On Stability in a Happens-Before Propagator for Concurrent Programs

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Motivations

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- **Deagle** won CONCURRENCYSAFETY (SV-COMP) twice (2022-2023)

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How?

- **Bounded Model Checking**
- **Consistency-Preserving Propagation [1]**
- **Decision Procedure for Happens-Before**

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Let's re-implement it!

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Contributions

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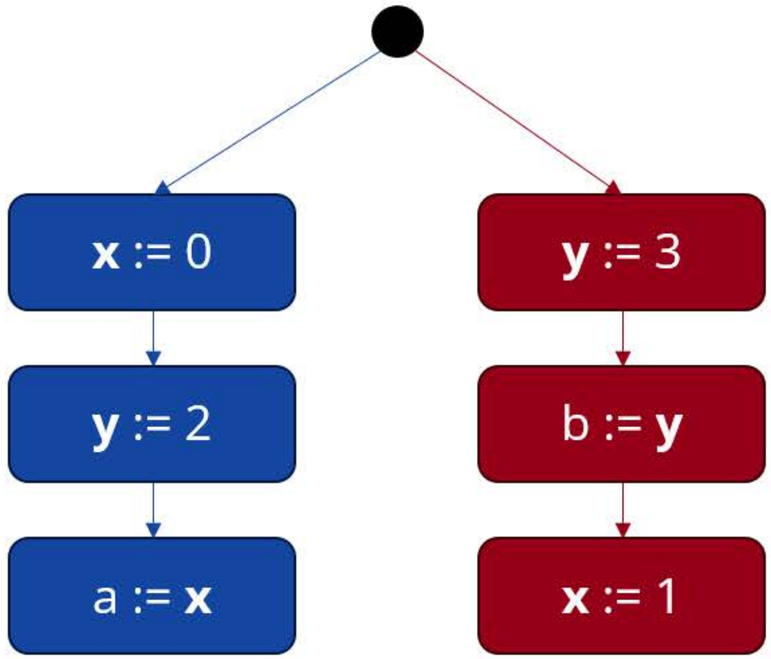
- Two proposals for fixing the algorithm
- Prove original claim for both proposals
- Experimentally analyze performance impact

Verification with Happens-Before Orders



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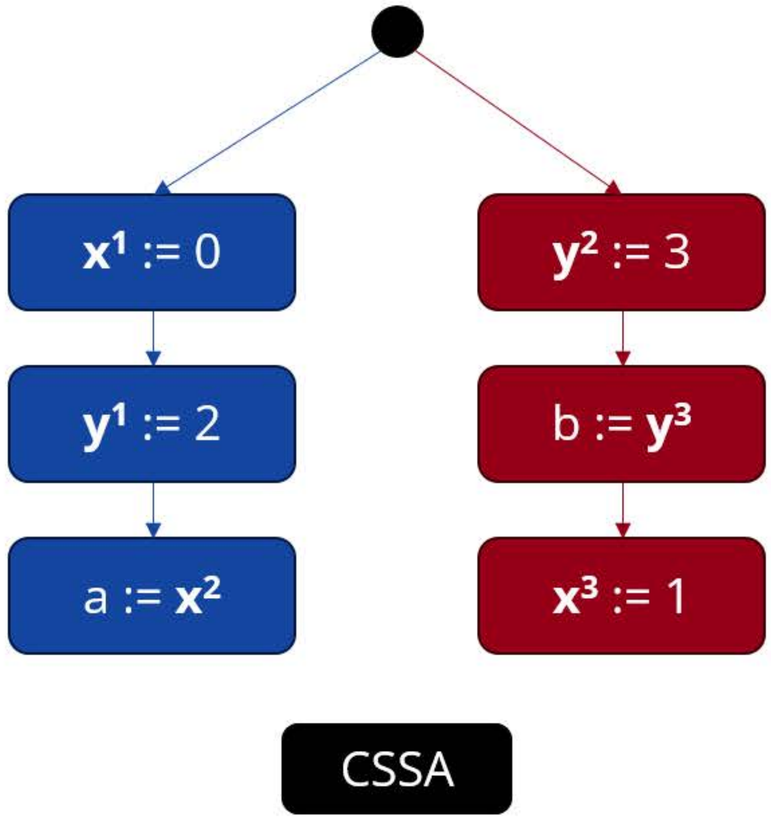

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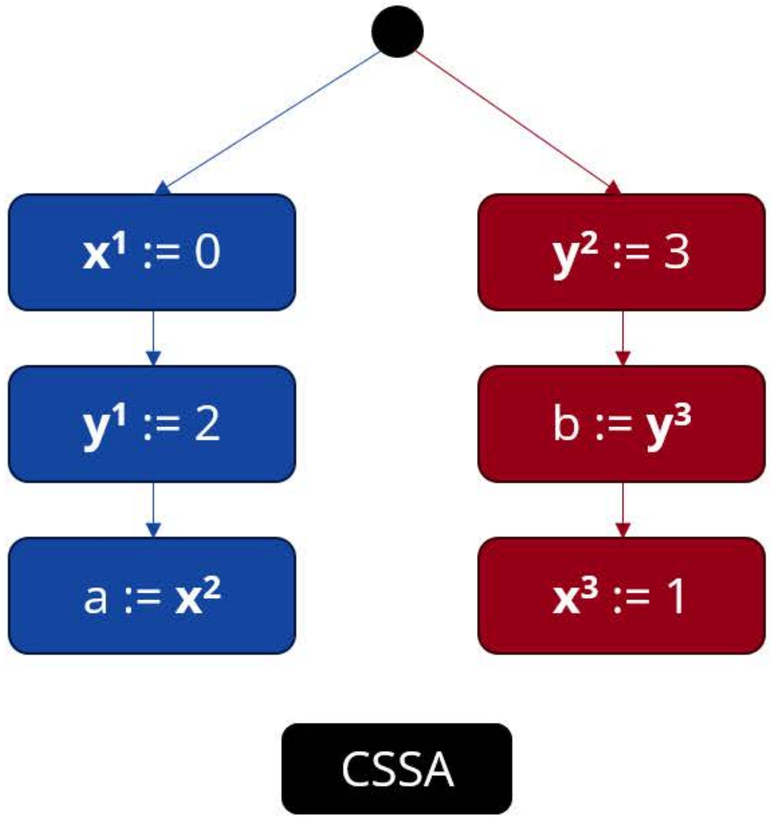

- ρ_{va}: write event values
  - $x^1==0$, $x^3==1$, $y^1==2$, $y^2==3$

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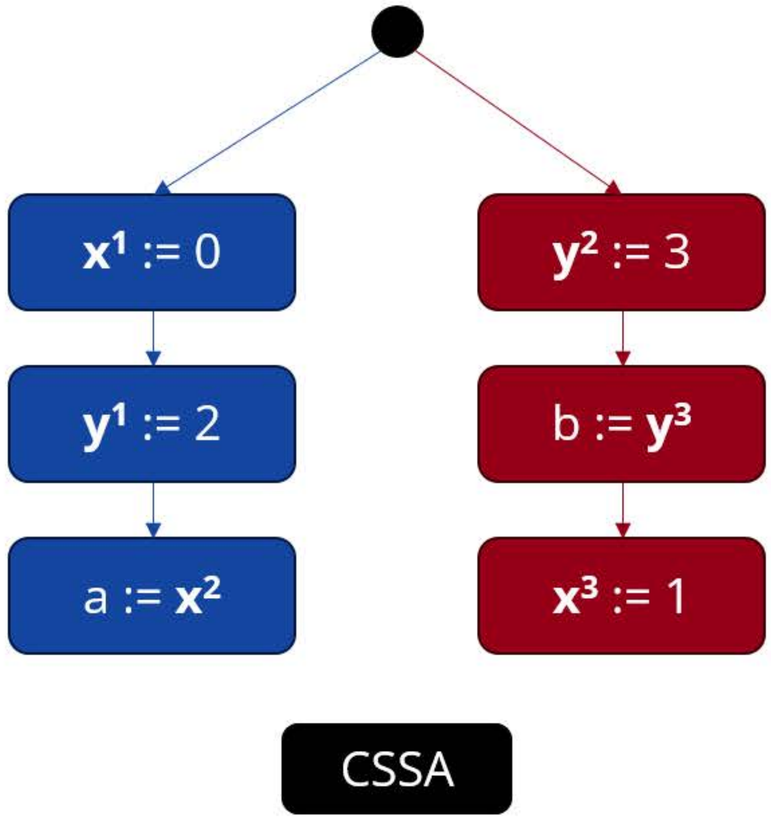

- ρ_{va}: write event values
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- $\rho_{rf\text{-}val}$: read event values
  - $rf^x_{1,2} \Rightarrow x^1==x^2,\ rf^x_{3,2} \Rightarrow x^3==x^2$
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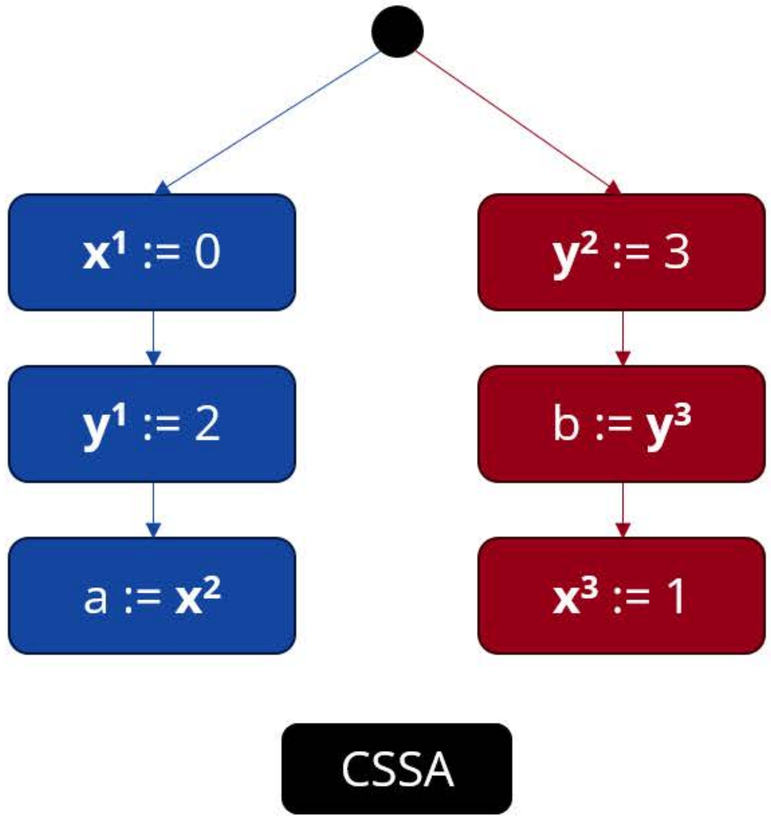

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  - $rf^x_{1,2}\ xor\ rf^x_{3,2},\ \ rf^y_{1,3}\ xor\ rf^y_{2,3}$

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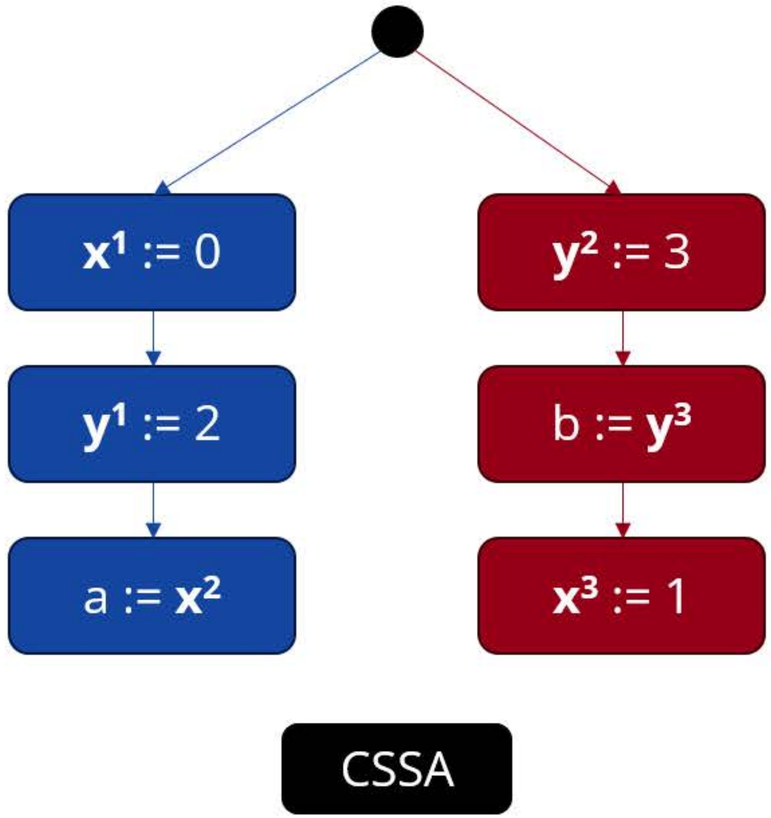

