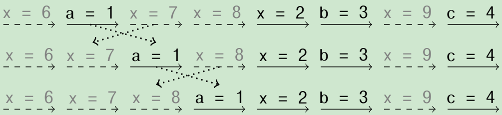

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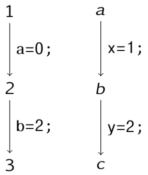
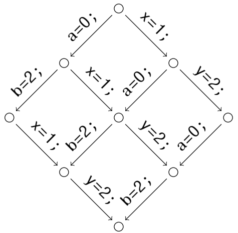
Movability is too strong a condition





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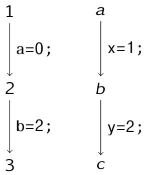

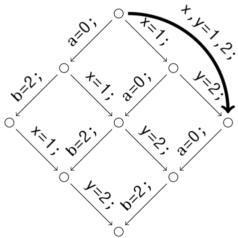

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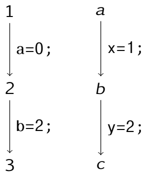

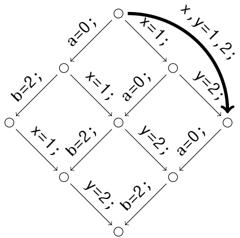

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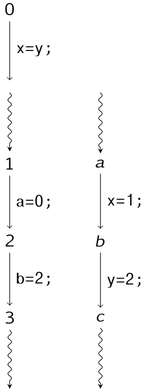

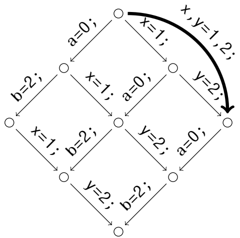

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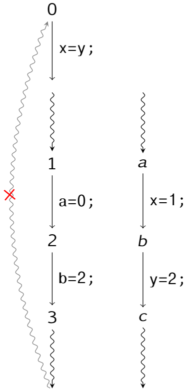

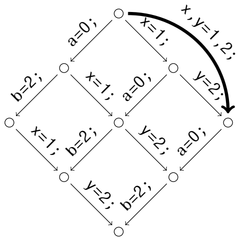

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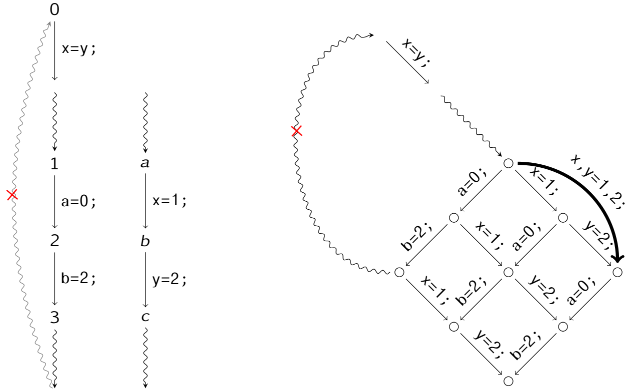

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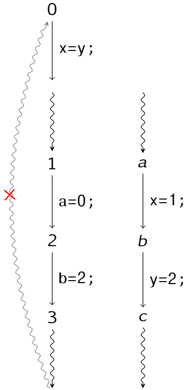

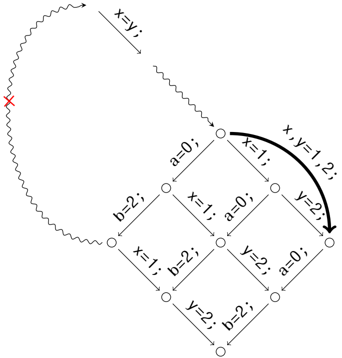

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Monotonicity is key!

Example

```
   int *data = NULL;
   void worker_thread(int tid) {
     if (data == NULL) {
       int *tmp = read_from_disk(1024);
W:     if (!CAS(&data, NULL, tmp)) free(tmp);
     }
     for (int i = 0; i < 512; i++)
R:     process(data[i + tid * 512]);
   }
   int main () {
     pthread_create(worker_thread, 0); // T1
     pthread_create(worker_thread, 1); // T2
   }
```

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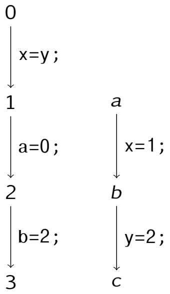
Example

Other dynamic conditions

- Pointers / array indices that don't change value.
- Atomic Compare-And-Swap (CAS) operations to permanently grab resources.

```
  pthread_create(worker_thread, 0); // T1
  pthread_create(worker_thread, 1); // T2
}
```

