Integrating Loop Acceleration into Bounded Model Checking

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Setting

Safety Problems by Example

Pre Variables: x, y Post Variables: x', y' (domain: $\mathbb{Z}$ – in this talk)

Start States: $\psi_s := x \leq 0 \land y \leq 0$ Error States: $\psi_e := y \geq 100$

Transition Formula: $\tau := \underbrace{(x < 100 \land x' = x + 1 \land y' = y)}_{\tau_i} \lor \underbrace{(x = 100 \land x' = 0 \land y' = y + 1)}_{\tau_r}$ (QF)

Example (Transition Relation)

$(23, 42) \to_\tau (24, 42)$ as $[x/23, y/42, x'/24, y'/42] \models \tau$

Dependency Graphs

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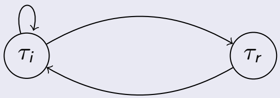

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$b \leftarrow 0$; add($\mathrm{vr}_b(\psi_s)$) where $\mathrm{vr}_b(x) := x_b, \mathrm{vr}_b(x') := x_{b+1}, \ldots$

while $\top$ **do**

- push(); add($\mathrm{vr}_b(\psi_e)$)
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A function with $\mathrm{accel}(\tau) := \tau^{\oplus}$ where $\to_{\tau^{\oplus}} \subseteq \to_{\tau}^{+}$.

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How? Many techniques, e.g…

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- recurrence solving

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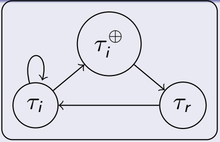
  else
    pop(); $\vec{\tau} \leftarrow$ trace();
    if $\vec{\tau}$ *ends with loop* $\vec{\tau}^{\circlearrowleft}$ **then**
      add(vr$_b(\tau \lor \text{accel}(\vec{\tau}^{\circlearrowleft}))$)
    else add(vr$_b(\tau)$)
  if check() $=$ unsat **then** **return** safe **else** b++



b	$\vec{\tau}$	SMT Problem	Model
0	[]	$\text{vr}_0(\psi_s) \land \text{vr}_0(\tau)$	$[x_1/1, \ldots, /0]$
1	$[\tau_i]$	$\ldots \land \text{vr}_1(\tau \lor \tau_i^{\oplus})$	$\ldots \cup [x_2/100, y_2/0]$
2	$[\tau_i, \tau_i^{\oplus}]$	$\ldots \land \text{vr}_2(\tau)$	$\ldots \cup [x_3/0, y_3/1]$
3	$[\tau_i, \tau_i^{\oplus}, \tau_r]$	$\ldots \land \text{vr}_3(\tau \lor \text{accel}(\vec{\tau}^{\circlearrowleft}))$	$\ldots \cup [x_4/0, y_4/100]$
4		$\ldots \land \text{vr}_4(\psi_e)$	

ABMC

Leading Example

Start States: $\psi_s := x \leq 0 \wedge y \leq 0$ Error States: $\psi_e := y \geq 100$

$$\text{Transition Formula: } \tau := \underbrace{(x < 100 \wedge x' = x + 1 \wedge y' = y)}_{\tau_i} \vee \underbrace{(x = 100 \wedge x' = 0 \wedge y' = y + 1)}_{\tau_r}$$

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ABMC

$b \leftarrow 0$; add($\mathrm{vr}_b(\psi_s)$)
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while $\top$ **do**
  push(); add($\mathrm{vr}_b(\psi_e)$)
  if check() = sat **then return** $\vec{\tau}$
  else
    pop(); $\vec{\tau} \leftarrow$ trace();
    if $\vec{\tau}$ *ends with loop* $\vec{\tau}^{\circlearrowleft}$ **then**
      add($\mathrm{vr}_b(\tau \vee \mathrm{accel}(\vec{\tau}^{\circlearrowleft}))$)
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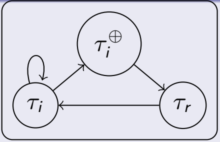

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ABMC

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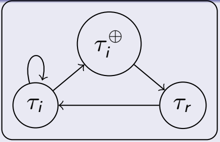

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ABMC

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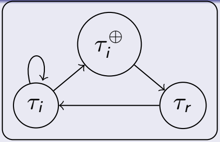