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- $\rho_{rf\text{-}ord}$: read-write ordering
  - $i \prec_{rf} j \iff rf_{ij}$
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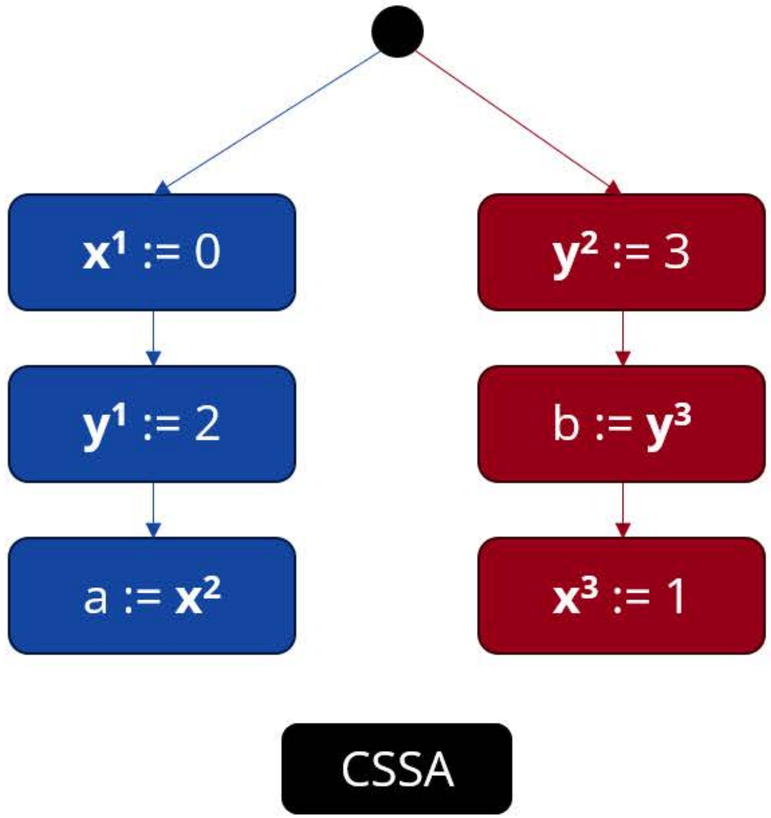
Verification with Happens-Before Orders



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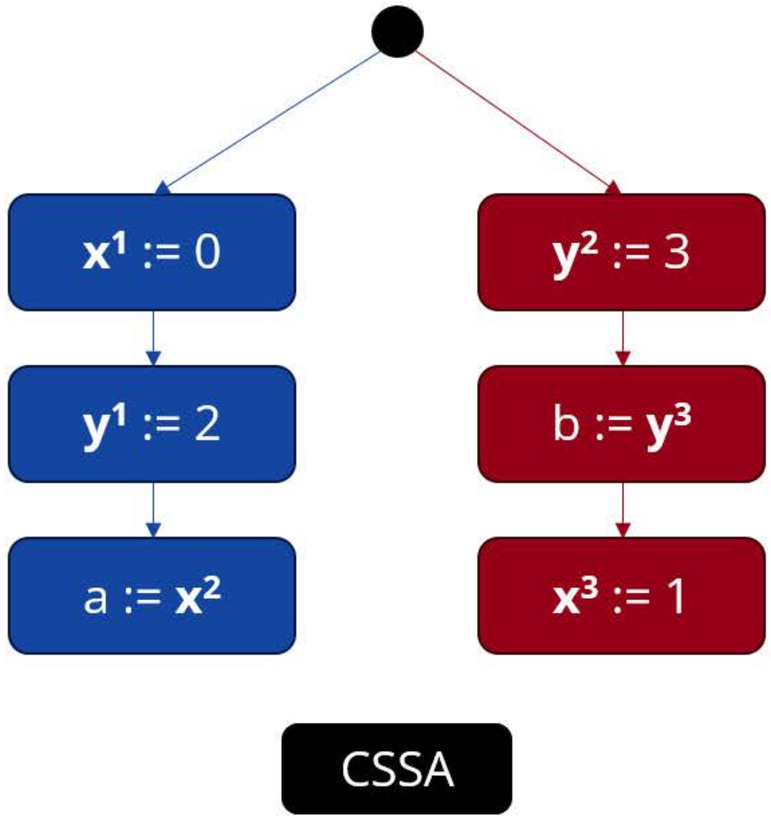

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Happens-before

Verification with Happens-Before Orders

- $\rho_{\text{rf-ord}}$: read-write ordering
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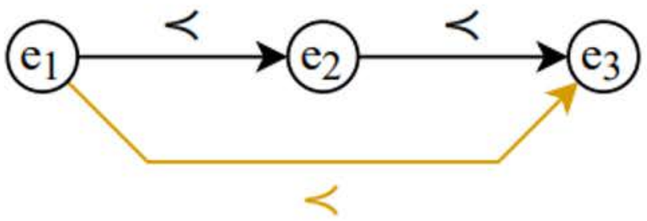
a) transitivity axiom:
$(e1 \prec e2) \land (e2 \prec e3) \Rightarrow (e1 \prec e3)$



(a) Transitivity

Verification with Happens-Before Orders

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(a) Transitivity (b) Write-Serialization

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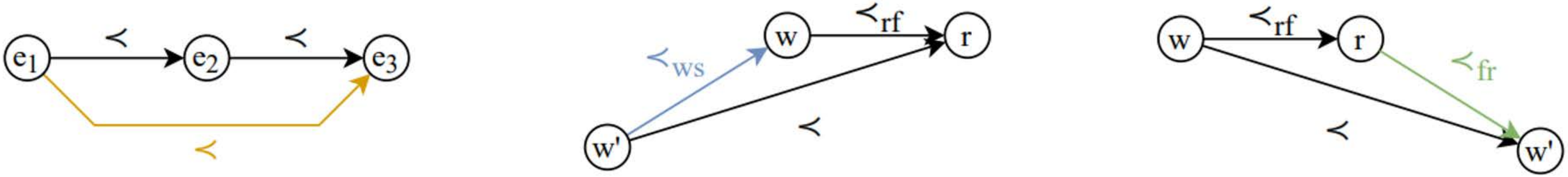

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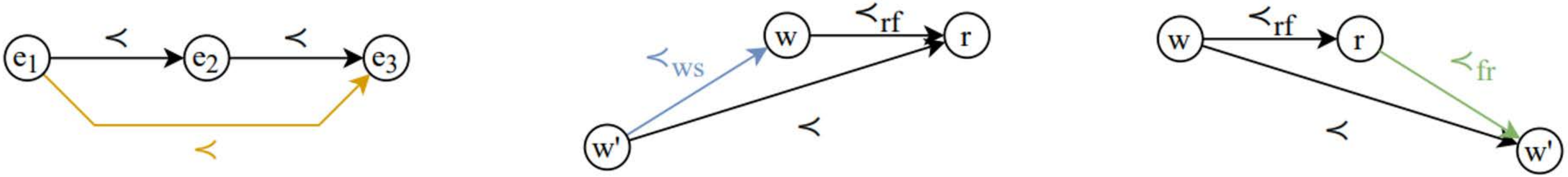
$\prec$ should be acylic



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Algorithm 1 Original Theory Propagation Algorithm [5], with typos fixed

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Input: l: Positive literal
proc PROPAGATE(l)
    if l is rf_ij then
        w_i, r_j := write and read of rf_ij
        ≺_rf ← ≺_rf ∪ {(w_i, r_j)}
        ≺ ← ≺ ∪ {(w_i, r_j)}
        TRANSITIVITY(w_i, r_j)
        foreach w_k s.t. grd_k do
            if (w_i, w_k, r_j) same-addr. then
                DERIVE(w_i, w_k, r_j)
            end if
        end foreach
    else if l is grd_k then
        w_k := write of grd_k
        foreach (w_i, r_i) ∈ ≺_rf do
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        end foreach
    end if
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```

```
Input: w_i, w_k, r_j: w_i ≺_rf r_j, grd_k
proc DERIVE(w_i, w_k, r_j)
    if w_k ≺ r_j then
        ≺ ← ≺ ∪ {(w_k, w_i)}
        TRANSITIVITY(w_k, w_i)
    else if w_i ≺ w_k then
        ≺ ← ≺ ∪ {(r_j, w_k)}
        TRANSITIVITY(r_j, w_k)
    end if
end proc
```

```
Input: e_1, e_2: e_1 ≺ e_2
proc TRANSITIVITY(e_1, e_2)
    foreach (e_2, e_3) ∈ ≺ do
        if (e_1, e_3) ∉ ≺ then
            ≺ ← ≺ ∪ {(e_1, e_3)}
            TRANSITIVITY(e_1, e_3)
        end if
    end foreach
    foreach (e_0, e_1) ∈ ≺ do
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        end if
    end foreach
end proc
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- Encode SMT formulae
- On branching: PROPAGATE()

Fewer backtracks (none due to $\prec$)

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    end if
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Input: w_i, w_k, r_j: w_i ≺_rf r_j, grd_k
proc DERIVE(w_i, w_k, r_j)
    if w_k ≺ r_j then
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        TRANSITIVITY(r_j, w_k)
    end if
end proc
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Input: e_1, e_2: e_1 ≺ e_2
proc TRANSITIVITY(e_1, e_2)
    foreach (e_2, e_3) ∈ ≺ do
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        end if
    end foreach
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        end if
    end foreach
end proc
```

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- Encode SMT formulae
- On branching: PROPAGATE()

Fewer backtracks (none due to $\prec$)

Claim: after PROPAGATE(), $\prec$ is *stable*

Algorithm 1 Original Theory Propagation Algorithm [5], with typos fixed

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Input: w_i, w_k, r_j: $w_i \prec_{rf} r_j, grd_k$
proc DERIVE(w_i, w_k, r_j)
  if $w_k \prec r_j$ **then**
    $\prec \leftarrow \prec \cup \{(w_k, w_i)\}$
    TRANSITIVITY(w_k, w_i)
  else if $w_i \prec w_k$ **then**
    $\prec \leftarrow \prec \cup \{(r_j, w_k)\}$
    TRANSITIVITY(r_j, w_k)
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end proc

Input: e_1, e_2: $e_1 \prec e_2$
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  foreach $(e_2, e_3) \in \prec$ **do**
    if $(e_1, e_3) \notin \prec$ **then**
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      TRANSITIVITY(e_1, e_3)
    end if
  end foreach
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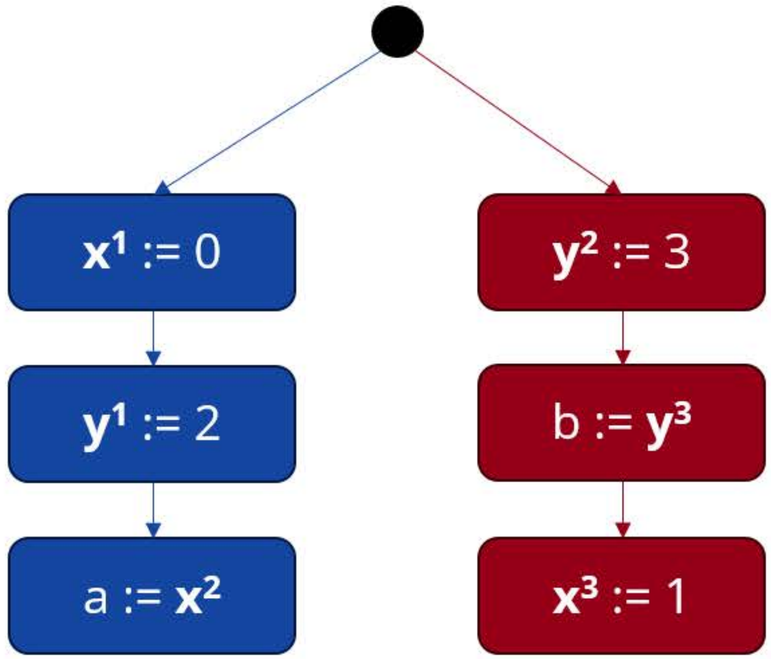

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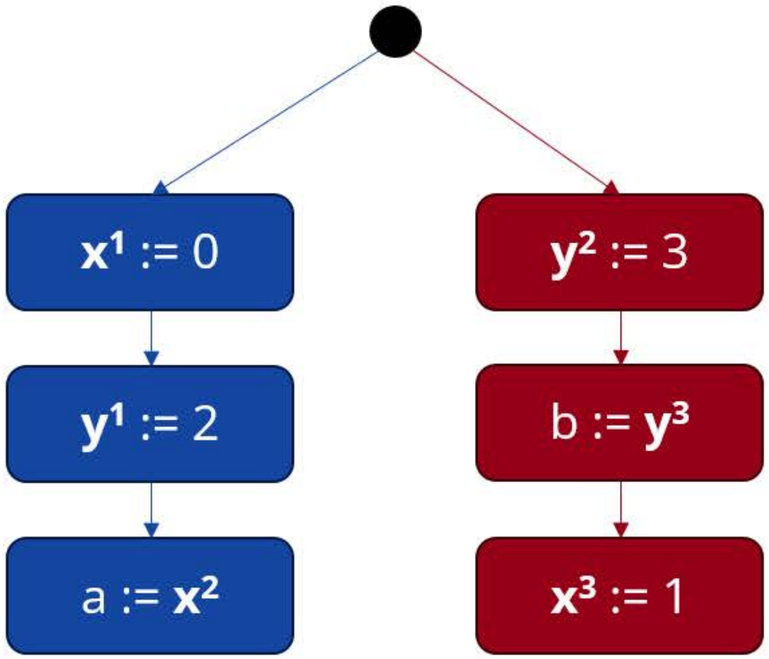
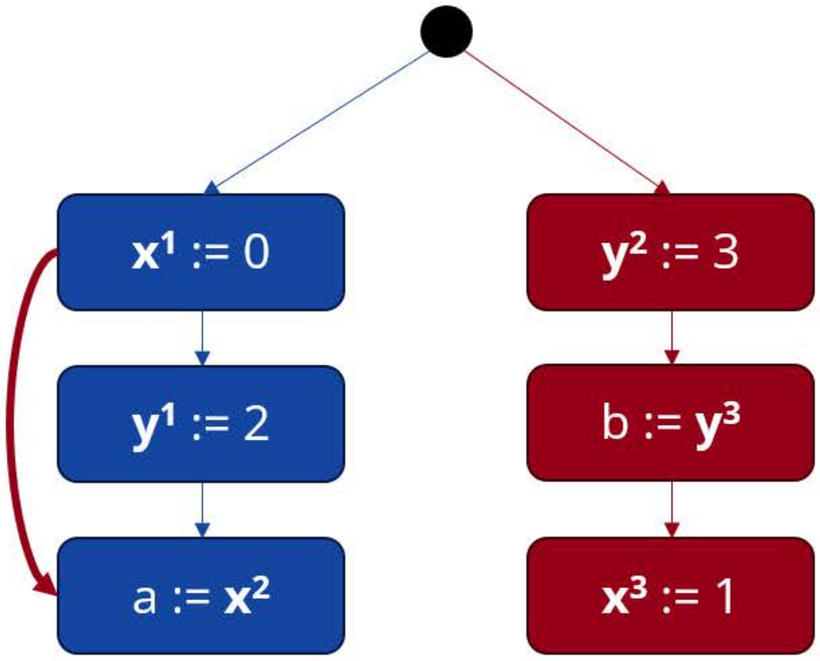


propagate($rf^x_{1,2}$)