Instrumentation with dynamic reduction



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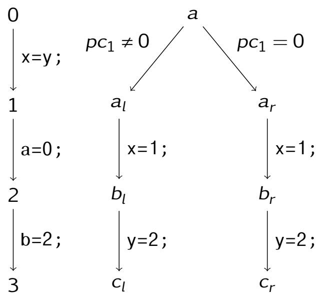

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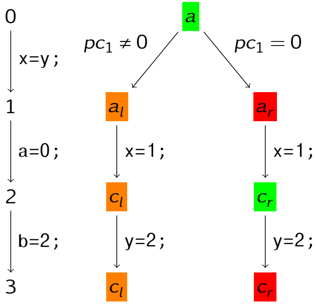

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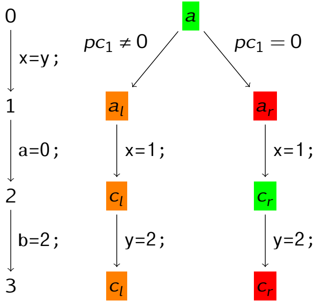

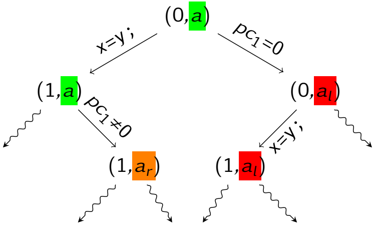

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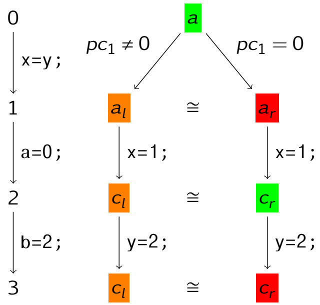

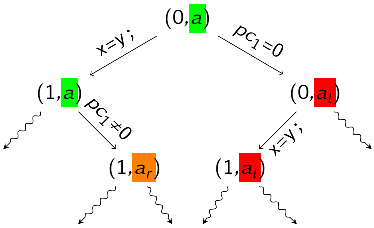

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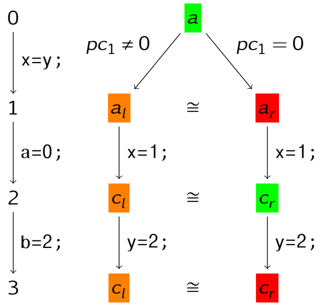

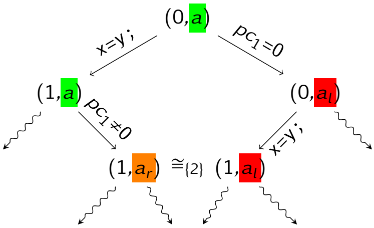

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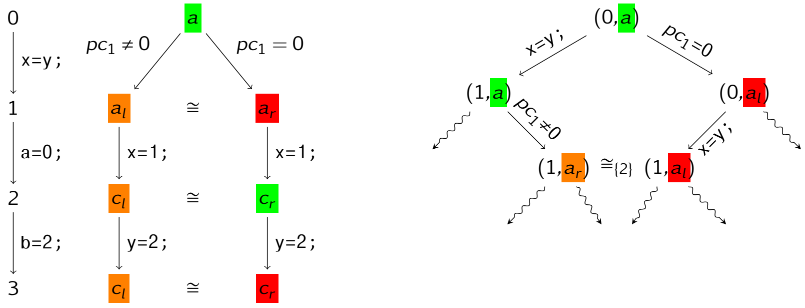

Definition (Dynamic *both*-moving conditions)

A state predicate c_α is a dynamic both-moving condition for an action α, if for all $j \neq i$:

1. $(c_\alpha \,/\!/\!\xrightarrow{\alpha}_i) \bowtie (c_\alpha \,/\!/\!\rightarrow_j)$
2. c_α is never disabled

Instrumentation with dynamic reduction

Example (Heuristics for other dynamic conditions)

```
int T[10] = {E,E,22,35,46,25,E,E,91,E};

int find-or-put(int v) {
   int hash = v / 10;
   for (int i = 0; i < 10; i++) {
      int index = (i + hash) % 10;
      if (CAS(&T[index], E, v)) {
         return INSERTED;
      } else if (T[index] == v)
         return FOUND;
   }
   return TABLE_FULL;
}
int main() {
   pthread_create(find-or-put, 25);
   pthread_create(find-or-put, 42);
}
```