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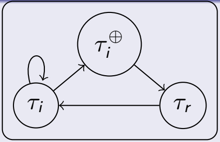

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ABMC

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  else
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      add($\mathrm{vr}_b(\tau \lor \mathrm{accel}(\vec{\tau}^{\circlearrowleft}))$)
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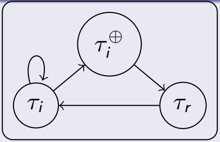
  if check() $=$ unsat **then return** safe **else** $b{+}{+}$



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ABMC

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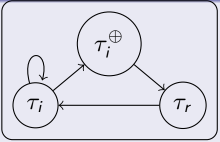

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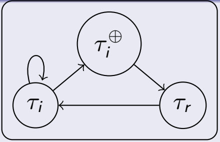

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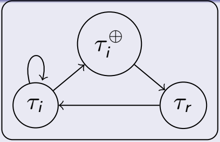

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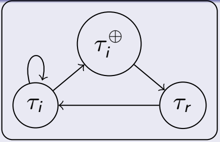

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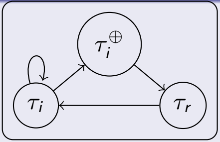

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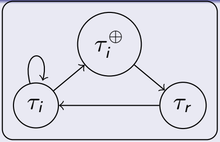

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ABMC

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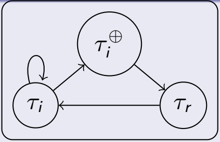
while $\top$ **do**
  $\mathsf{push}();$ $\mathsf{add}(\mathsf{vr}_b(\psi_e))$
  if $\mathsf{check}() = \mathsf{sat}$ **then return** $\vec{\tau}$
  else
    $\mathsf{pop}();$ $\vec{\tau} \leftarrow \mathsf{trace}();$
    if *$\vec{\tau}$ ends with loop $\vec{\tau}^{\circlearrowleft}$* **then**
      $\mathsf{add}(\mathsf{vr}_b(\tau \lor \mathsf{accel}(\vec{\tau}^{\circlearrowleft})))$
    else $\mathsf{add}(\mathsf{vr}_b(\tau))$
  if $\mathsf{check}() = \mathsf{unsat}$ **then return** safe **else** $b{+}{+}$



b	$\vec{\tau}$	SMT Problem	Model
0	[]	$\mathsf{vr}_0(\psi_s) \land \mathsf{vr}_0(\tau)$	$[x_1/1, \ldots/0]$
1	$[\tau_i]$	$\ldots \land \mathsf{vr}_1(\tau \lor \tau_i^{\oplus})$	$\ldots \cup [x_2/100, y_2/0]$
2	$[\tau_i, \tau_i^{\oplus}]$	$\ldots \land \mathsf{vr}_2(\tau)$	$\ldots \cup [x_3/0, y_3/1]$
3	$[\tau_i, \tau_i^{\oplus}, \tau_r]$	$\ldots \land \mathsf{vr}_3(\tau \lor \mathsf{accel}(\vec{\tau}^{\circlearrowleft}))$	$\ldots \cup [x_4/0, y_4/100]$
4		$\ldots \land \mathsf{vr}_4(\psi_e)$	

ABMC

Leading Example

Start States: $\psi_s := x \leq 0 \land y \leq 0$ Error States: $\psi_e := y \geq 100$

$$\text{Transition Formula: } \tau := \underbrace{(x < 100 \land x' = x + 1 \land y' = y)}_{\tau_i} \lor \underbrace{(x = 100 \land x' = 0 \land y' = y + 1)}_{\tau_r}$$

$$\tau_i^{\oplus} := x + n \leq 100 \land x' = x + n \land y' = y \land n > 0$$

ABMC

$b \leftarrow 0;\quad \mathsf{add}(\mathsf{vr}_b(\psi_s))$
if check() $=$ unsat **then return** safe
while $\top$ **do**
  push(); $\quad \mathsf{add}(\mathsf{vr}_b(\psi_e))$
  if check() $=$ sat **then** **return** $\vec{\tau}$
  else
    pop(); $\quad \vec{\tau} \leftarrow$ trace();
    if $\vec{\tau}$ *ends with loop* $\vec{\tau}^{\circlearrowleft}$ **then**
      $\mathsf{add}(\mathsf{vr}_b(\tau \lor \mathsf{accel}(\vec{\tau}^{\circlearrowleft})))$
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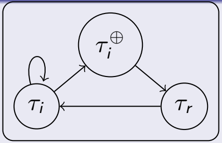
  if check() $=$ unsat **then** **return** safe **else** $b{+}{+}$



