Efficient Black-box Checking of Snapshot Isolation in Databases

(Conference VLDB'2024)

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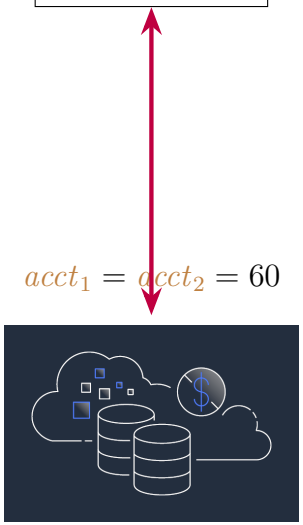
Transaction and Isolation Level

A transaction is a *group* of operations that is executed atomically.

$x_1 \leftarrow \mathsf{R}(acct_1)$
$x_2 \leftarrow \mathsf{R}(acct_2)$
if $x_1 + x_2 > 100$
  $x_2 \leftarrow x_2 - 100$
  $\mathsf{W}(acct_2, x_2)$



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$acct_1 = acct_2 = 60$

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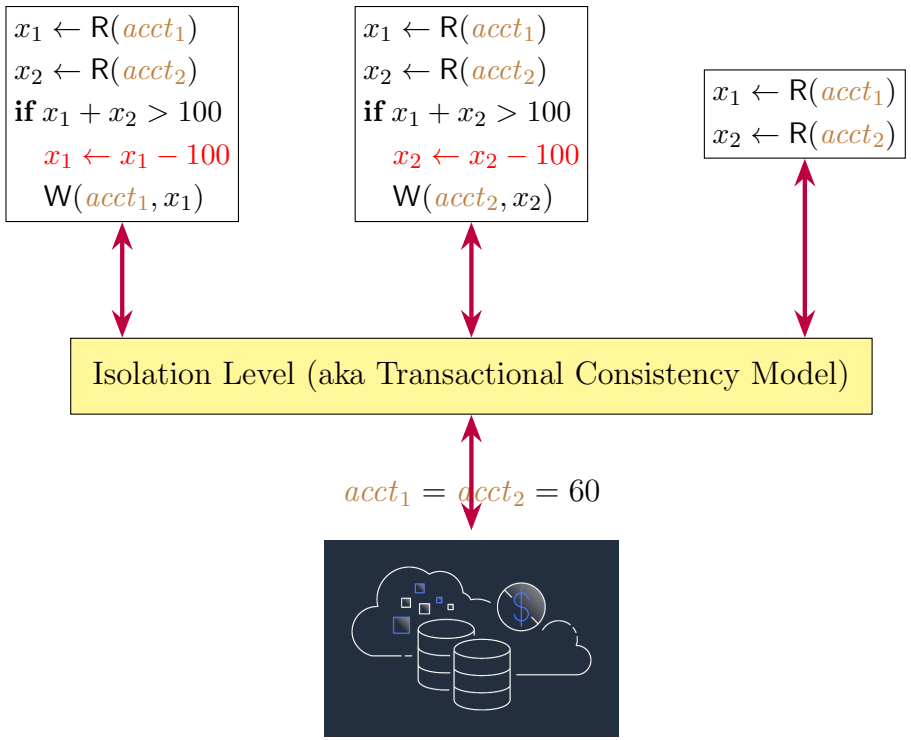
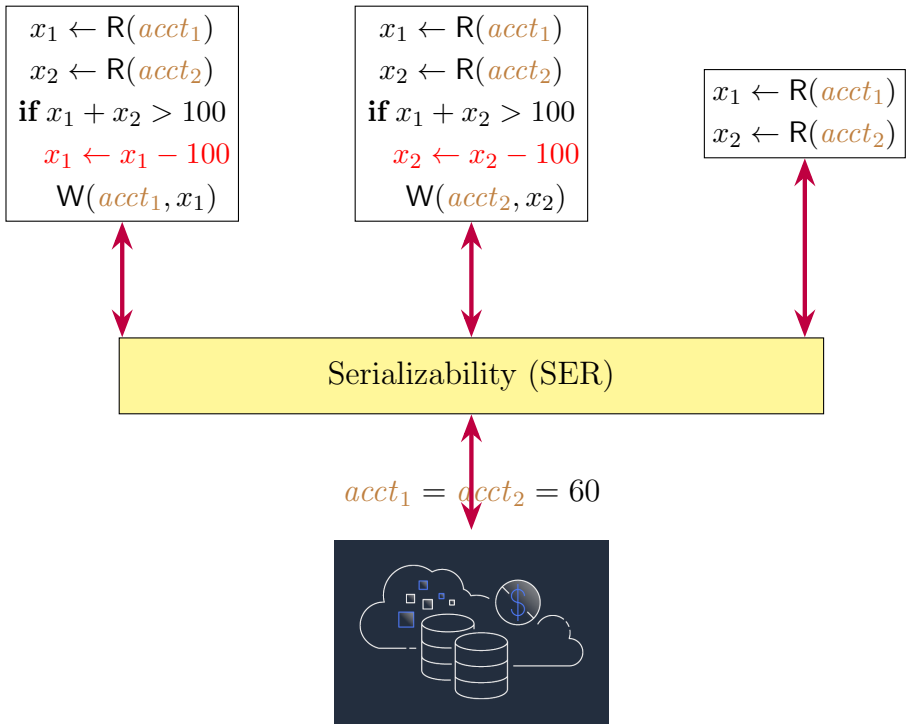


The isolation levels specify how they are isolated from each other.

Serializability (SER)

All transactions appear to execute in some total order.



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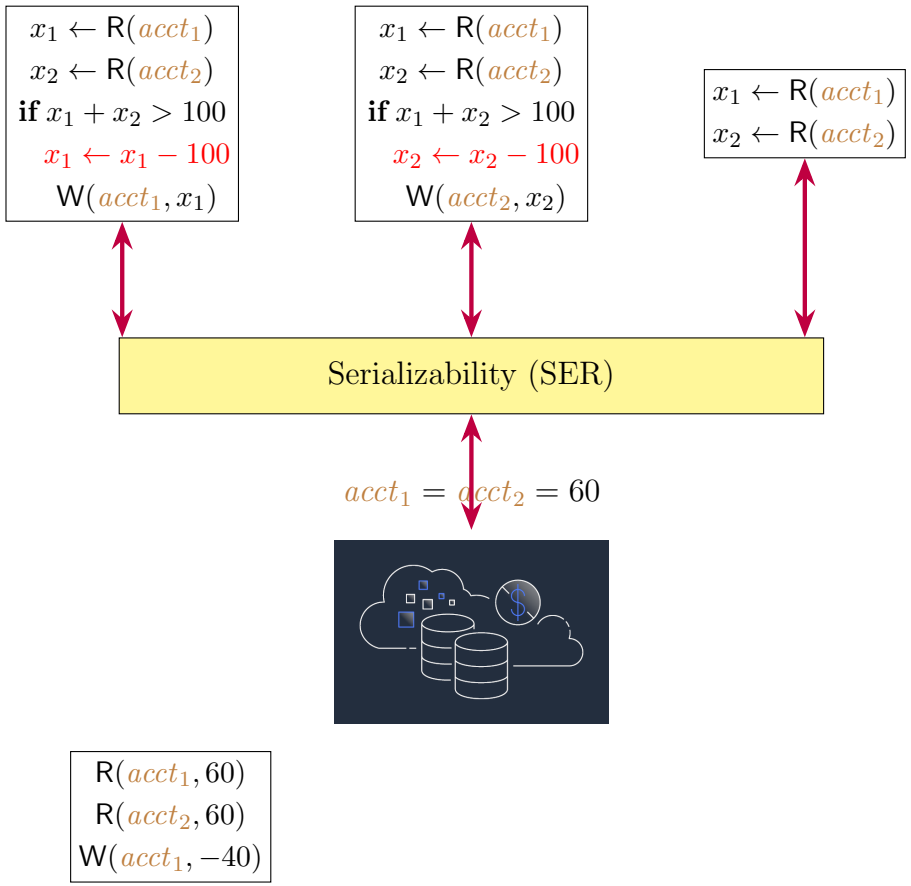