$x_1 \prec x_2$ $x_1 \prec_{rf} x_2$

Consistency-Preserving Propagation



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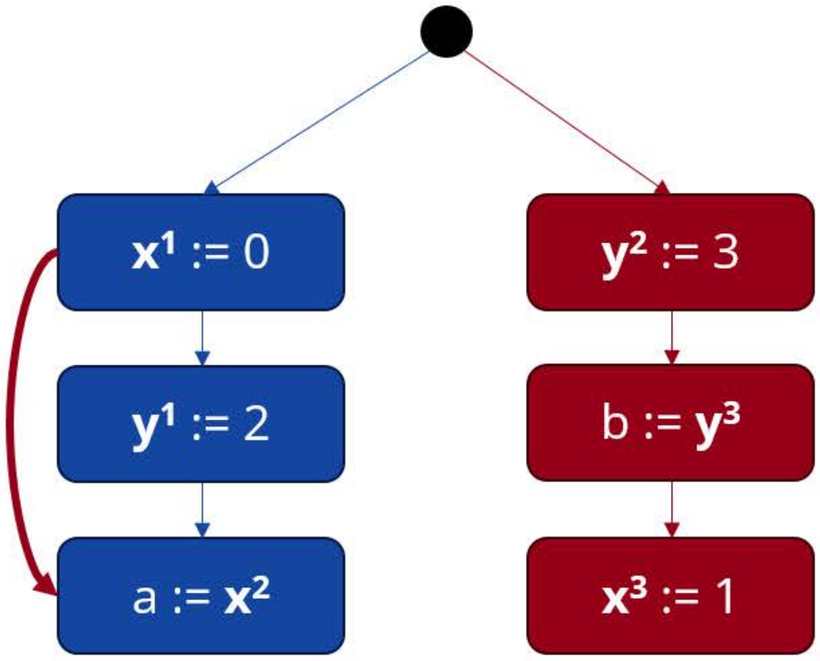

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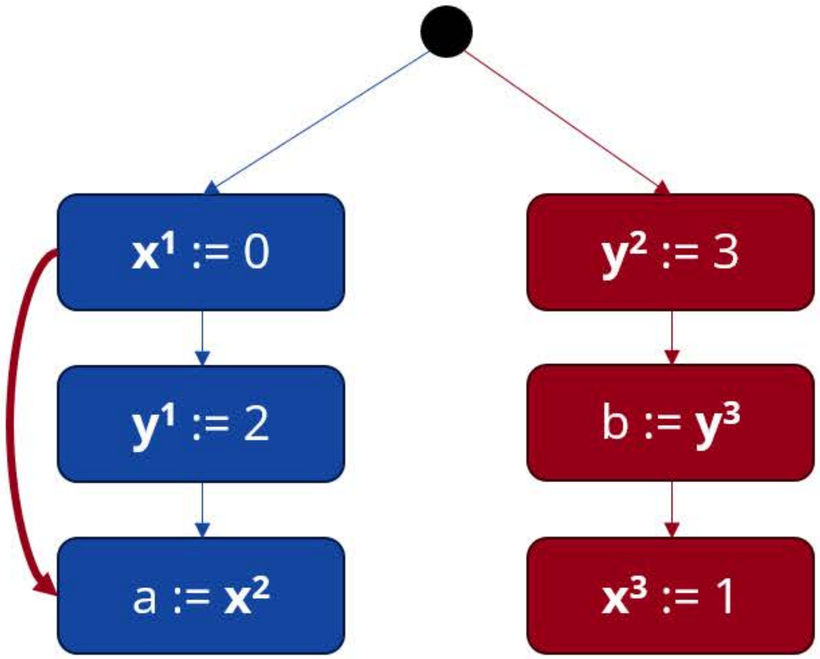

propagate($rf^x_{1,2}$)
transitivity(x_1, x_2)
derive(x_1, x_3, x_2)

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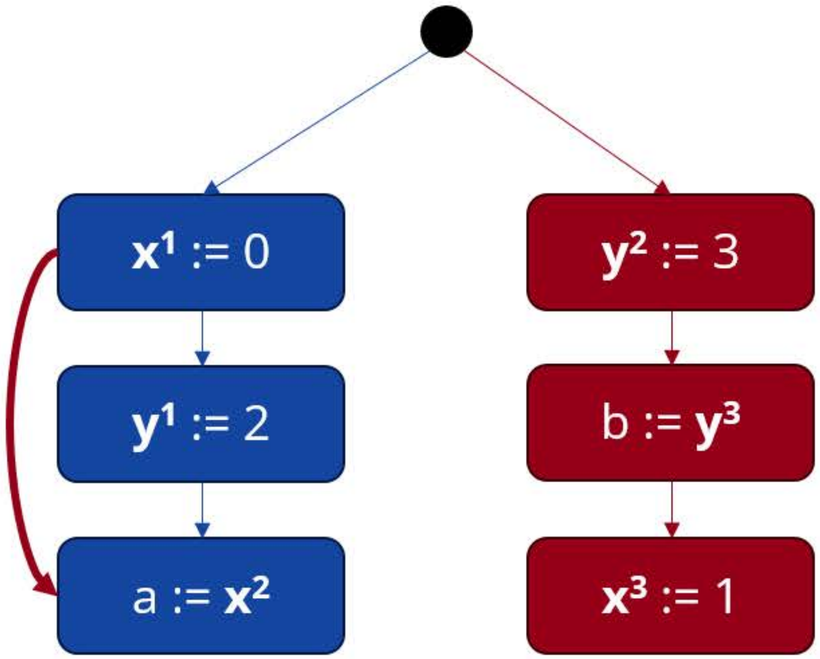

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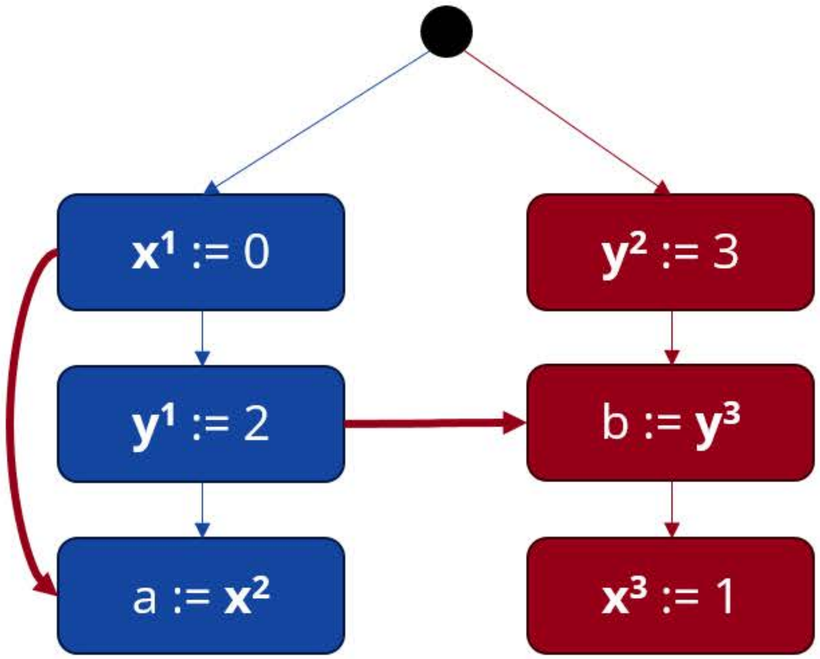

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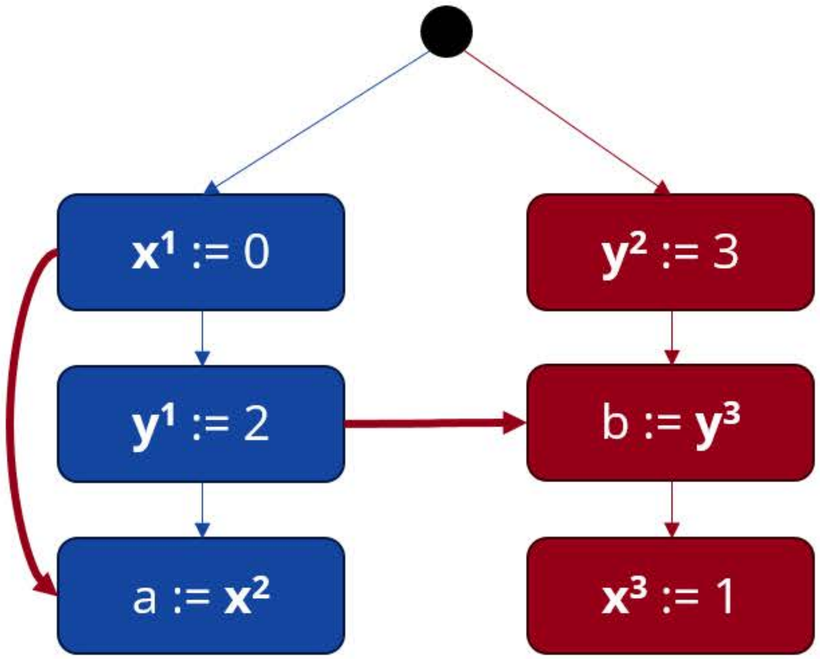
Consistency-Preserving Propagation



propagate($rf^x_{1,2}$) $\quad$ $x_1 \prec x_2$ $\quad$ $x_1 \prec_{rf} x_2$

transitivity(x_1, x_2)

derive(x_1, x_3, x_2)

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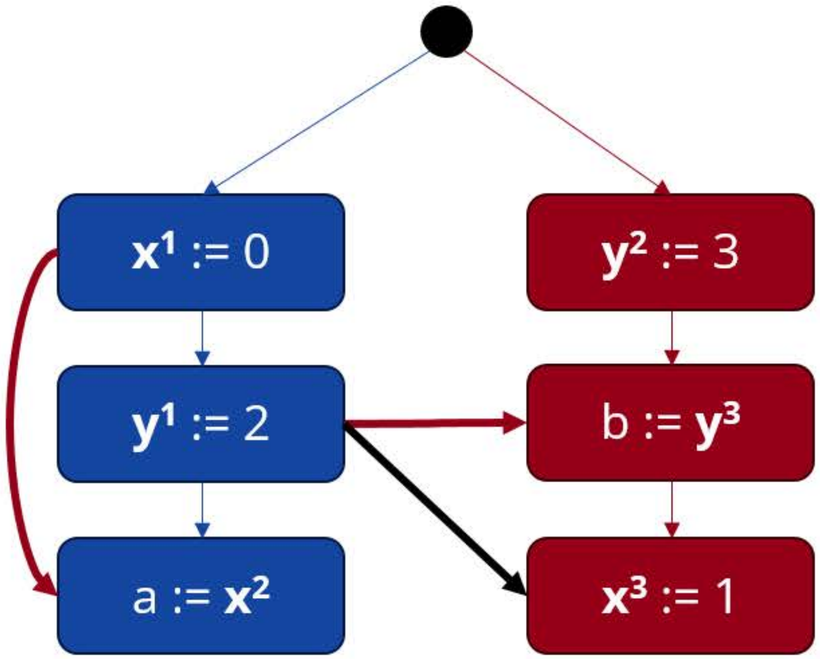
Consistency-Preserving Propagation



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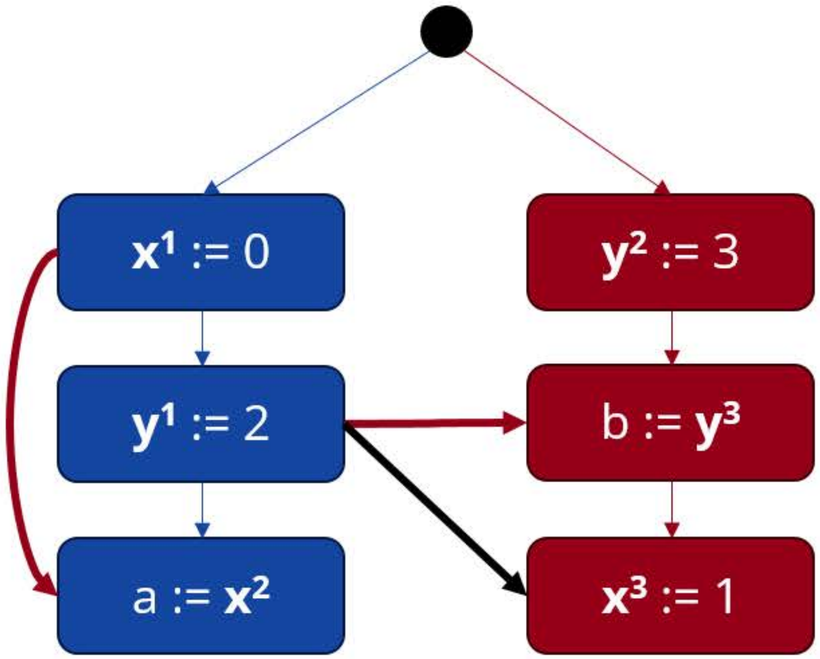