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ABMC

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while $\top$ **do**
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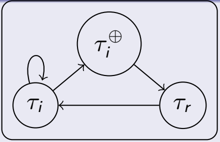

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ABMC

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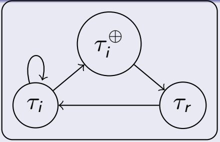

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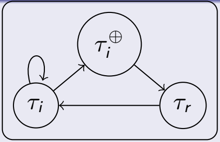

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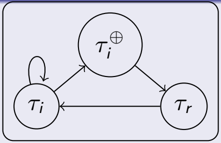

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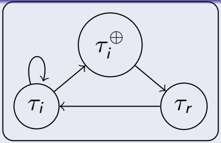

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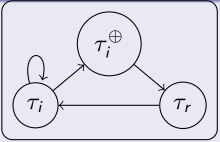

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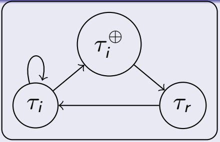

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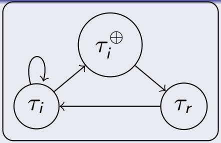

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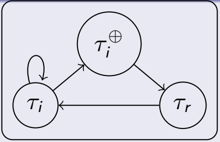

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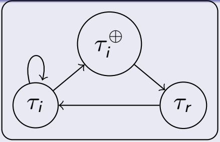

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$$\text{Transition Formula: } \tau := \underbrace{(x < 100 \land x' = x + 1 \land y' = y)}_{\tau_i} \lor \underbrace{(x = 100 \land x' = 0 \land y' = y + 1)}_{\tau_r}$$

$$\tau_i^{\oplus} := x + n \leq 100 \land x' = x + n \land y' = y \land n > 0$$

ABMC

$b \leftarrow 0$; add($\mathrm{vr}_b(\psi_s)$)
if check() = unsat **then return** safe
while $\top$ **do**
  push(); add($\mathrm{vr}_b(\psi_e)$)
  if check() = sat **then return** $\vec{\tau}$
  else
    pop(); $\vec{\tau} \leftarrow$ trace();
    if $\vec{\tau}$ *ends with loop* $\vec{\tau}^{\circlearrowleft}$ **then**
      add($\mathrm{vr}_b(\tau \lor \mathrm{accel}(\vec{\tau}^{\circlearrowleft}))$)
    else add($\mathrm{vr}_b(\tau)$)
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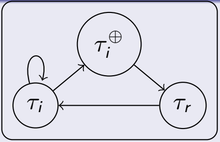

b	$\vec{\tau}$	SMT Problem	Model
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4		$\ldots \land \mathrm{vr}_4(\psi_e)$	

ABMC

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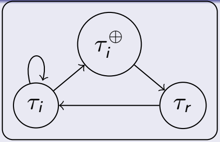

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ABMC

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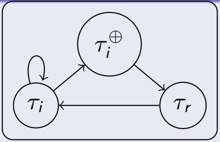

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ABMC

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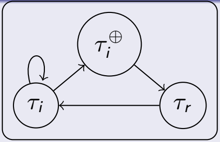

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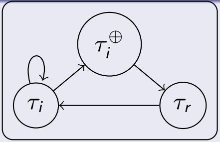

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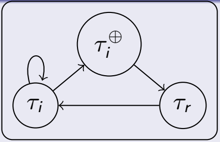

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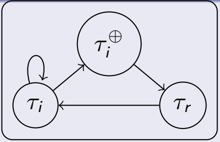

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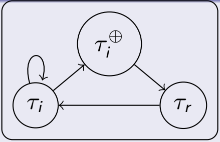

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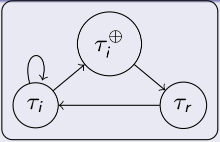