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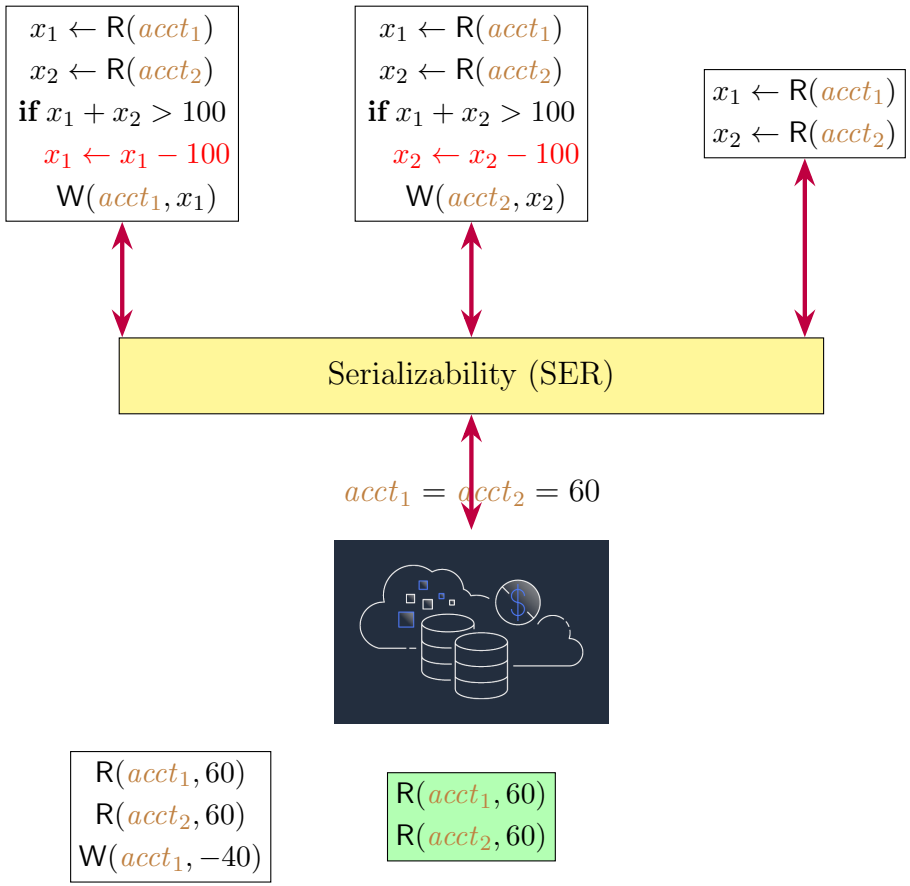

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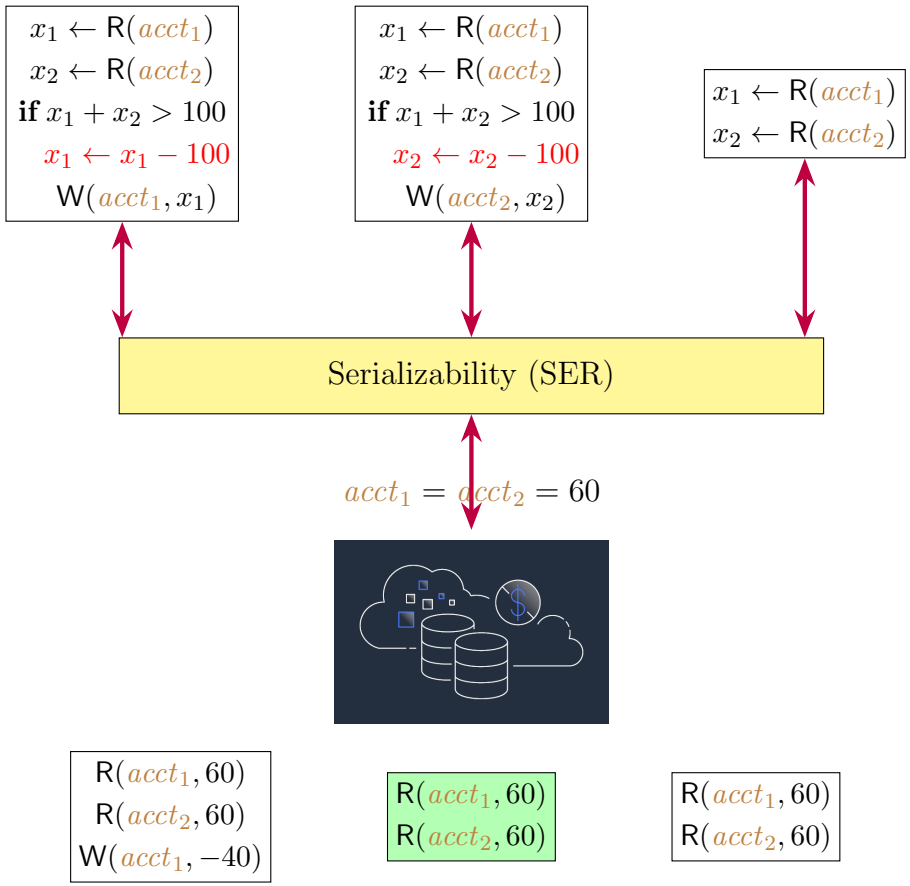

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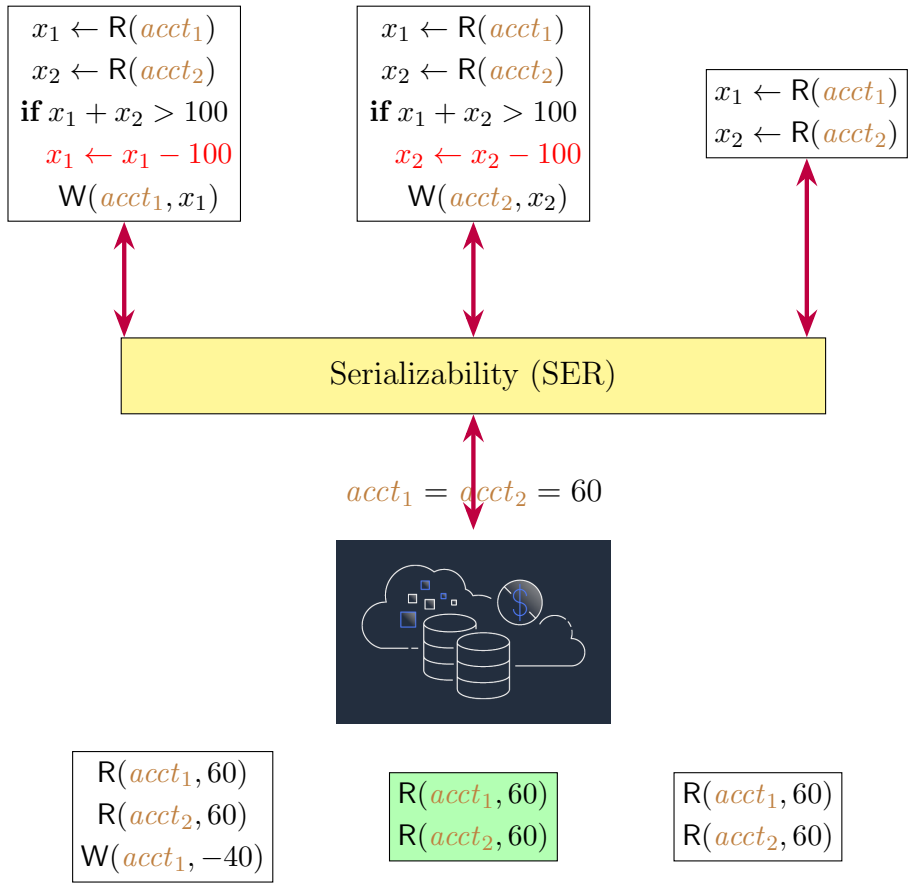
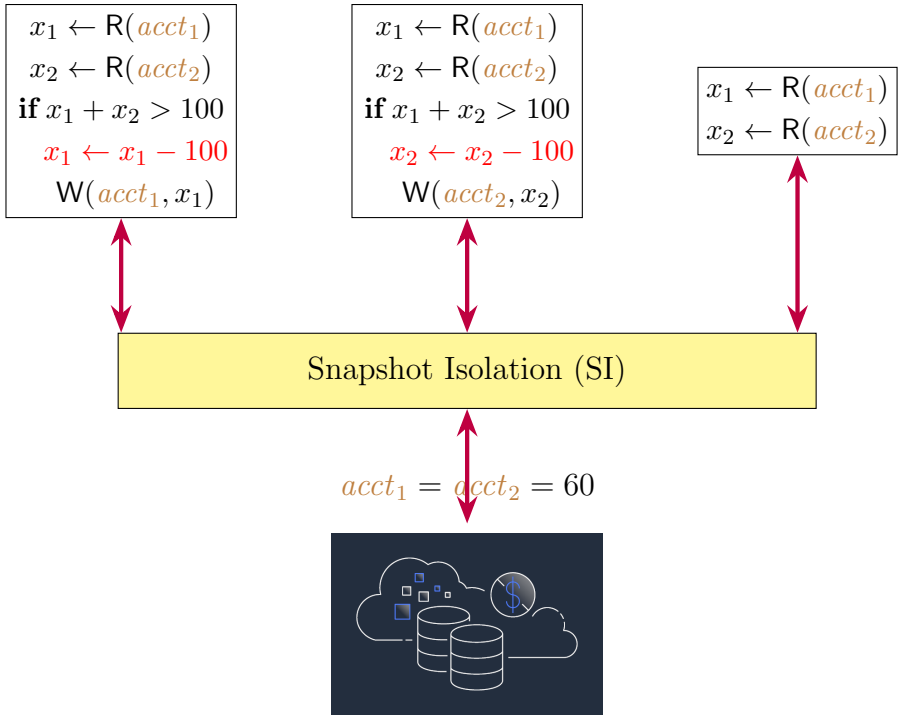


too expensive, especially for distributed transactions

Snapshot Isolation (SI)