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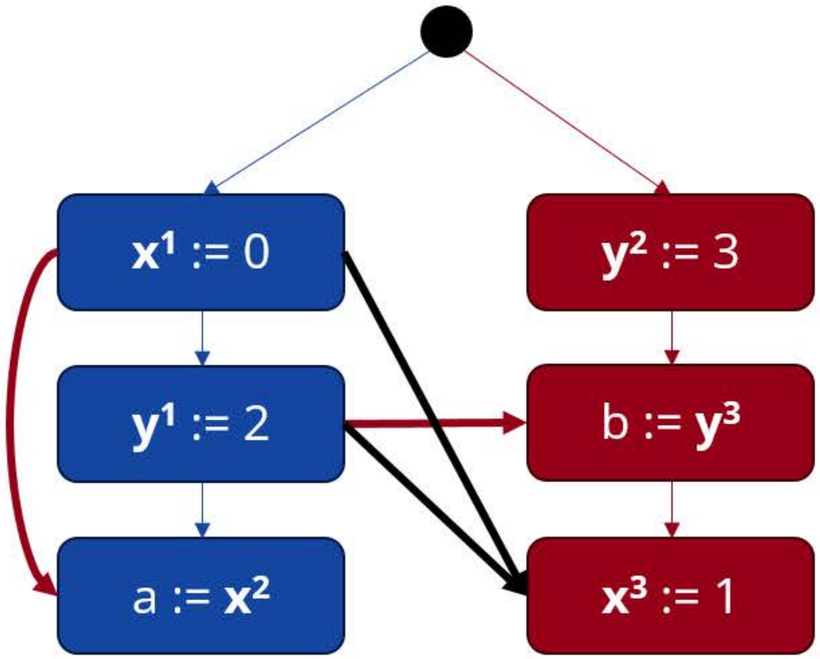

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transitivity(y_1, y_3) $\quad$ $y_1 \prec x_3$

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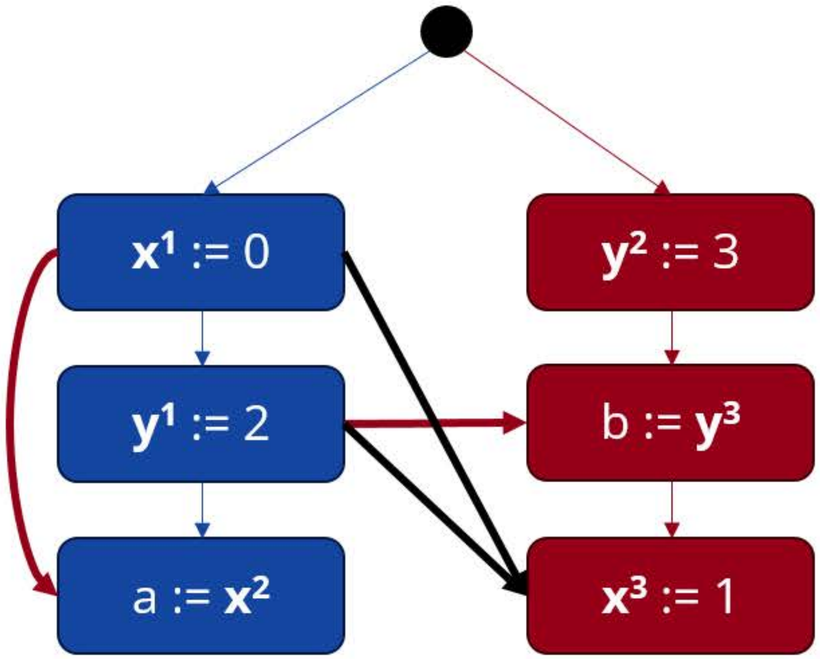

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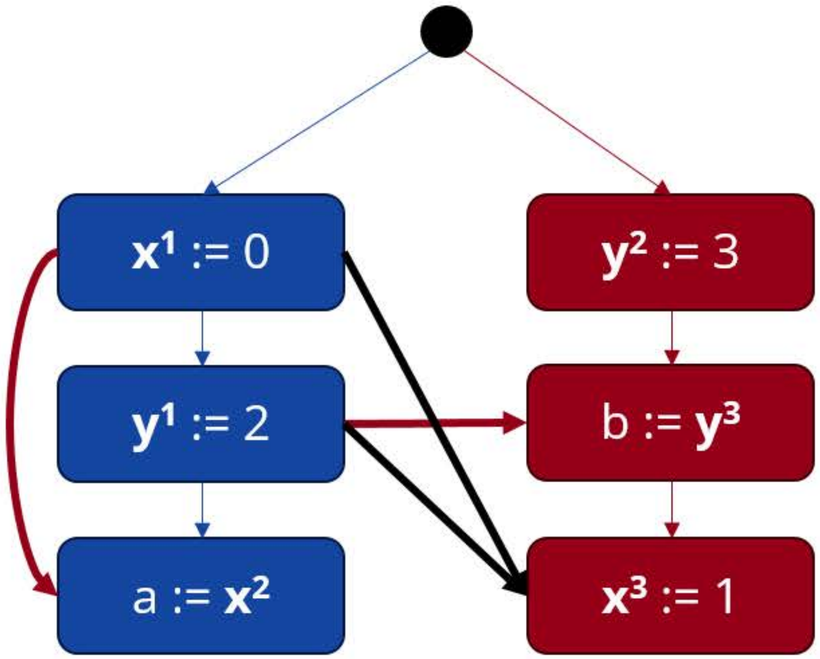

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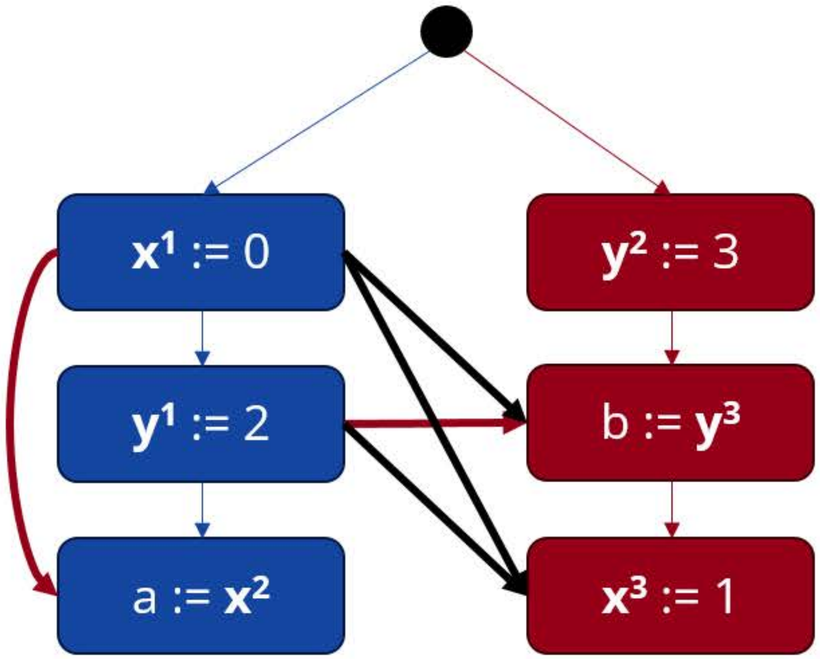

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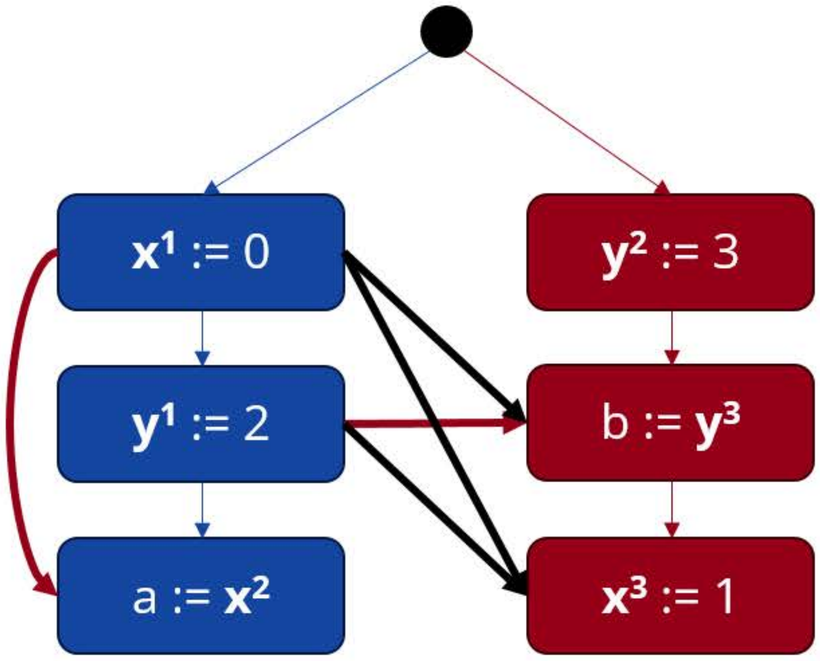
Consistency-Preserving Propagation



propagate($rf^x_{1,2}$)	$x_1 \prec x_2$ $x_1 \prec_{rf} x_2$
transitivity(x_1, x_2)	
derive(x_1, x_3, x_2)	
propagate($rf^y_{1,3}$)	$y_1 \prec y_3$ $y_1 \prec_{rf} y_3$
transitivity(y_1, y_3)	$y_1 \prec x_3$
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transitivity(x_1, x_3)	
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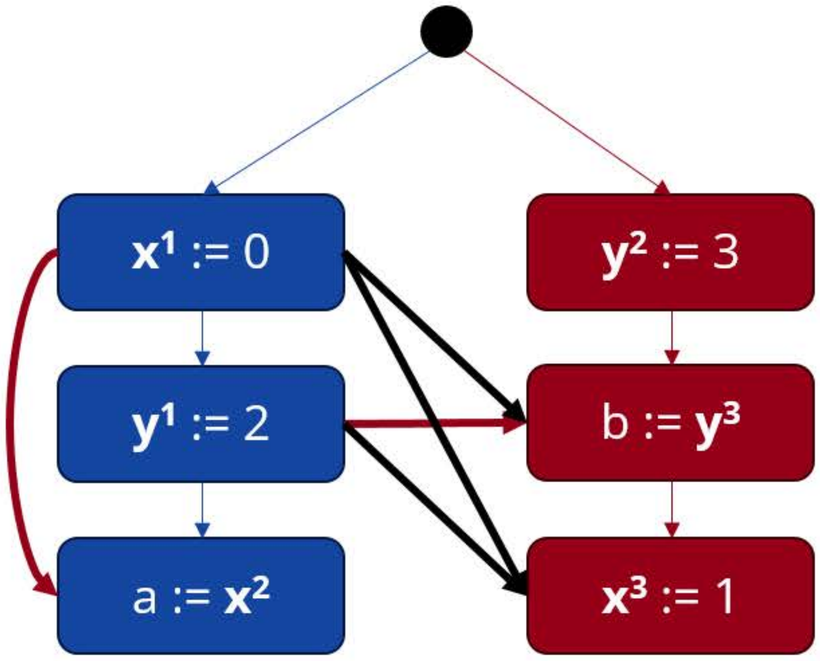
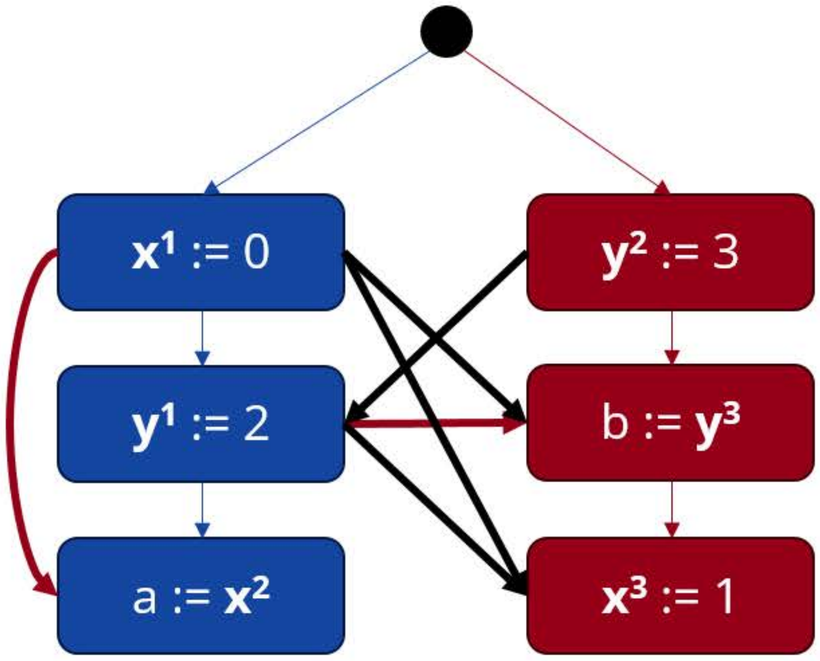
transitivity(x_1, y_3)	