Instrumentation with dynamic reduction

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         return FOUND;
   }
   return TABLE_FULL;
}
int main() {
   pthread_create(find-or-put, 25);
   pthread_create(find-or-put, 42);
}
```

c_α := `T[index] != E`

Movability up to bisimulation

Definition (Right-commutativity up to bisimulation ($\overrightarrow{\bowtie}_X$))

The transition relation $\xrightarrow{\alpha}_i$ right-commutes with $\xrightarrow{\beta}_j$ up to $\cong_X$, notation $\xrightarrow{\alpha}_i \overrightarrow{\bowtie}_X \xrightarrow{\beta}_j$, iff:

$$\forall \sigma_1, \sigma_2, \sigma_3 : \begin{array}{ccc} \sigma_1 & & \\ \downarrow \alpha & & \\ \sigma_2 & \xrightarrow{\beta}_j & \sigma_3 \end{array} \quad \Rightarrow \exists \sigma_3', \sigma_4 : \begin{array}{ccccc} \sigma_1 & \xrightarrow{\beta}_j & \sigma_4 & & \\ \downarrow \alpha & & & \searrow \alpha & \\ \sigma_2 & \xrightarrow{\beta}_j & \sigma_3 & \cong_X & \sigma_3' \end{array}$$

Definition (Right-movability up to bisimulation)

The action α of thread i is a right-mover up to $\cong_X$, iff for all $j \neq i$: $\xrightarrow{\alpha}_i \overrightarrow{\bowtie}_X \rightarrow_j$

Transaction Reduction

[Flanagan, Qadeer SoftMC'03]

Theorem (Reduction)

Let $(\rightarrow, \mathcal{S})$ be a transition system. For all $i, j \neq i$, let $\mathcal{S} = R_i \uplus L_i \uplus N_i$ such that

0. $L_i \,/\!\!/\!\rightarrow_i\!\setminus\!\!\setminus R_i = \emptyset$ — *post does not reach pre*
1. $\rightarrow_i\!\setminus\!\!\setminus R_i \overrightarrow{\bowtie} \rightarrow_j$ — *$\rightarrow_i$ into pre right commutes with $\rightarrow_j$*
2. $L_i \,/\!\!/\!\rightarrow_i \overleftarrow{\bowtie} \rightarrow_j$ — *$\rightarrow_i$ from post left commutes with $\rightarrow_j$*
3. $\forall \sigma \in L_i : \exists \sigma' \in N_i : \sigma \rightarrow_i^* \sigma'$ — *post phases terminate*

Let $\hookrightarrow_i \triangleq \bigcup_{j \neq i} N_j \,/\!\!/\!\rightarrow_i$ (i can only transition when all j are in an external state).

Suppose $\sigma \rightarrow^* \sigma'$, $\sigma \in N$ and $\sigma' \in N$, then there is an $\sigma'' \in N$ s.t. $\sigma \hookrightarrow^* \sigma''$.

Dynamic Transaction Reduction

[Günther, Laarman, Sokolova, Weissenbacher VMCAI'17]

Theorem (Reduction)

Let $(\rightarrow, \mathcal{S})$ be a transition system. For all $i, j \neq i$, let $\mathcal{S} = R_i \uplus L_i \uplus N_i$ such that
For each thread i, there exists a thread bisimulation relation $\cong_i$, and:

0. $L_i /\!\!/\!\rightarrow_i \!\backslash\!\backslash\, R_i = \emptyset$ — *post does not reach pre*
1. $\rightarrow_i \!\backslash\!\backslash\, R_i \overrightarrow{\bowtie}_{\{j\}} \rightarrow_j$ — *$\rightarrow_i$ into pre right commutes with $\rightarrow_j$*
2. $L_i /\!\!/\!\rightarrow_i \overleftarrow{\bowtie}_{\{i,j\}} \rightarrow_j$ — *$\rightarrow_i$ from post left commutes with $\rightarrow_j$*
3. $\forall \sigma \in L_i : \exists \sigma' \in N_i : \sigma \rightarrow_i^* \sigma'$ — *post phases terminate*
4. $\cong_i \subseteq L_j^2 \cup R_j^2 \cup N_j^2$ — *($\cong_i$ entails j-phase-equality)*