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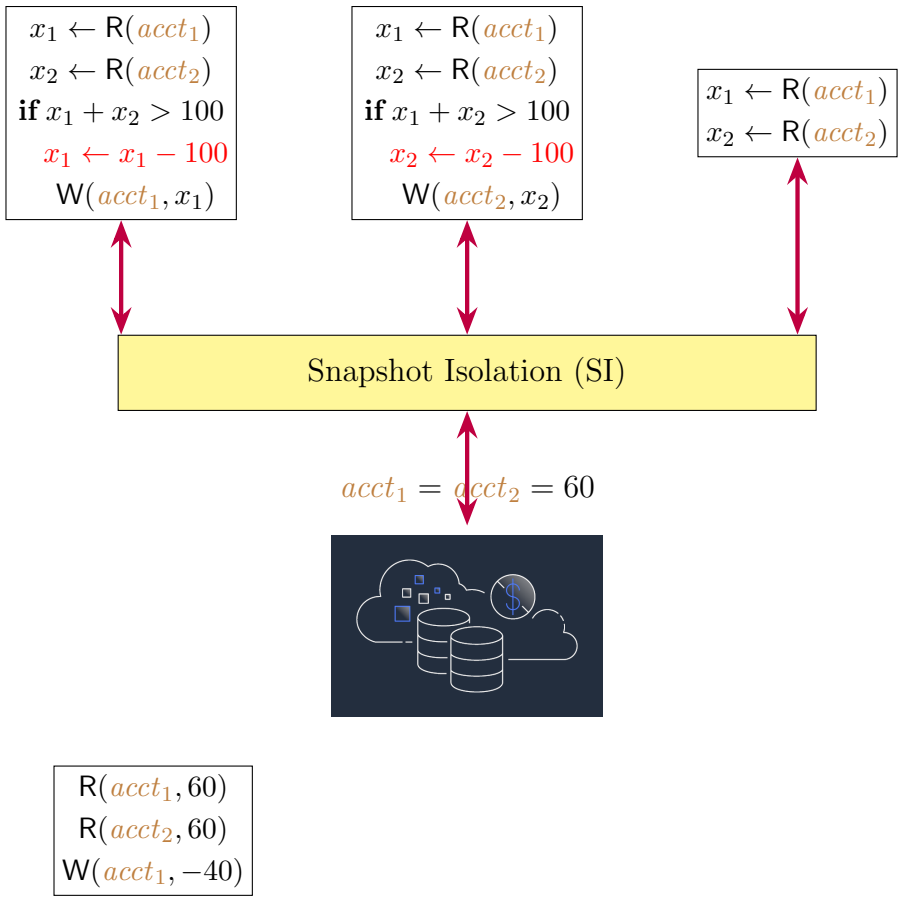

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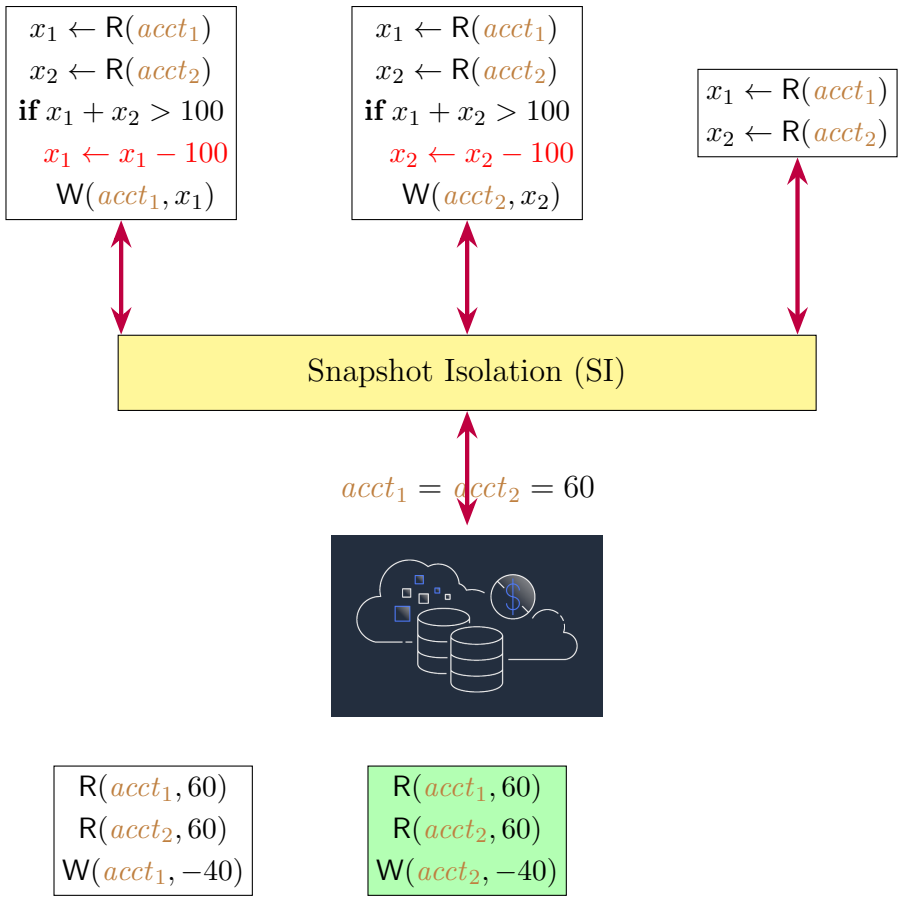

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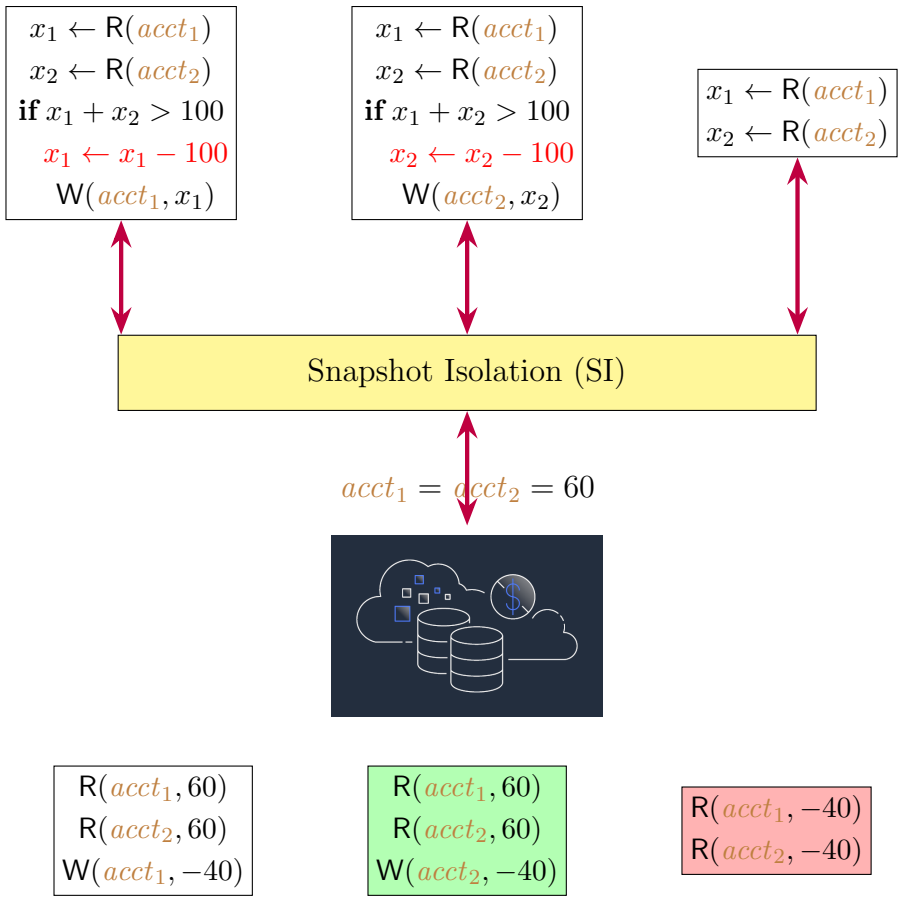