Consistency-Preserving Propagation



propagate($rf^x_{1,2}$)	$x_1 \prec x_2$ $x_1 \prec_{rf} x_2$
transitivity(x_1, x_2)	
derive(x_1, x_3, x_2)	
propagate($rf^y_{1,3}$)	$y_1 \prec y_3$ $y_1 \prec_{rf} y_3$
transitivity(y_1, y_3)	$y_1 \prec x_3$
transitivity(y_1, x_3)	$x_1 \prec x_3$
transitivity(x_1, x_3)	
	$x_1 \prec y_3$
transitivity(x_1, y_3)	
derive(y_1, y_2, y_3)	$y_2 \prec y_1$

Consistency-Preserving Propagation



propagate($rf^x_{1,2}$)	$x_1 \prec x_2$ $x_1 \prec_{rf} x_2$
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transitivity(x_1, x_3)	
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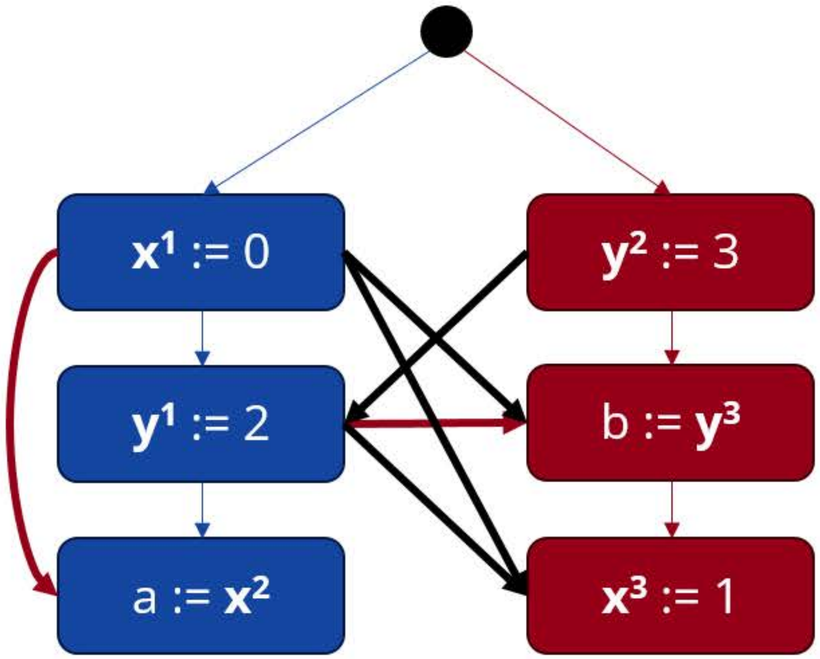
transitivity(x_1, y_3)	
derive(y_1, y_2, y_3)	$y_2 \prec y_1$

Consistency-Preserving Propagation



propagate($rf^x_{1,2}$)	$x_1 \prec x_2$	$x_1 \prec_{rf} x_2$
transitivity(x_1, x_2)		
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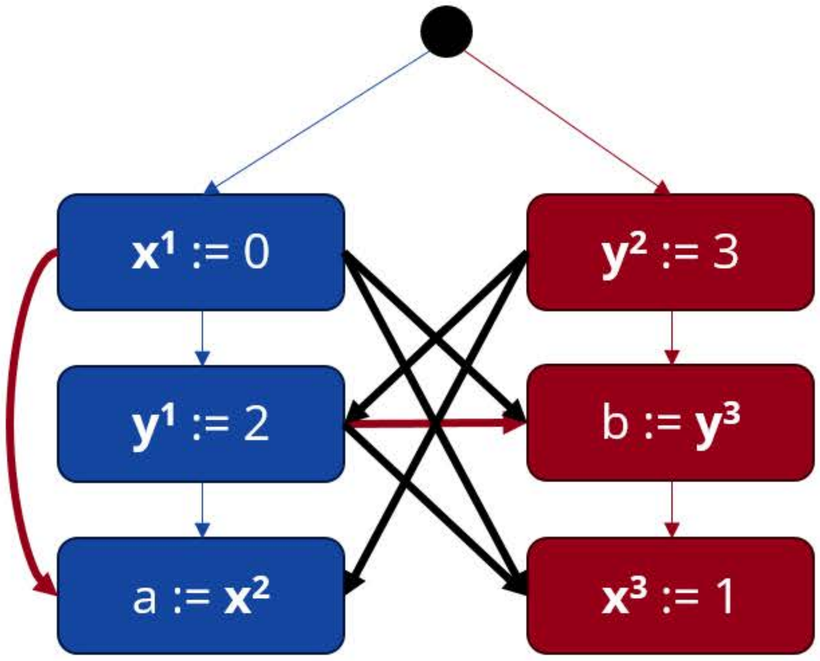

propagate($rf^x_{1,2}$)	$x_1 \prec x_2$	$x_1 \prec_{rf} x_2$
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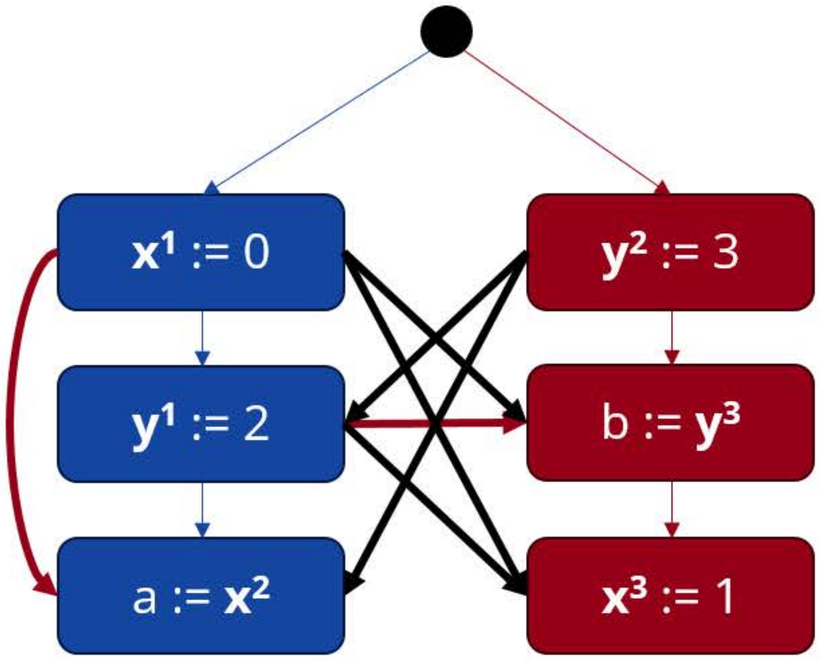

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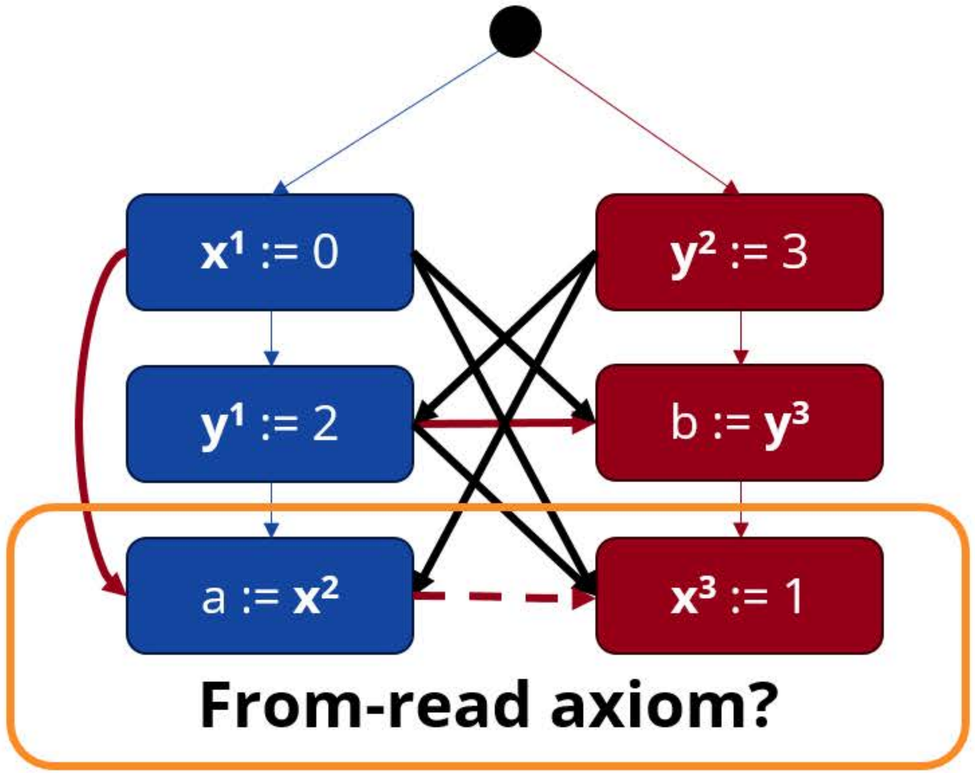
Consistency-Preserving Propagation



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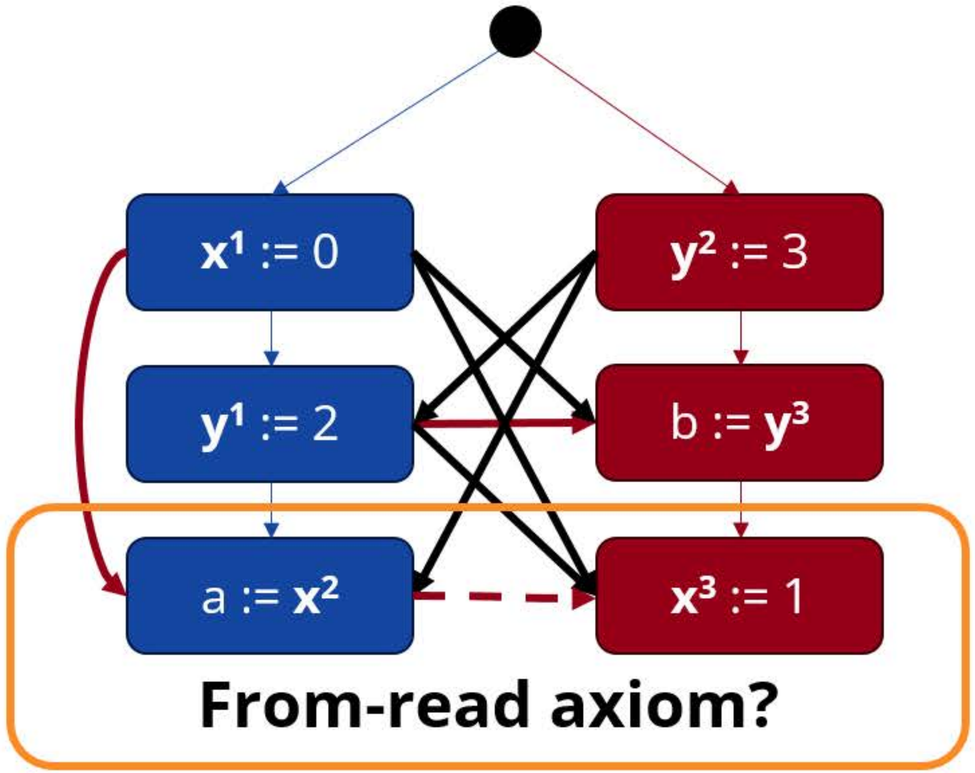

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propagate($rf^y_{1,3}$)	$y_1 \prec y_3$ $\quad y_1 \prec_{rf} y_3$
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transitivity(y_2, y_1)	$y_2 \prec x_2$
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Stability is **not** preserved!

Propagation for Sequential Consistency

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- The algorithm:
  - **Linear** in rf-assignments!

Algorithm 1 Original Theory Propagation Algorithm [5], with typos fixed

Input: l: Positive literal

```
proc PROPAGATE(l)
    if l is rf_ij then
        w_i, r_j := write and read of rf_ij
        ≺_rf ← ≺_rf ∪ {(w_i, r_j)}
        ≺ ← ≺ ∪ {(w_i, r_j)}
        TRANSITIVITY(w_i, r_j)
        foreach w_k s.t. grd_k do
            if (w_i, w_k, r_j) same-addr. then
                DERIVE(w_i, w_k, r_j)
            end if
        end foreach
    else if l is grd_k then
        w_k := write of grd_k
        foreach (w_i, r_i) ∈ ≺_rf do
            if (w_i, w_k, r_j) same-addr. then
                DERIVE(w_i, w_k, r_j)
            end if
        end foreach
    end if
end proc
```

Input: w_i, w_k, r_j: $w_i \prec_{rf} r_j, grd_k$

```
proc DERIVE(w_i, w_k, r_j)
    if w_k ≺ r_j then
        ≺ ← ≺ ∪ {(w_k, w_i)}
        TRANSITIVITY(w_k, w_i)
    else if w_i ≺ w_k then
        ≺ ← ≺ ∪ {(r_j, w_k)}
        TRANSITIVITY(r_j, w_k)
    end if
end proc
```

Input: e_1, e_2: $e_1 \prec e_2$

```
proc TRANSITIVITY(e_1, e_2)
    foreach (e_2, e_3) ∈ ≺ do
        if (e_1, e_3) ∉ ≺ then
            ≺ ← ≺ ∪ {(e_1, e_3)}
            TRANSITIVITY(e_1, e_3)
        end if
    end foreach
    foreach (e_0, e_1) ∈ ≺ do
        if (e_0, e_2) ∉ ≺ then
            ≺ ← ≺ ∪ {(e_0, e_2)}
            TRANSITIVITY(e_0, e_2)
        end if
    end foreach
end proc
```