Let $\hookrightarrow_i \triangleq \bigcup_{j \neq i} N_j /\!\!/\!\rightarrow_i$ (i can only transition when all j are in an external state).
Let $\rightsquigarrow_i \triangleq N_i /\!\!/ (\hookrightarrow_i \!\backslash\!\backslash\, \overline{N_i})^* \hookrightarrow_i \!\backslash\!\backslash\, N_i$ (block steps skip internal states)
Suppose $\sigma \rightarrow^* \sigma'$, $\sigma \in N$ and $\sigma' \in N$, then there is an $\sigma'' \in N$ s.t. $\sigma \rightsquigarrow^* \sigma''$.

Complete instrumentation

$G_i \triangleq (V_i, \delta_i)$	V_i', δ' in G_i' (pictured)
$\forall (l_a, \alpha, l_b) \in \delta_i$:	$l_a^N \xrightarrow{c_\alpha /\!/ \alpha} l_b^R$, $l_a^N \xrightarrow{\neg c_\alpha /\!/ \alpha} l_b^L$
$\forall (l_a, \alpha, l_b) \in \delta_i$:	$l_a^{R'} \xrightarrow{c_\alpha /\!/ \alpha} l_b^R$, $l_a^{R'} \xrightarrow{\neg c_\alpha /\!/ \alpha} l_b^L$
$\forall l_a \in V_i$:	$l_a^R \xrightarrow{\text{true}} l_a^{R'}$
$\forall l_a \in V_i \setminus LFS_i$:	$l_a^L \xrightarrow{c(l_a)} l_a^{L'}$, $l_a^L \xrightarrow{\neg c(l_a)} l_a^N$ with $c(l_a) \triangleq \bigwedge_{(l_a,\alpha,l_b)\in\delta_i} c_\alpha$
$\forall (l_a, \alpha, l_b) \in \delta_i, l_a \in V_i \setminus LFS_i$:	$l_a^{L'} \xrightarrow{\alpha} l_b^L$
$\forall l_a \in LFS_i$:	$l_a^L \xrightarrow{\text{true}} l_a^N$

Complete instrumentation

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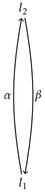
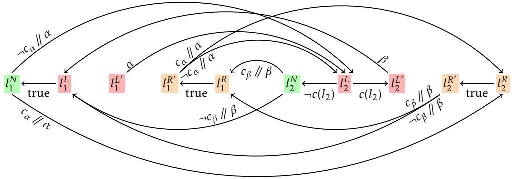
$\forall (l_a, \alpha, l_b) \in \delta_i, l_a \in V_i \setminus LFS_i :$	$l_a^{L'} \xrightarrow{\alpha} l_b^L$
$\forall l_a \in LFS_i :$	$l_a^L \xrightarrow{\text{true}} l_a^N$





VVT

Vienna Verification Tool [Günther, Laarman, Weissenbacher SVCOMP'16]

http://vvt.forsyte.at/ (open source)

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- BMC with all dynamic reductions (*BMC-dyn* in the graphs);
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- IC3 with all dynamic reductions (*IC3-dyn*); and
- IC3 with only static reductions (*IC3-phase*).

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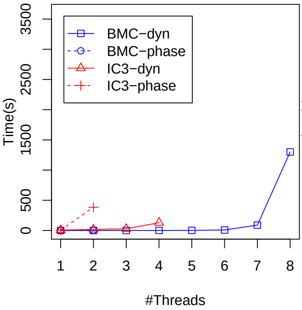
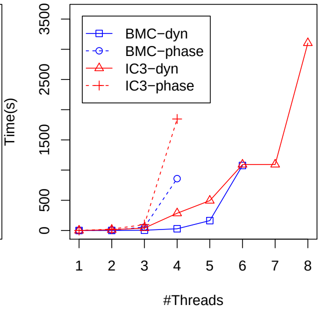


Lazy initialization



Dynamic locking

VVT

Vienna Verification Tool [Günther, Laarman, Weissenbacher SVCOMP'16]

`http://vvt.forsyte.at/` (open source)

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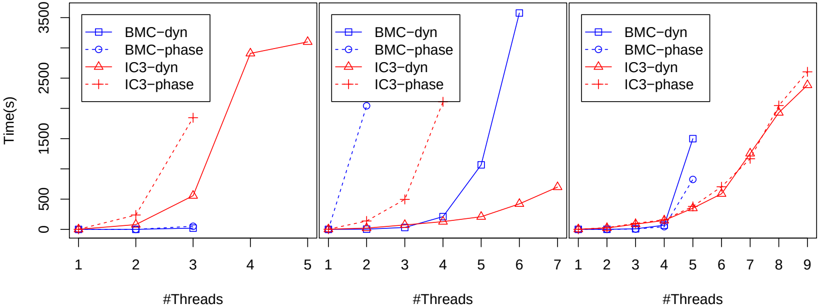
- IC3 with all dynamic reductions (*IC3-dyn*); and
- IC3 with only static reductions (*IC3-phase*).



Hash table reads/writes   Hash table reads   Hash table writes

Conclusions

Contributions

- Dynamic movers as in stubborn set POR
- "Straight-forward" instrumentation and encoding
- Dynamic mover conditions are suitable for symbolic model checking

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- Dynamic movers as in stubborn set POR
- "Straight-forward" instrumentation and encoding
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Open Questions

- Is a weaker reduction theorem possible?
- How do transactions compare to POR?