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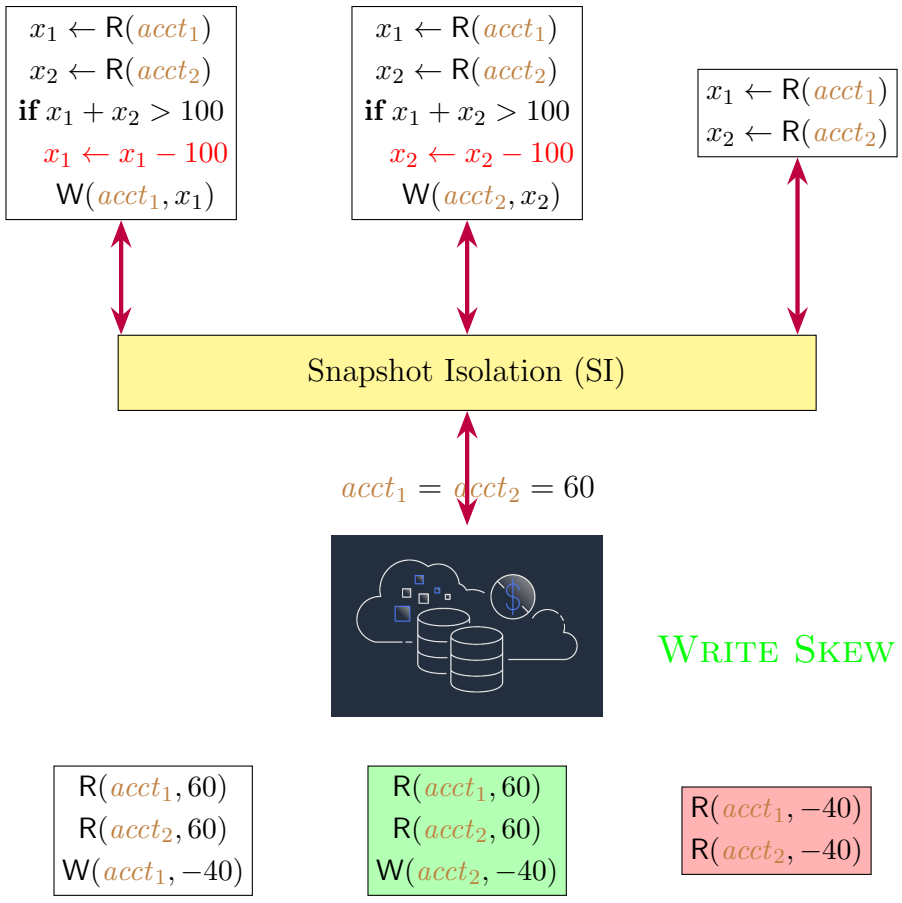

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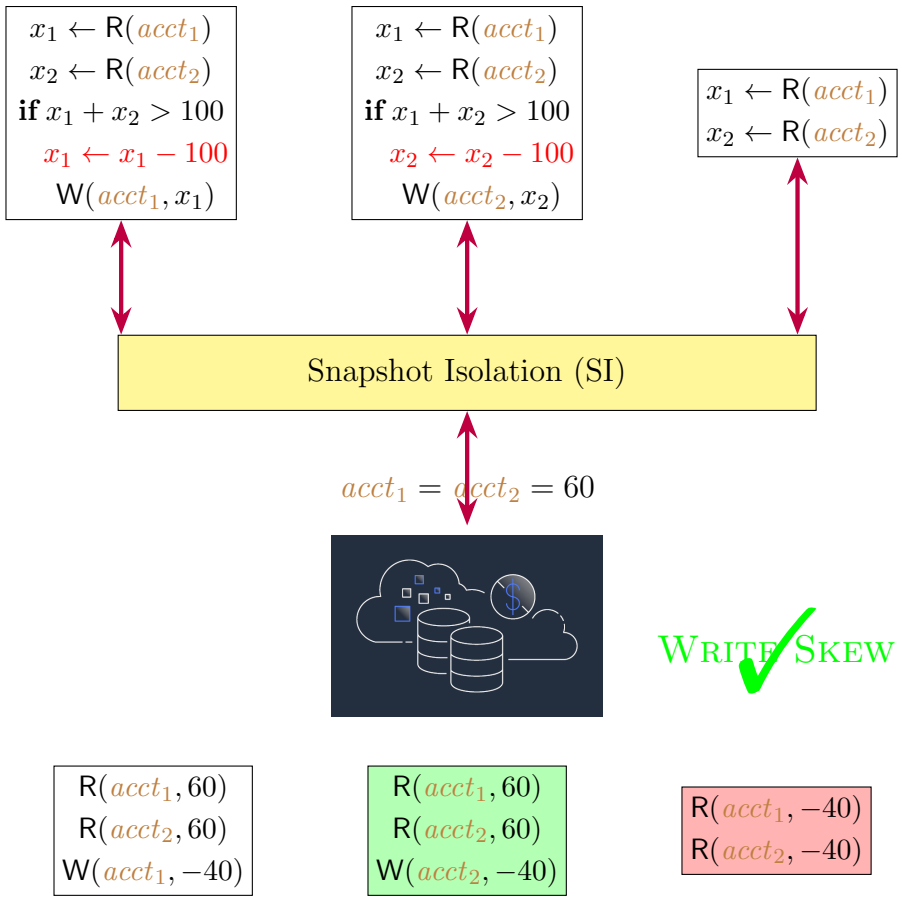

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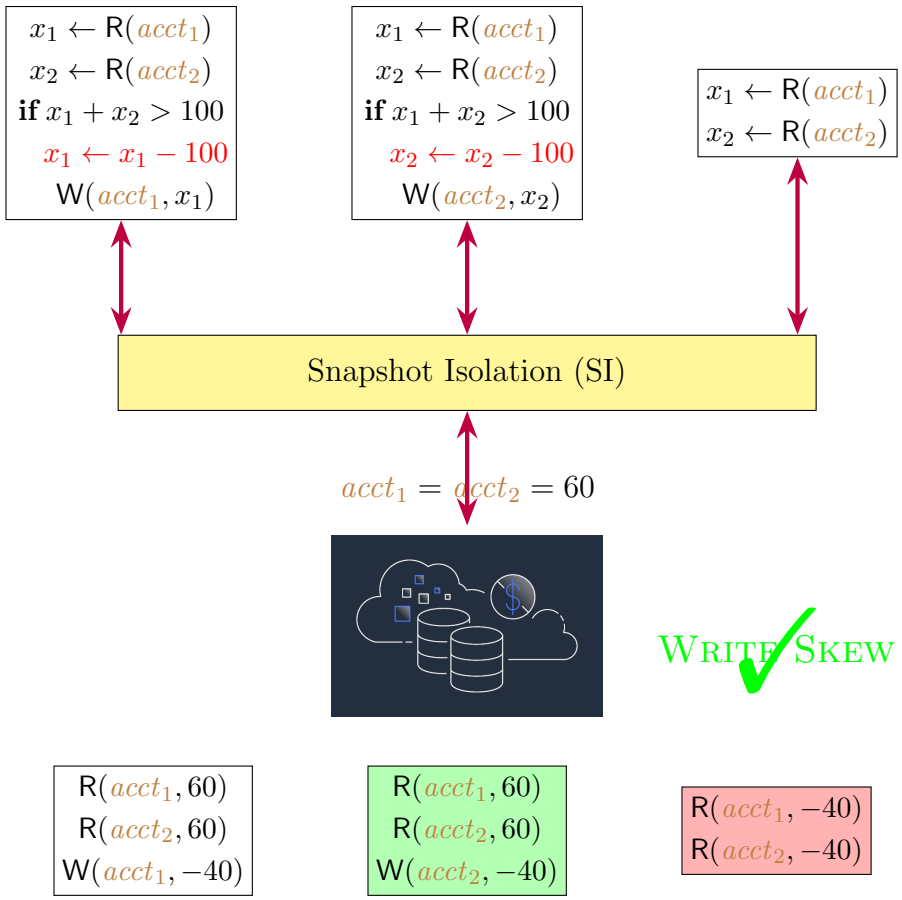

Snapshot Read: Each transaction reads data from a *snapshot* of committed data valid as of the (logical) time the transaction started.