Propagation for Sequential Consistency

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- Write-Read pairing (VSC-Read problem): **NP-complete**
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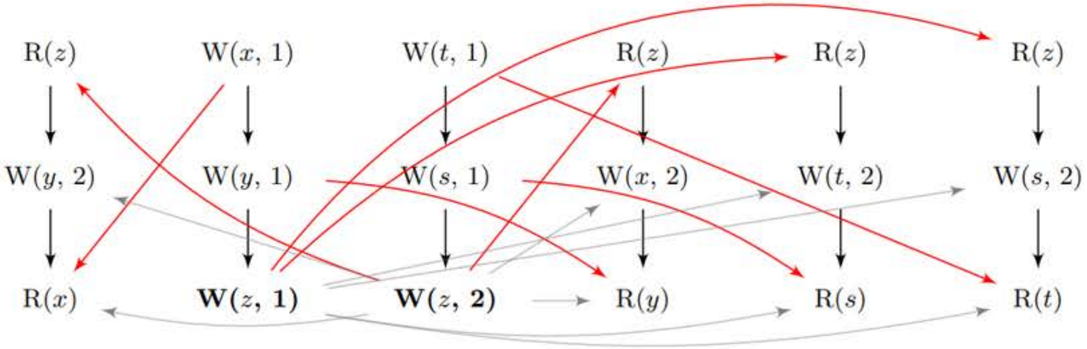

Algorithm 1 Original Theory Propagation Algorithm [5], with typos fixed

Input: l: Positive literal
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  if l is rf_{ij} **then**
    w_i, r_j := write and read of rf_{ij}
    $\prec_{rf} \leftarrow \prec_{rf} \cup \{(w_i, r_j)\}$
    $\prec \leftarrow \prec \cup \{(w_i, r_j)\}$
    TRANSITIVITY(w_i, r_j)
    foreach w_k *s.t.* grd_k **do**
      if (w_i, w_k, r_j) same-addr. **then**
        DERIVE(w_i, w_k, r_j)
      end if
    end foreach
  else if l is grd_k **then**
    w_k := write of grd_k
    foreach $(w_i, r_i) \in \prec_{rf}$ **do**
      if (w_i, w_k, r_j) same-addr. **then**
        DERIVE(w_i, w_k, r_j)
      end if
    end foreach
  end if
end proc

Input: w_i, w_k, r_j: $w_i \prec_{rf} r_j, grd_k$
proc DERIVE(w_i, w_k, r_j)
  if $w_k \prec r_j$ **then**
    $\prec \leftarrow \prec \cup \{(w_k, w_i)\}$
    TRANSITIVITY(w_k, w_i)
  else if $w_i \prec w_k$ **then**
    $\prec \leftarrow \prec \cup \{(r_j, w_k)\}$
    TRANSITIVITY(r_j, w_k)
  end if
end proc

Input: e_1, e_2: $e_1 \prec e_2$
proc TRANSITIVITY(e_1, e_2)
  foreach $(e_2, e_3) \in \prec$ **do**
    if $(e_1, e_3) \notin \prec$ **then**
      $\prec \leftarrow \prec \cup \{(e_1, e_3)\}$
      TRANSITIVITY(e_1, e_3)
    end if
  end foreach
  foreach $(e_0, e_1) \in \prec$ **do**
    if $(e_0, e_2) \notin \prec$ **then**
      $\prec \leftarrow \prec \cup \{(e_0, e_2)\}$
      TRANSITIVITY(e_0, e_2)
    end if
  end foreach
end proc

Propagation for Sequential Consistency

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- Write-Read pairing (VSC-Read problem): **NP-complete**
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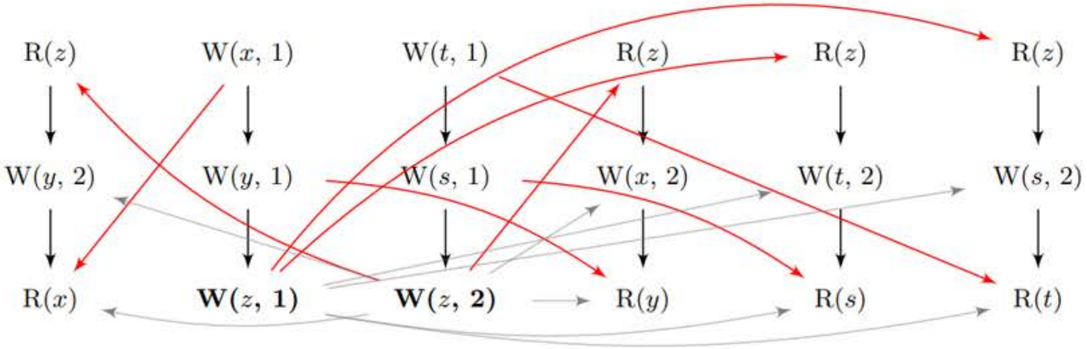

Weak Sequential Consistency

Algorithm 1 Original Theory Propagation Algorithm [5], with typos fixed

Input: l: Positive literal
proc PROPAGATE(l)
  if l is rf_{ij} **then**
    w_i, r_j := write and read of rf_{ij}
    $\prec_{rf} \leftarrow \prec_{rf} \cup \{(w_i, r_j)\}$
    $\prec \leftarrow \prec \cup \{(w_i, r_j)\}$
    TRANSITIVITY(w_i, r_j)
    foreach w_k *s.t.* grd_k **do**
      if (w_i, w_k, r_j) same-addr. **then**
        DERIVE(w_i, w_k, r_j)
      end if
    end foreach
  else if l is grd_k **then**
    w_k := write of grd_k
    foreach $(w_i, r_i) \in \prec_{rf}$ **do**
      if (w_i, w_k, r_j) same-addr. **then**
        DERIVE(w_i, w_k, r_j)
      end if
    end foreach
  end if
end proc

Input: w_i, w_k, r_j: $w_i \prec_{rf} r_j, grd_k$
proc DERIVE(w_i, w_k, r_j)
  if $w_k \prec r_j$ **then**
    $\prec \leftarrow \prec \cup \{(w_k, w_i)\}$
    TRANSITIVITY(w_k, w_i)
  else if $w_i \prec w_k$ **then**
    $\prec \leftarrow \prec \cup \{(r_j, w_k)\}$
    TRANSITIVITY(r_j, w_k)
  end if
end proc

Input: e_1, e_2: $e_1 \prec e_2$
proc TRANSITIVITY(e_1, e_2)
  foreach $(e_2, e_3) \in \prec$ **do**
    if $(e_1, e_3) \notin \prec$ **then**
      $\prec \leftarrow \prec \cup \{(e_1, e_3)\}$
      TRANSITIVITY(e_1, e_3)
    end if
  end foreach
  foreach $(e_0, e_1) \in \prec$ **do**
    if $(e_0, e_2) \notin \prec$ **then**
      $\prec \leftarrow \prec \cup \{(e_0, e_2)\}$
      TRANSITIVITY(e_0, e_2)
    end if
  end foreach
end proc

Summary of problems

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- Stability claim: due to **propagation algorithm**

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  - Causes happens-before orders to be **missed**

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- Stability claim: due to **propagation algorithm**
  - Causes happens-before orders to be **missed**
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    - Easily fixable to allow SC: try to order all writes post-propagation

Fixing Stability

Retrospectively

Repeat PROPAGATE until no new changes occur

Proof of Stability

Prospectively

Find issue and fix it

Proof of Stability

Experimental Evaluation

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RQ4: Performance of retrospective vs. prospective algorithms in Theta

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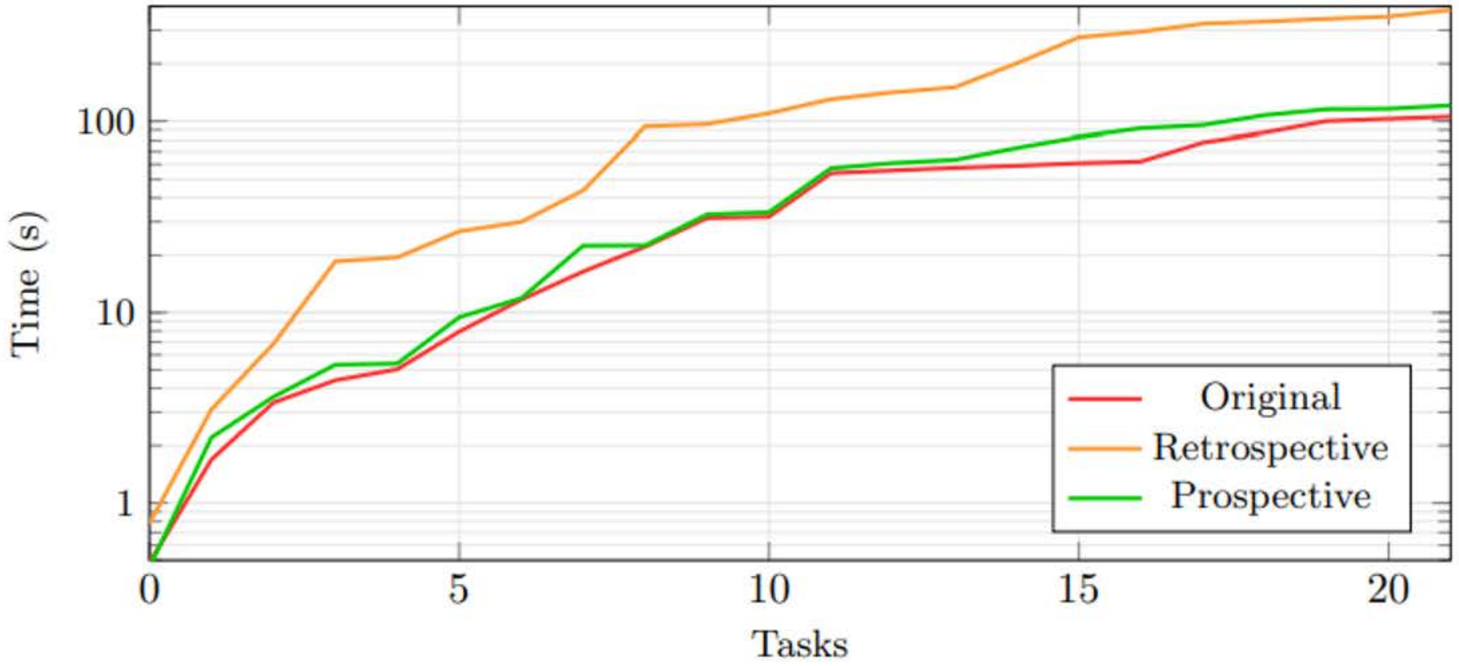

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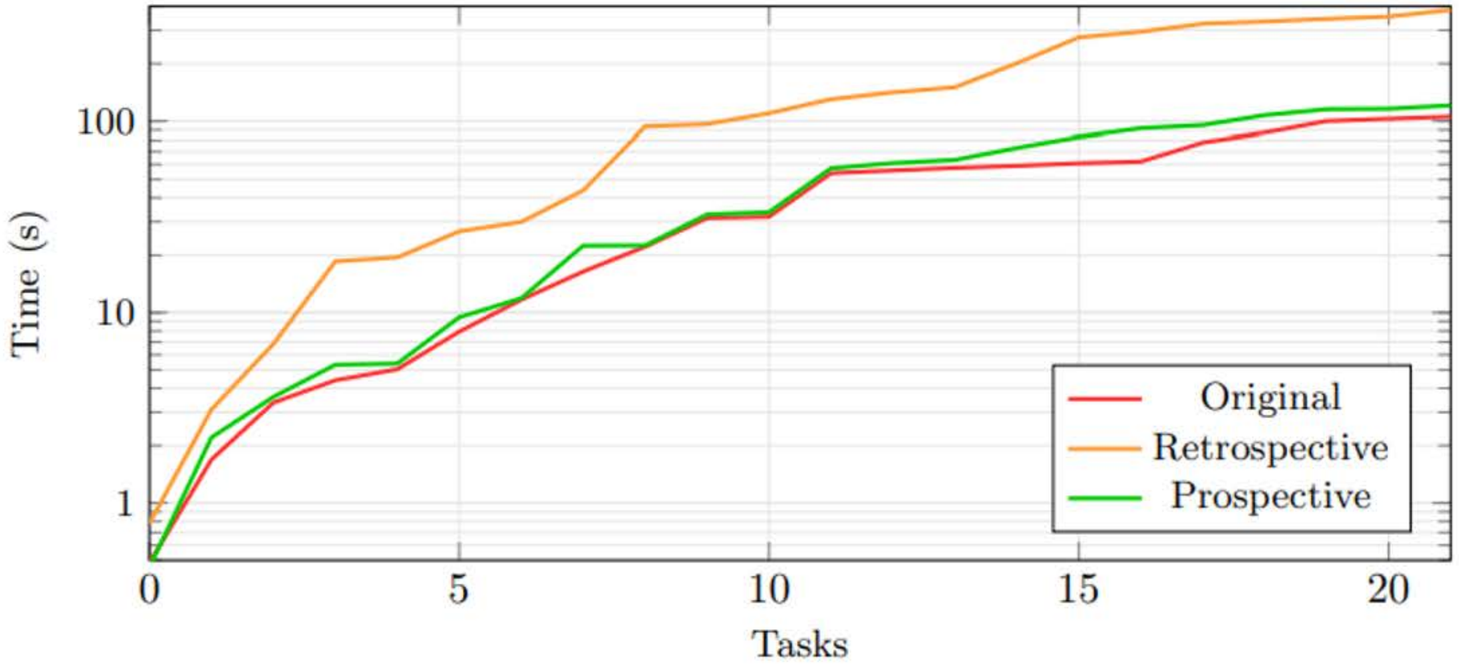