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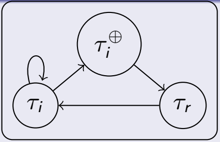

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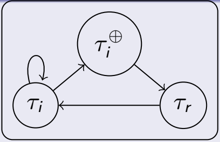

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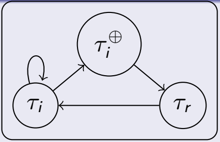

b	$\vec{\tau}$	SMT Problem	Model
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1	$[\tau_i]$	$\ldots \land \mathrm{vr}_1(\tau \lor \tau_i^{\oplus})$	$\ldots \cup [x_2/100, y_2/0]$
2	$[\tau_i, \tau_i^{\oplus}]$	$\ldots \land \mathrm{vr}_2(\tau)$	$\ldots \cup [x_3/0, y_3/1]$
3	$[\underbrace{\tau_i, \tau_i^{\oplus}, \tau_r}_{\vec{\tau}^{\circlearrowleft}}]$	$\ldots \land \mathrm{vr}_3(\tau \lor \mathrm{accel}(\vec{\tau}^{\circlearrowleft}))$	$\ldots \cup [x_4/0, y_4/100]$
4		$\ldots \land \mathrm{vr}_4(\psi_e)$	

Evaluation

CHC-Comp '23 Benchmarks	unsafe ✓	safe ✓
LoAT ABMC	72	75
Golem TPA	64	83
LoAT BMC	60	36
Z3 BMC	57	21
LoAT ADCL	56	0
Golem BMC	55	20
Spacer (Z3)	51	151
Eldarica	46	107

x: runtime in s
y: unsat proofs

x: length of c.ex.
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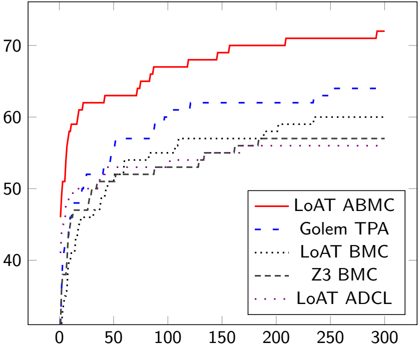

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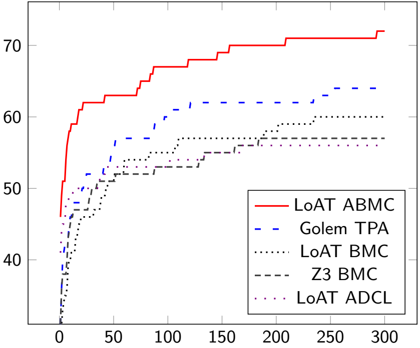

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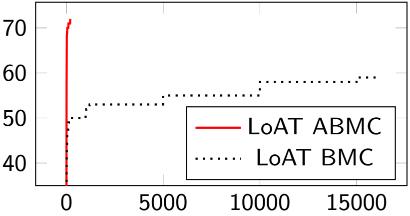

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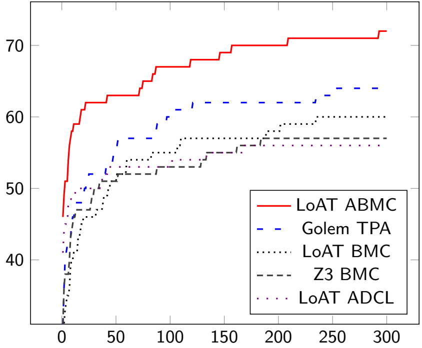

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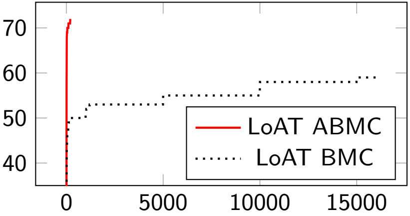

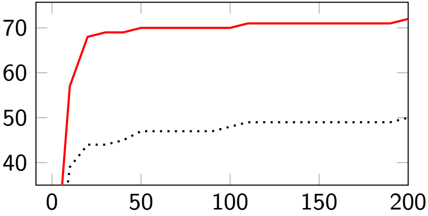

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Acceleration rocks!

See paper for...

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- **heuristics to fine-tune acceleration**
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