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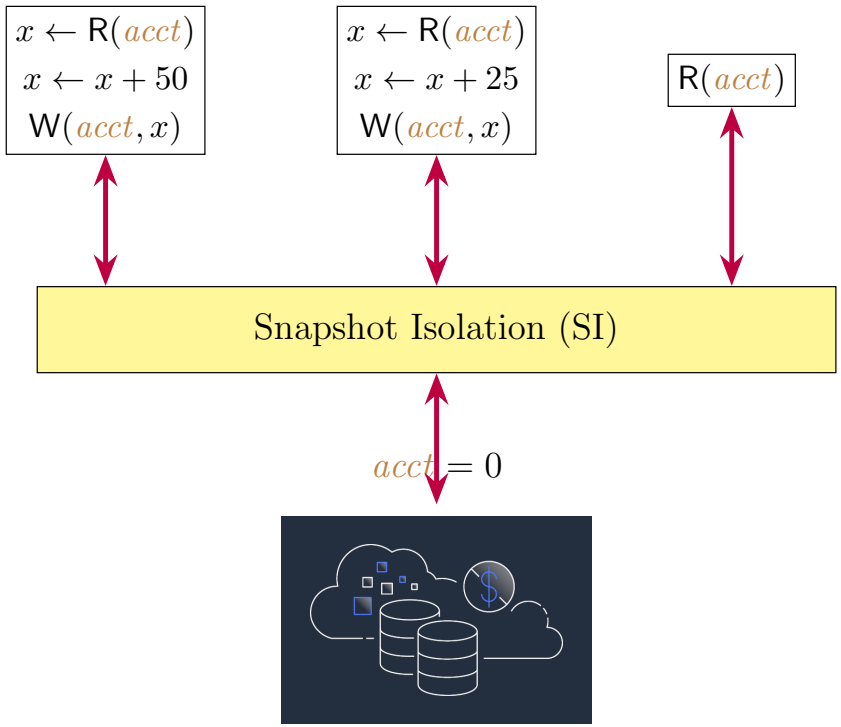

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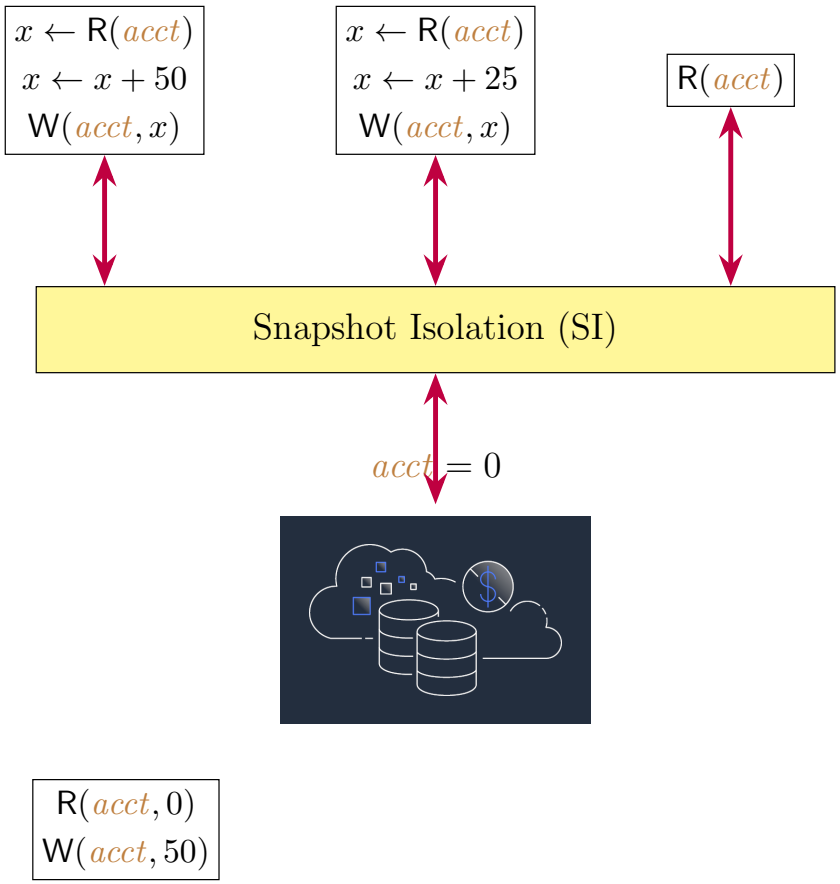

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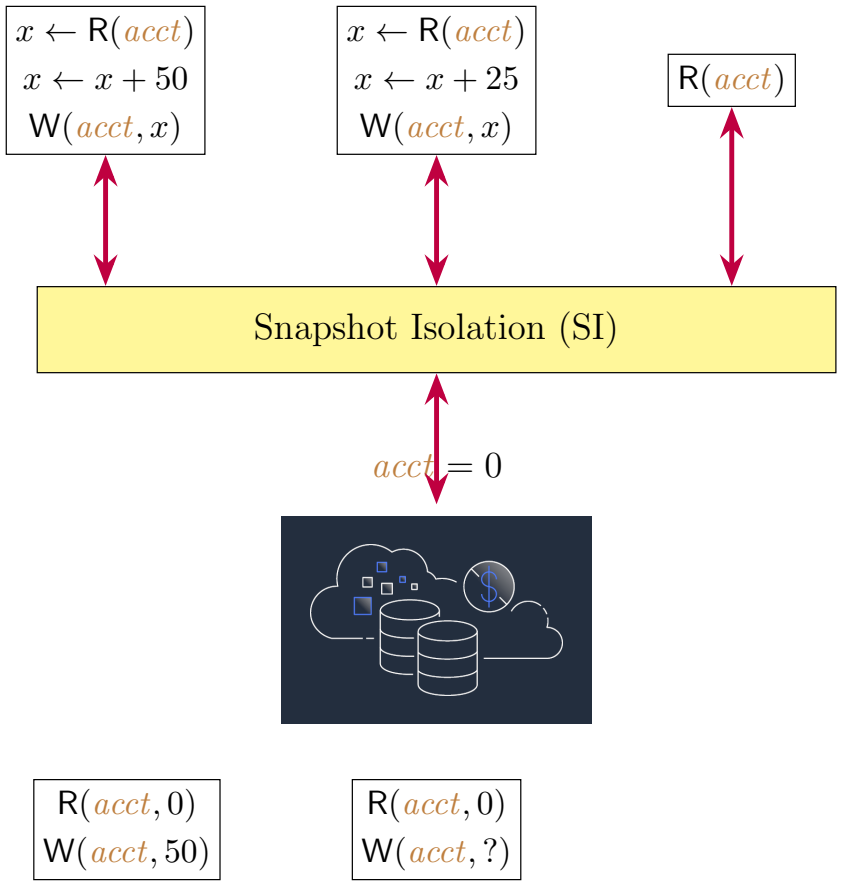

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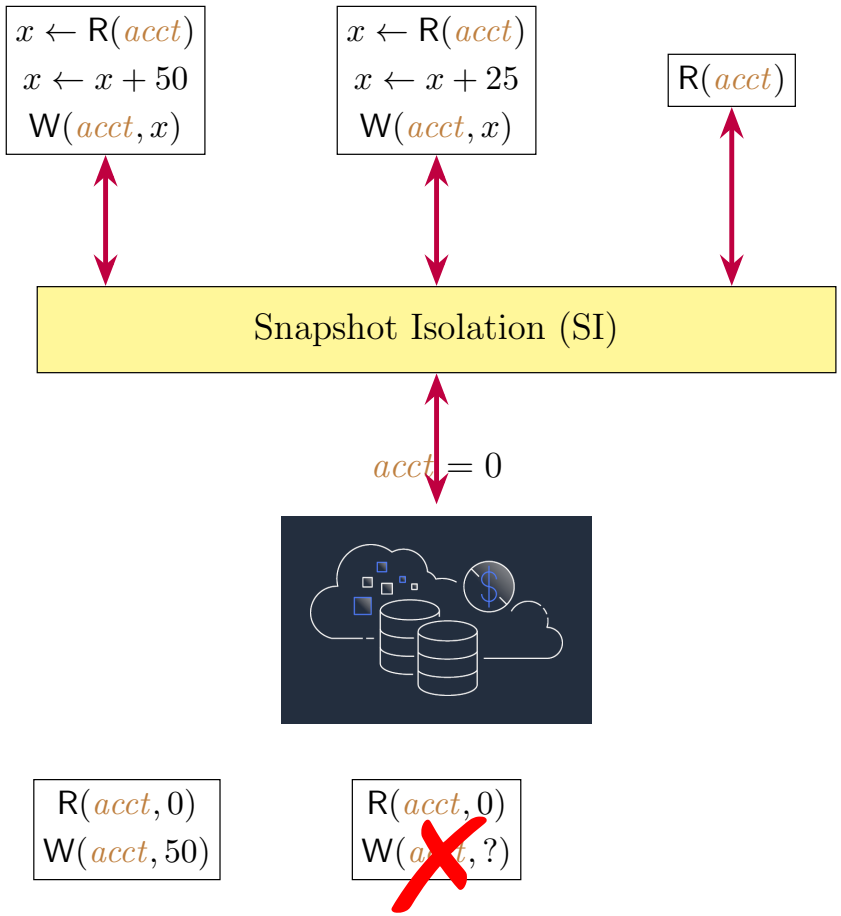

Snapshot Write: Concurrent transactions cannot write to the same key. One of them must be aborted.