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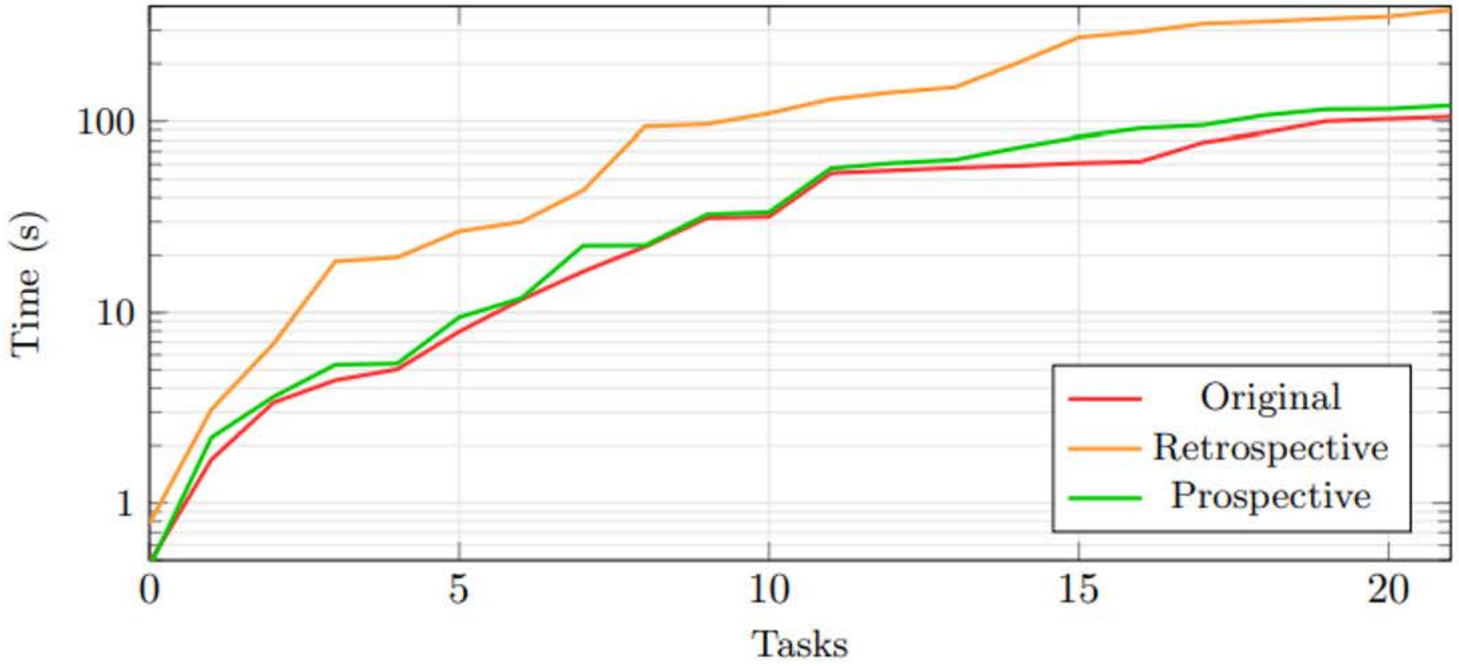

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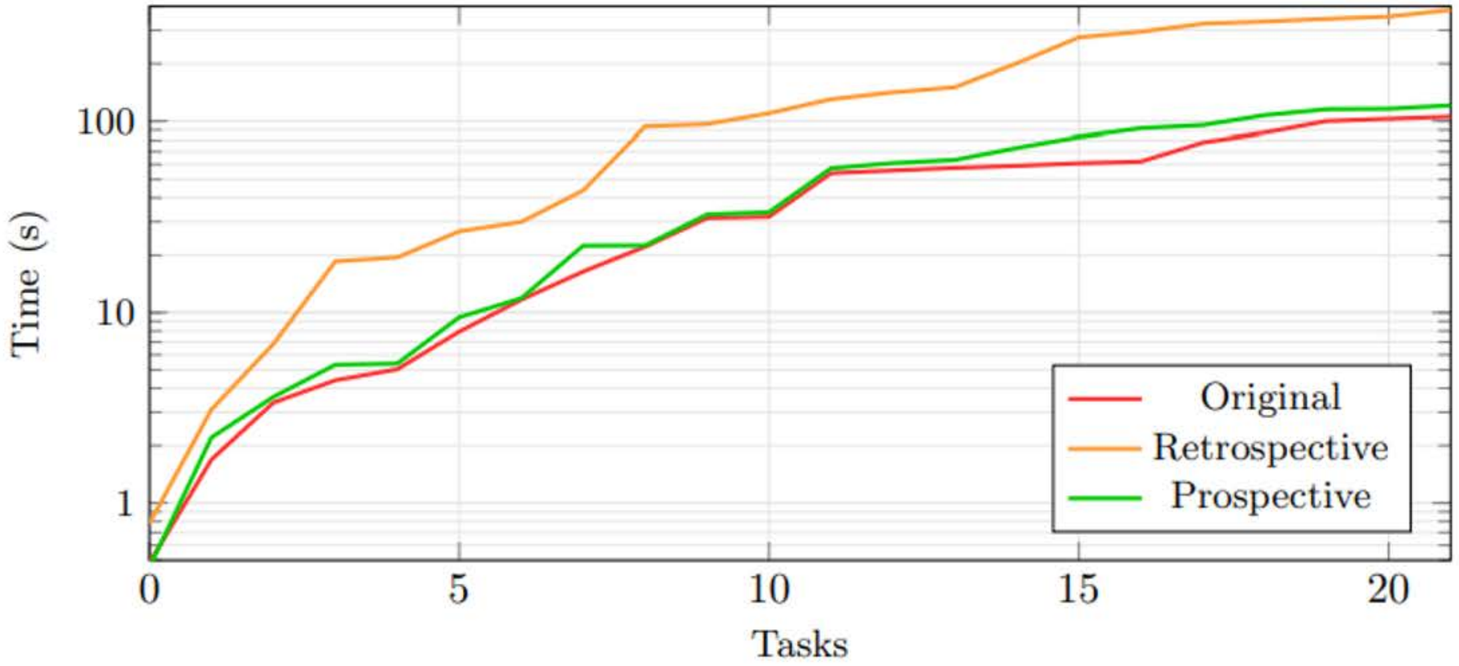

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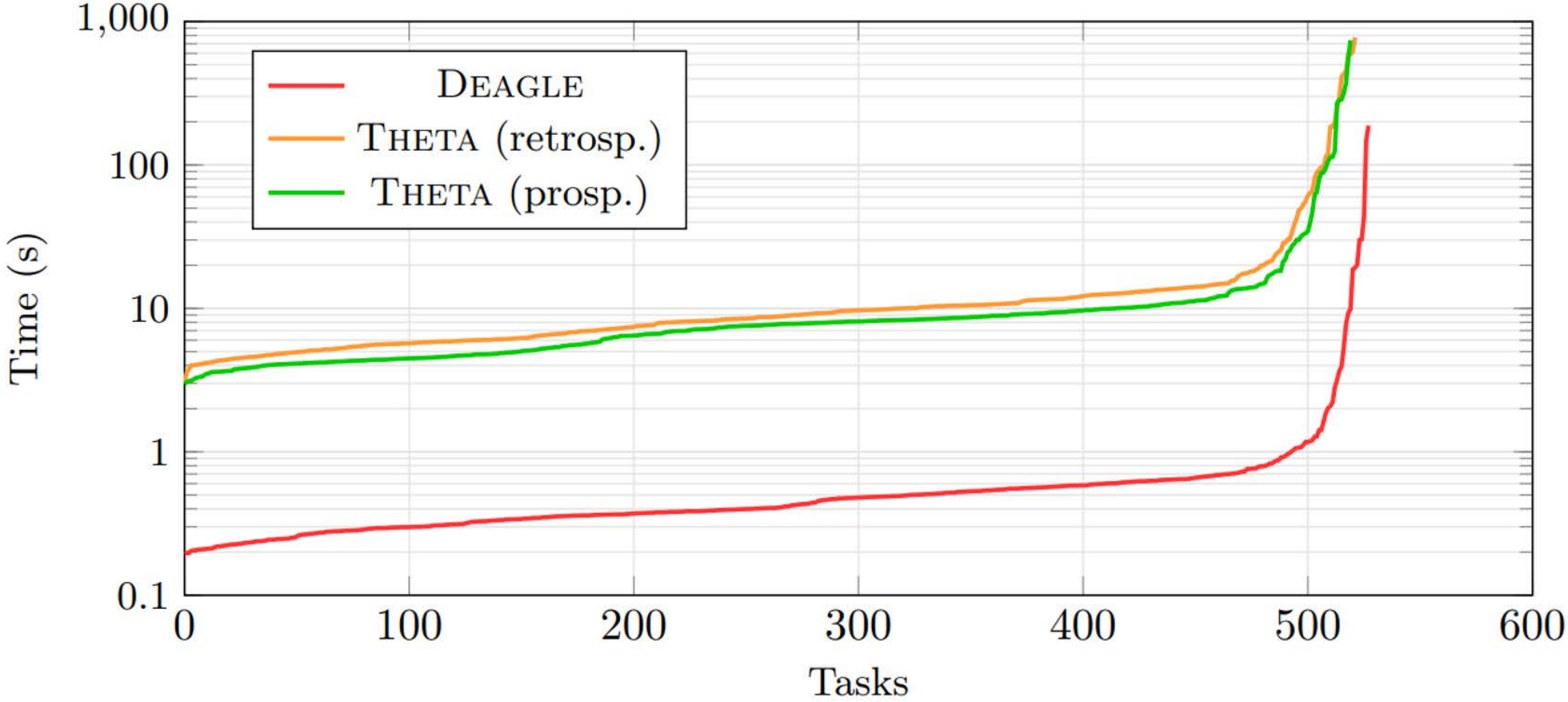
  - Mostly due to unrolling limits, not pushed to repo

Implementation in Theta



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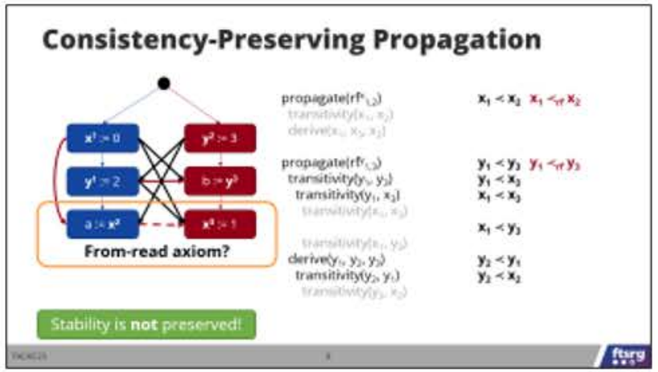

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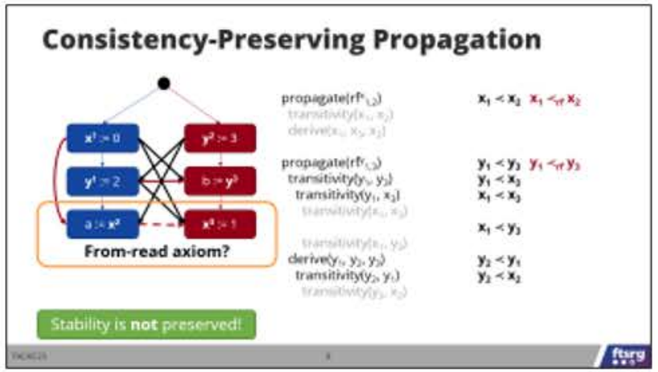

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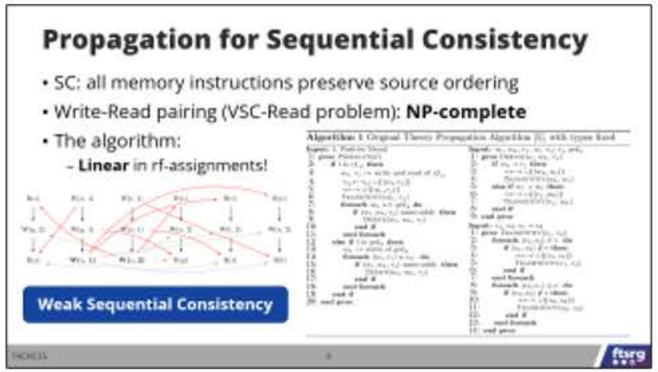

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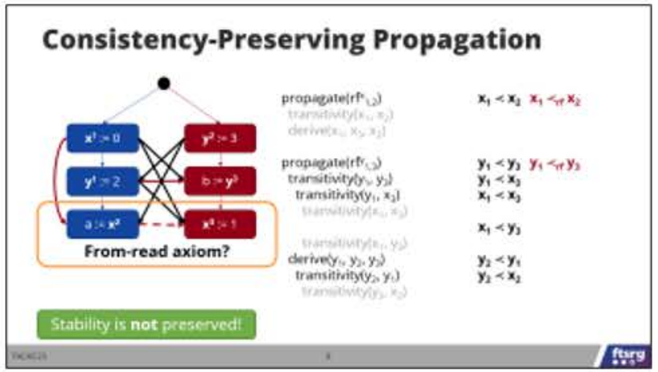

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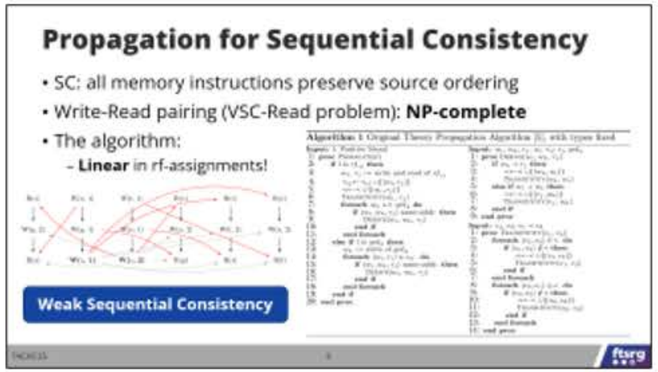