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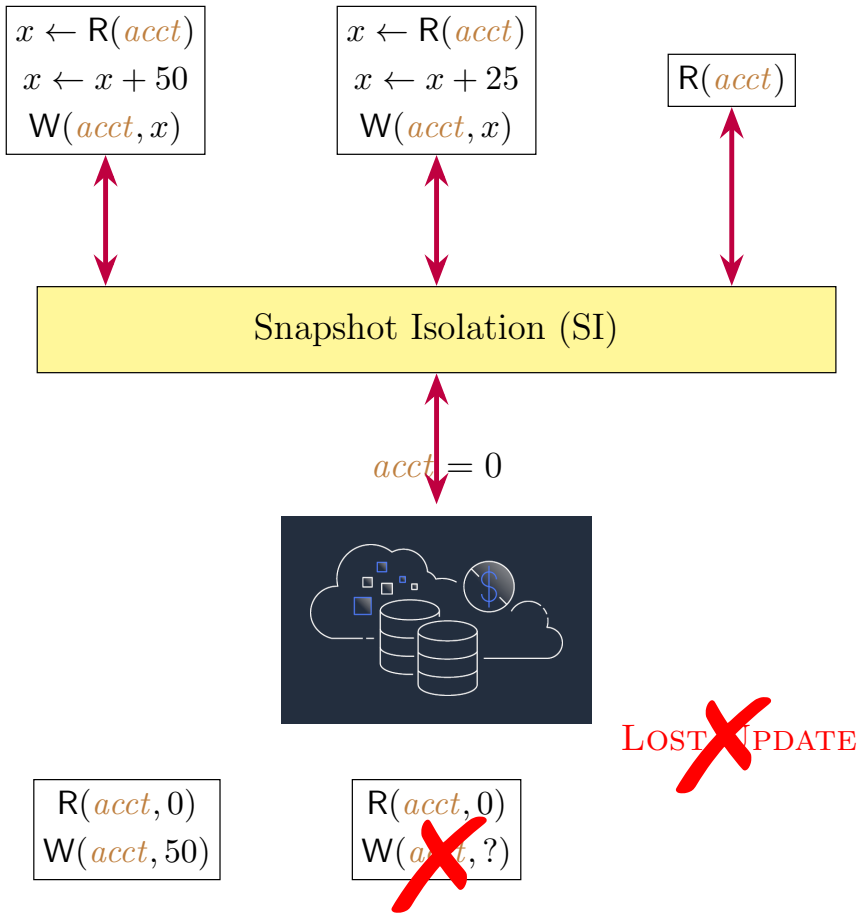

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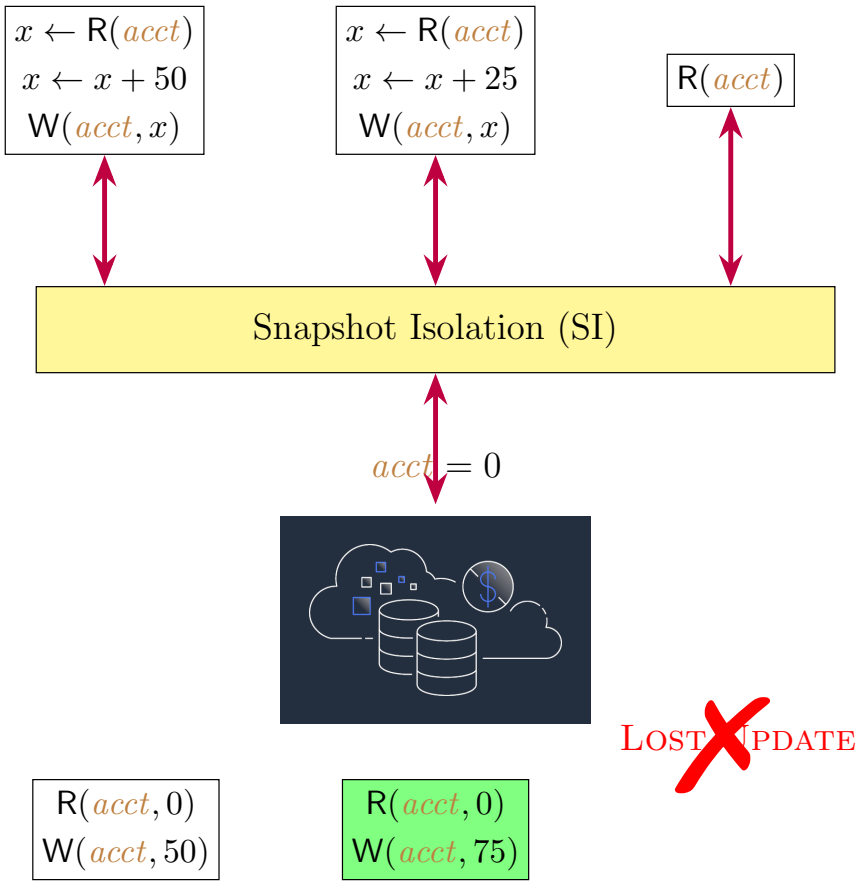

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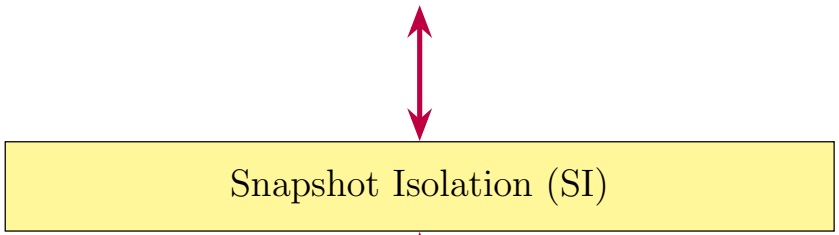

Snapshot Isolation (SI)

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$\mathsf{W}(x, post)$

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$\mathsf{W}(x, post)$

$\mathsf{R}(x, post)$
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$\mathsf{W}(x, post)$

$\mathsf{R}(x, post)$
$\mathsf{W}(y, comment)$

$\mathsf{R}(x, empty)$
$\mathsf{R}(y, comment)$

Snapshot Isolation (SI)

Snapshot Isolation (SI)

Causality Violation

$\mathsf{W}(x, post)$	$\mathsf{R}(x, post)$ $\mathsf{W}(y, comment)$	$\mathsf{R}(x, empty)$ $\mathsf{R}(y, comment)$

Snapshot Isolation (SI)

Snapshot Isolation (SI)

CAUSALITY VIOLATION

W(x, *post*)

R(x, *post*)
W(y, *comment*)

R(x, *empty*)
R(y, *comment*)

Databases and Snapshot Isolation

database logos

Many databases claim to support SI.

Databases and Snapshot Isolation

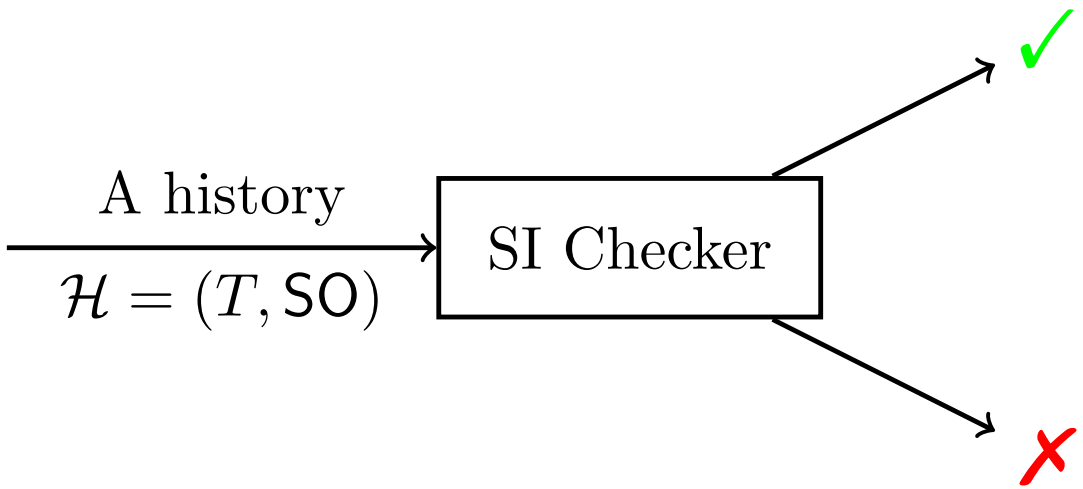
+papers

Databases may fail to provide SI as they claim.

The SI Checking Problem

Definition (The SI Checking Problem)

The SI checking problem is the decision problem of determing whether a given history $\mathcal{H} = (T, \mathsf{SO})$ satisfies SI?



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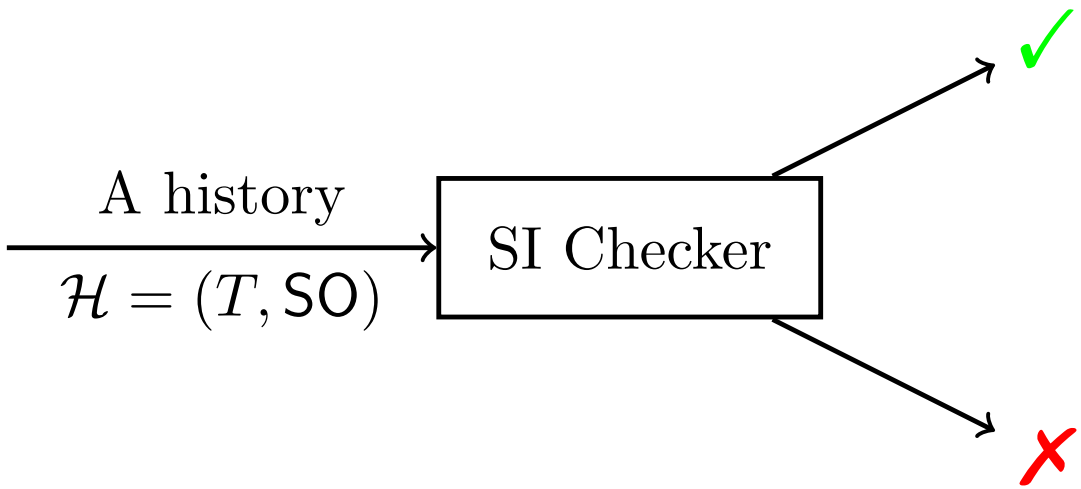
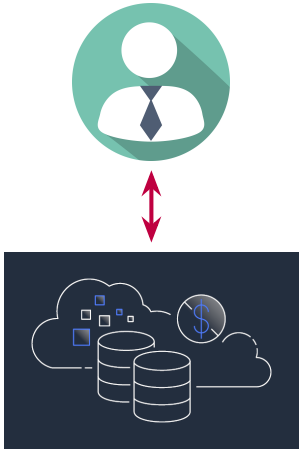


SO : *session order* among the set T of transactions

The SI Checking Problem

Black-box checking: do not rely on database internals



The histories are collected from database logs.

The SI Checking Problem

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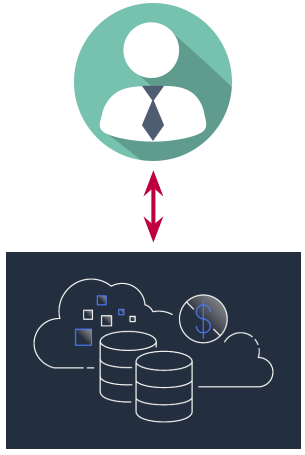

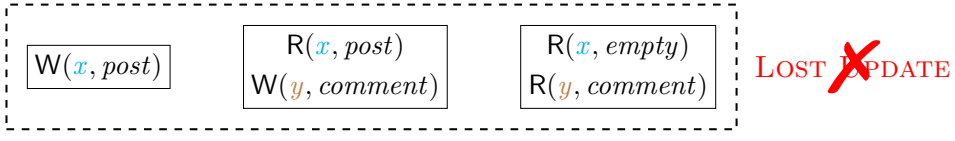

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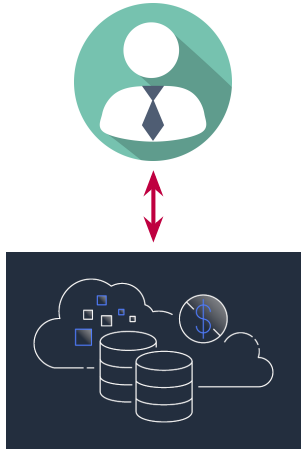

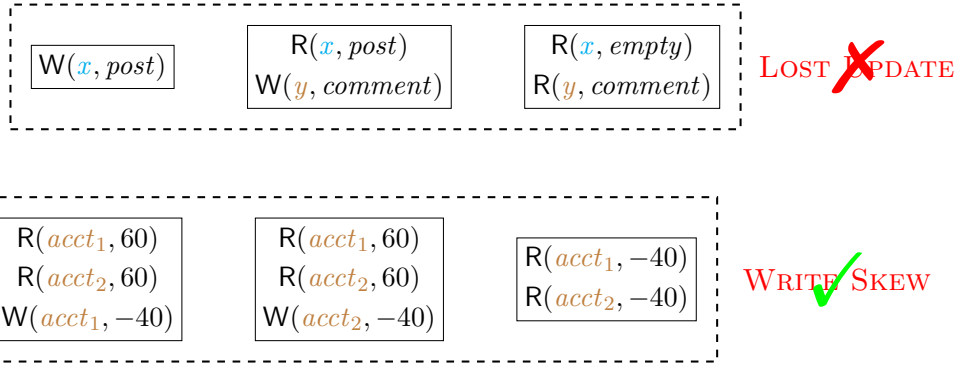

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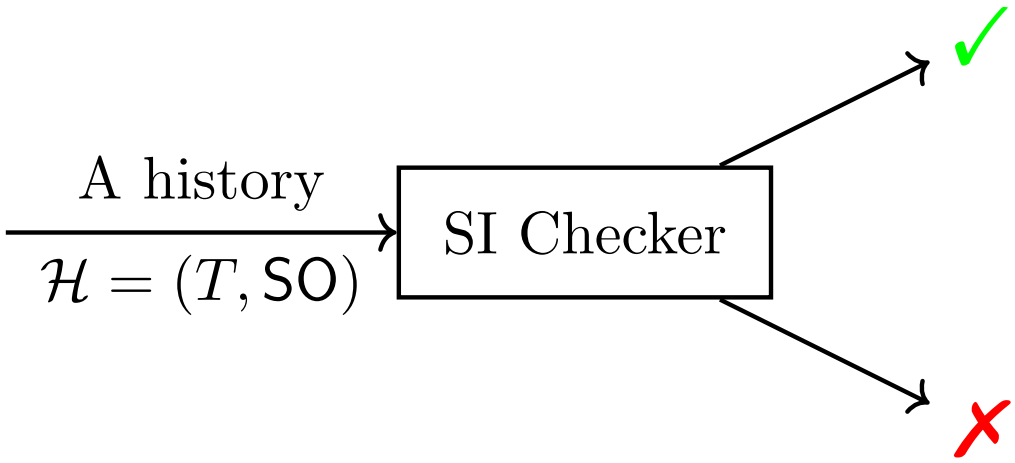

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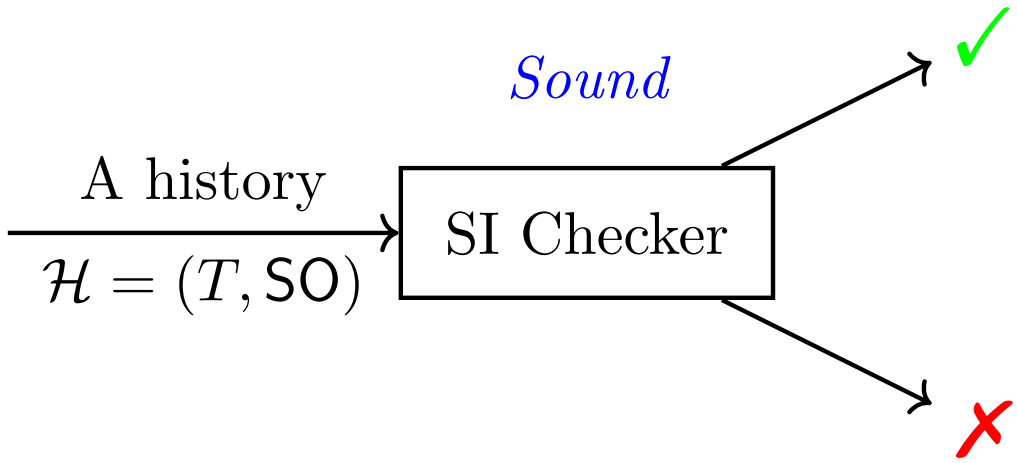
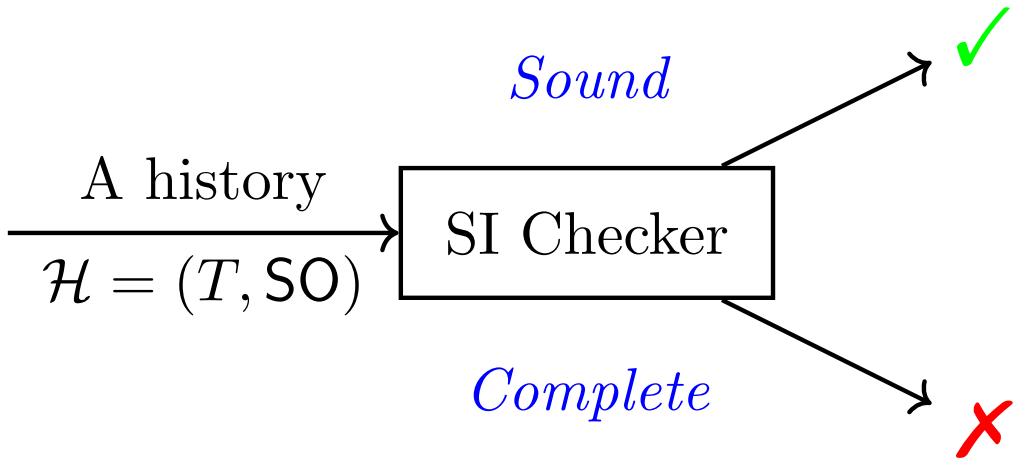