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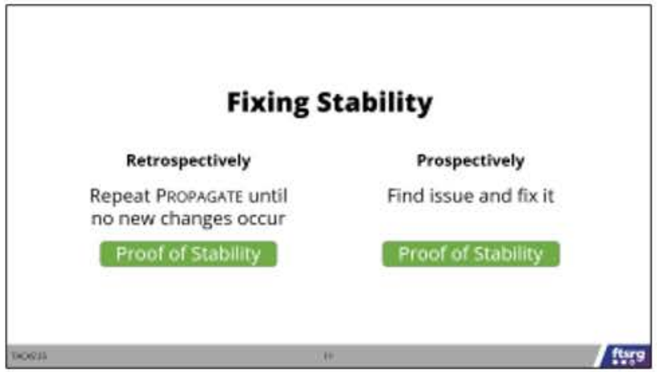

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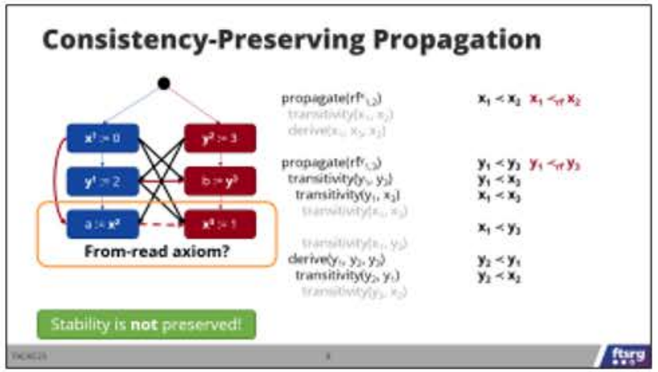

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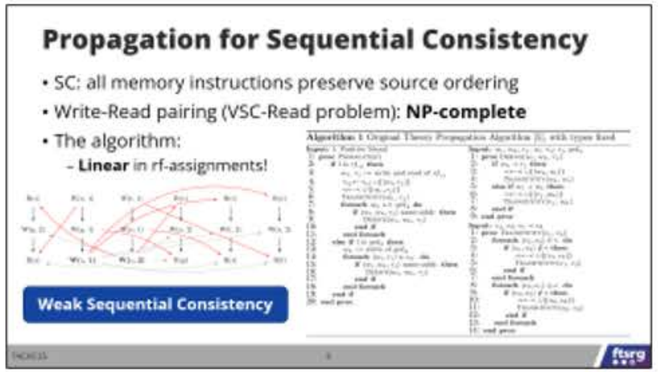

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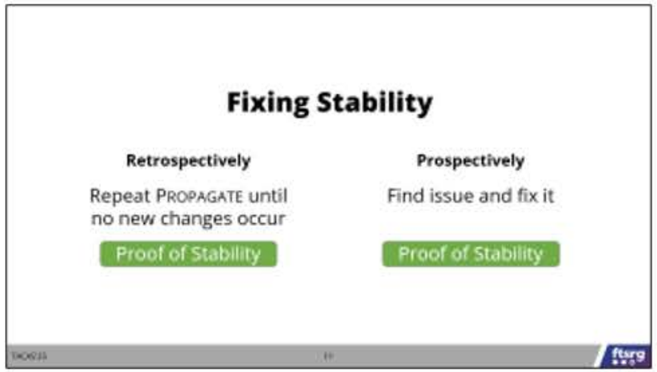

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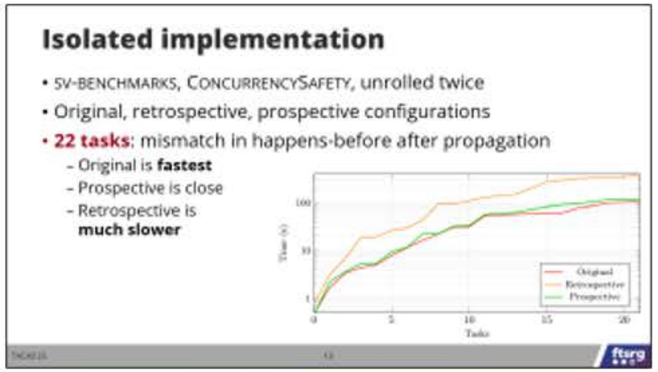

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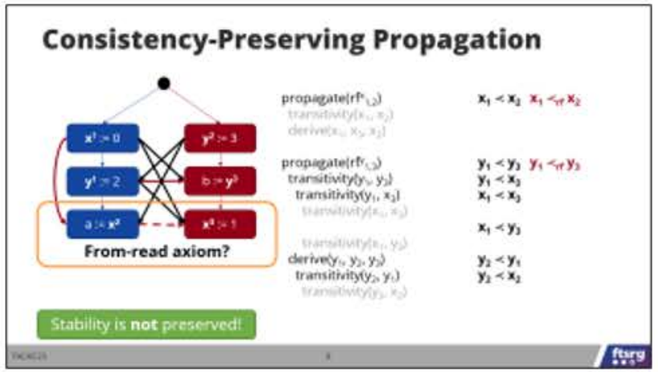

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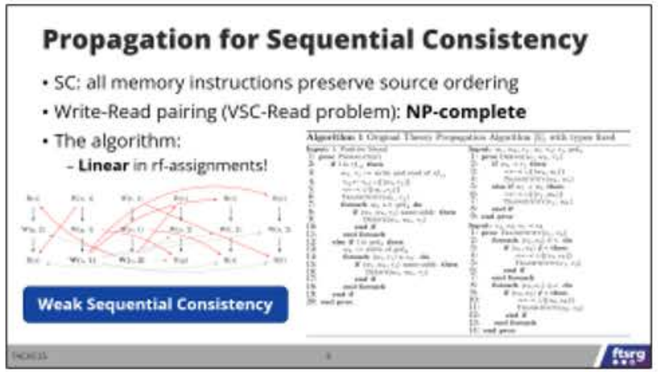

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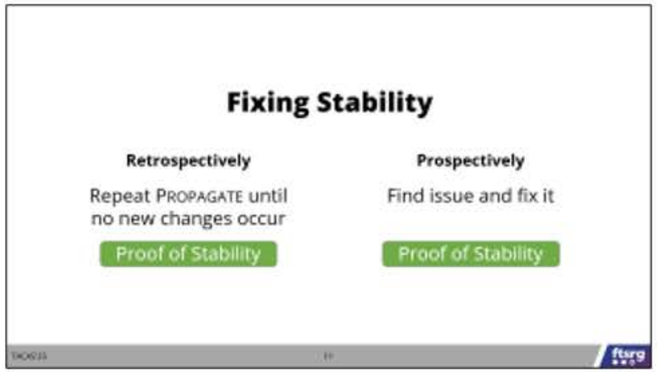

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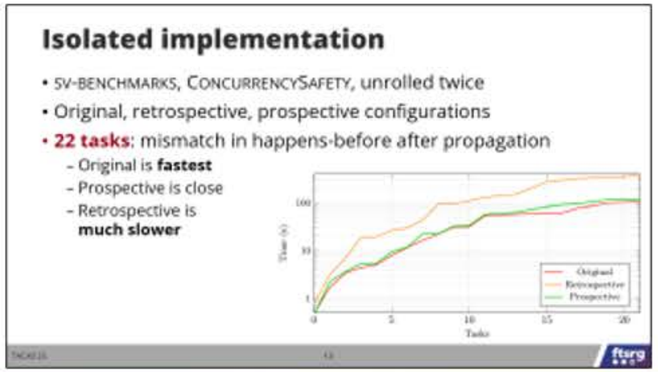

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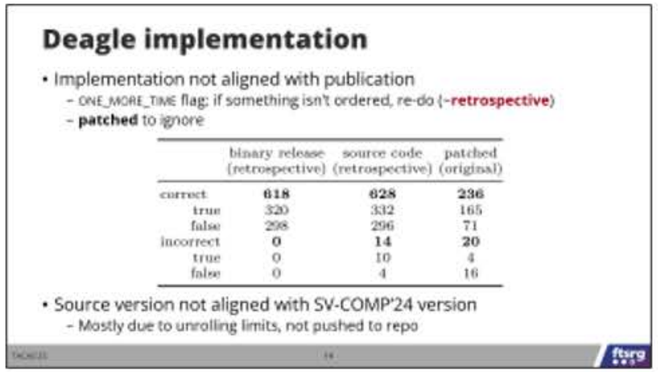

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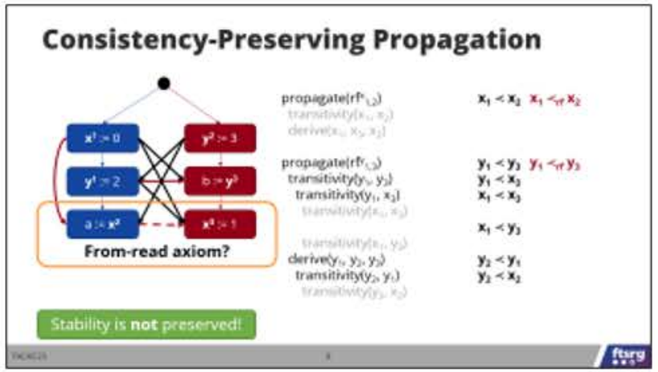

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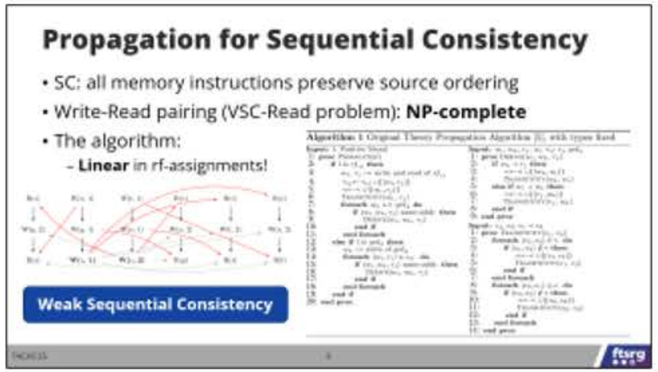

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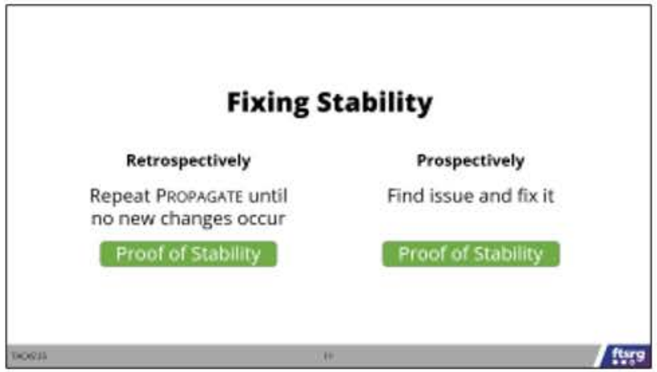

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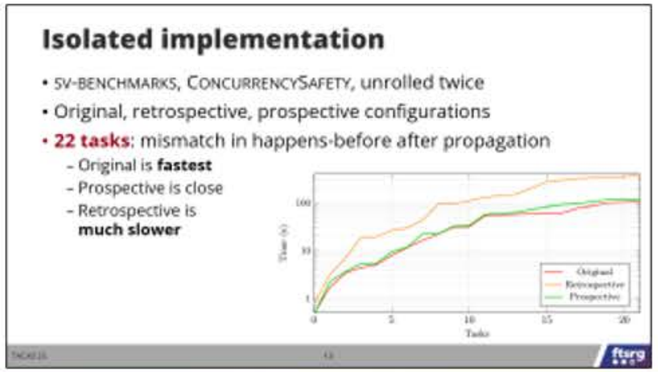

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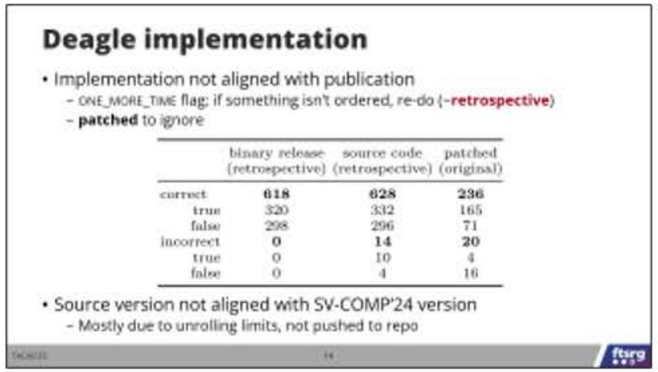

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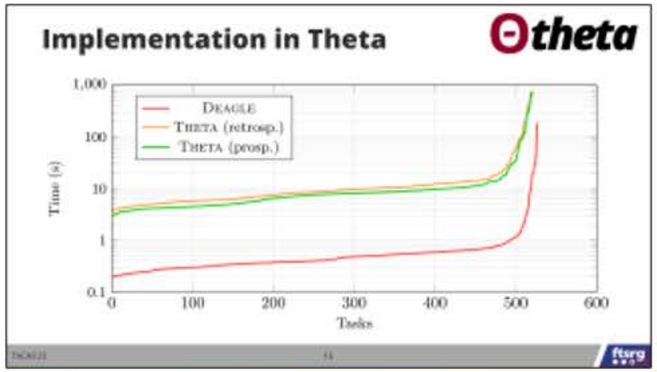

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