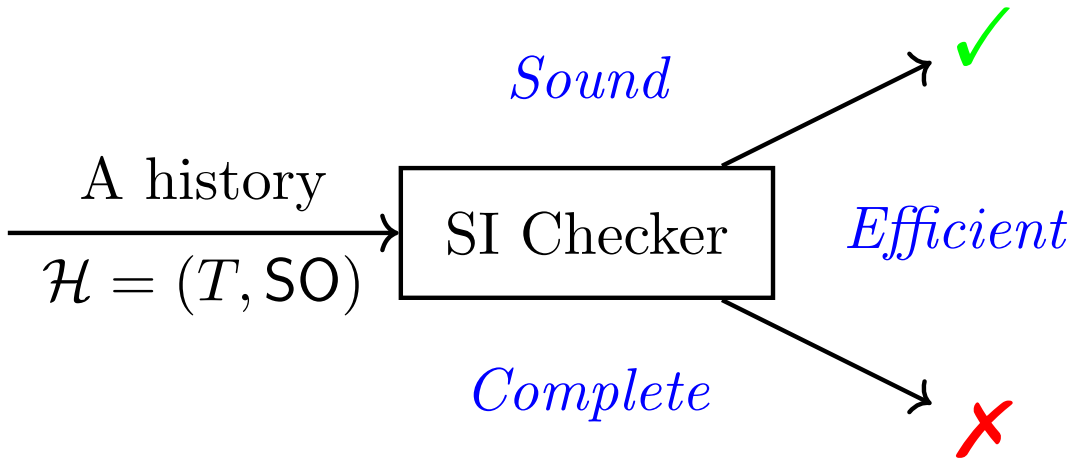
Sound: If the checker says ✗, then the history does *not* satisfy SI.

The SI Checking Problem



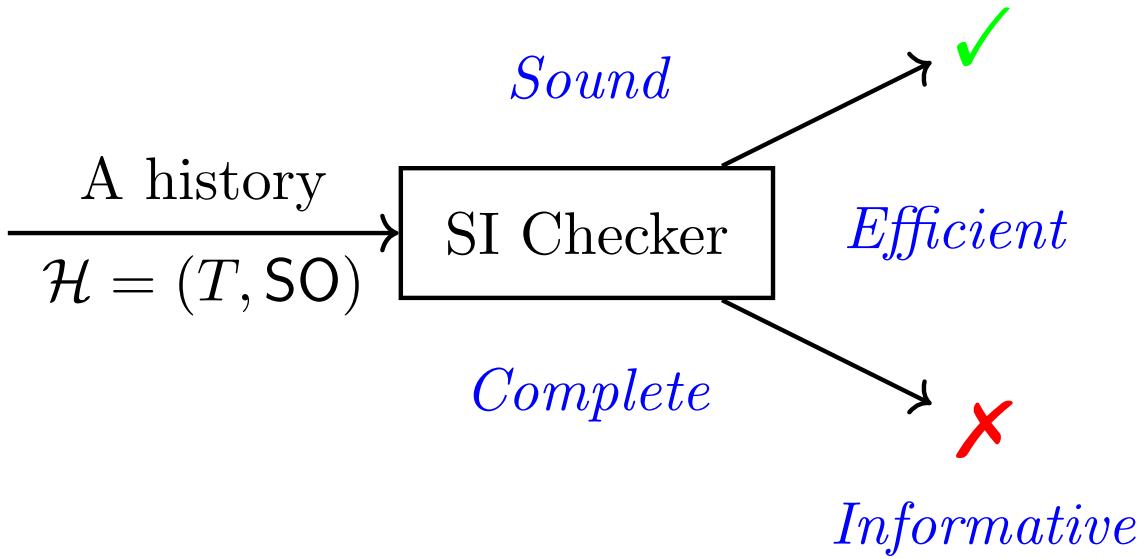
Complete: If the checker says ✓, then the history *satisfies* SI.

The SI Checking Problem



Efficient: The checker should *scale* up to large workloads.

The SI Checking Problem

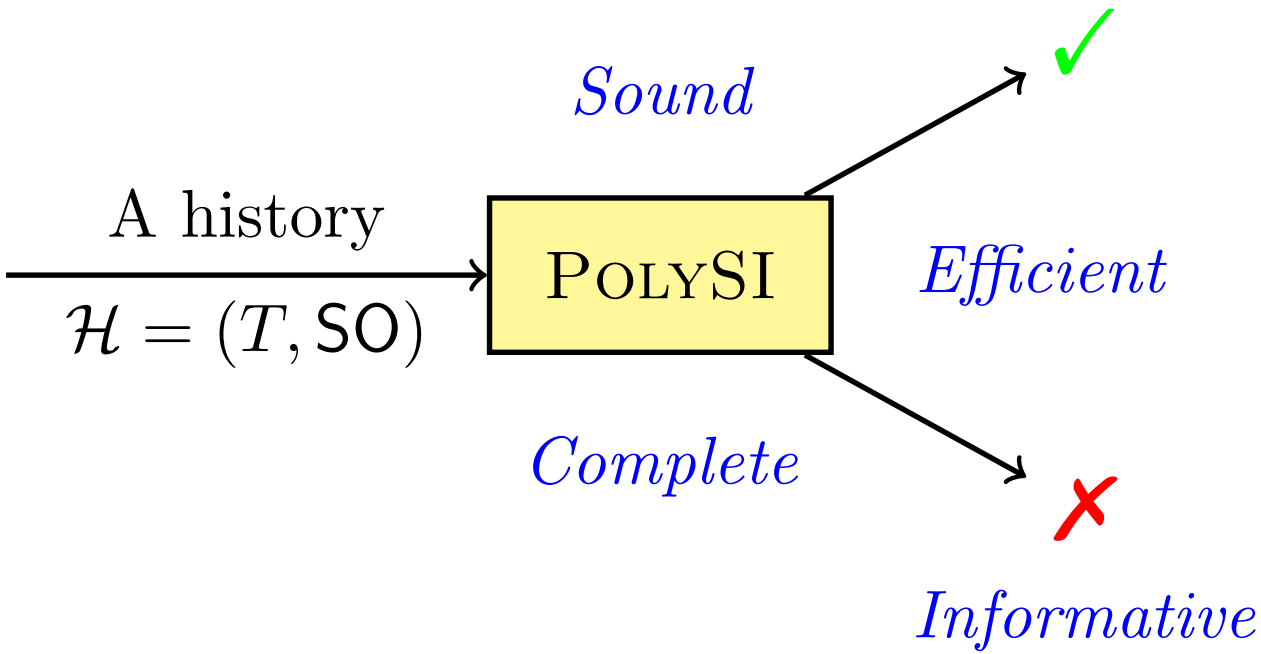


Informative: The checker should provide understandable *counterexamples* if it says ✗.

The SI Checking Problem

related-work

Contribution: the PolySI Checker



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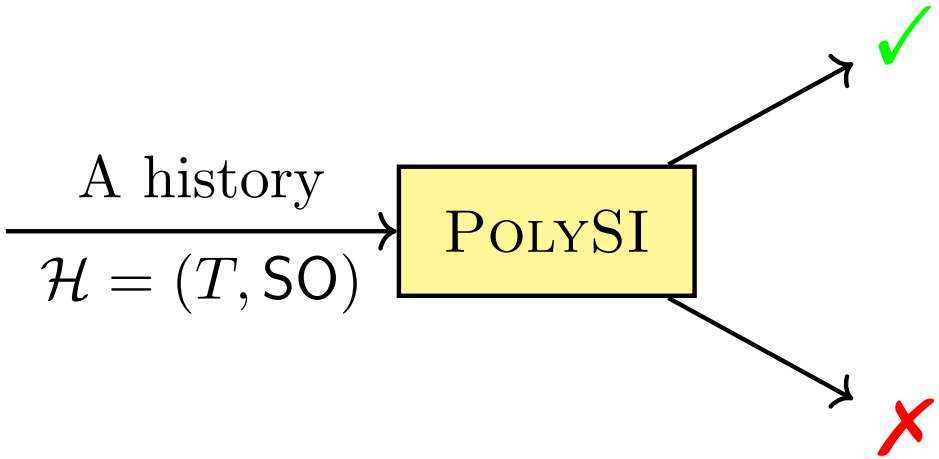

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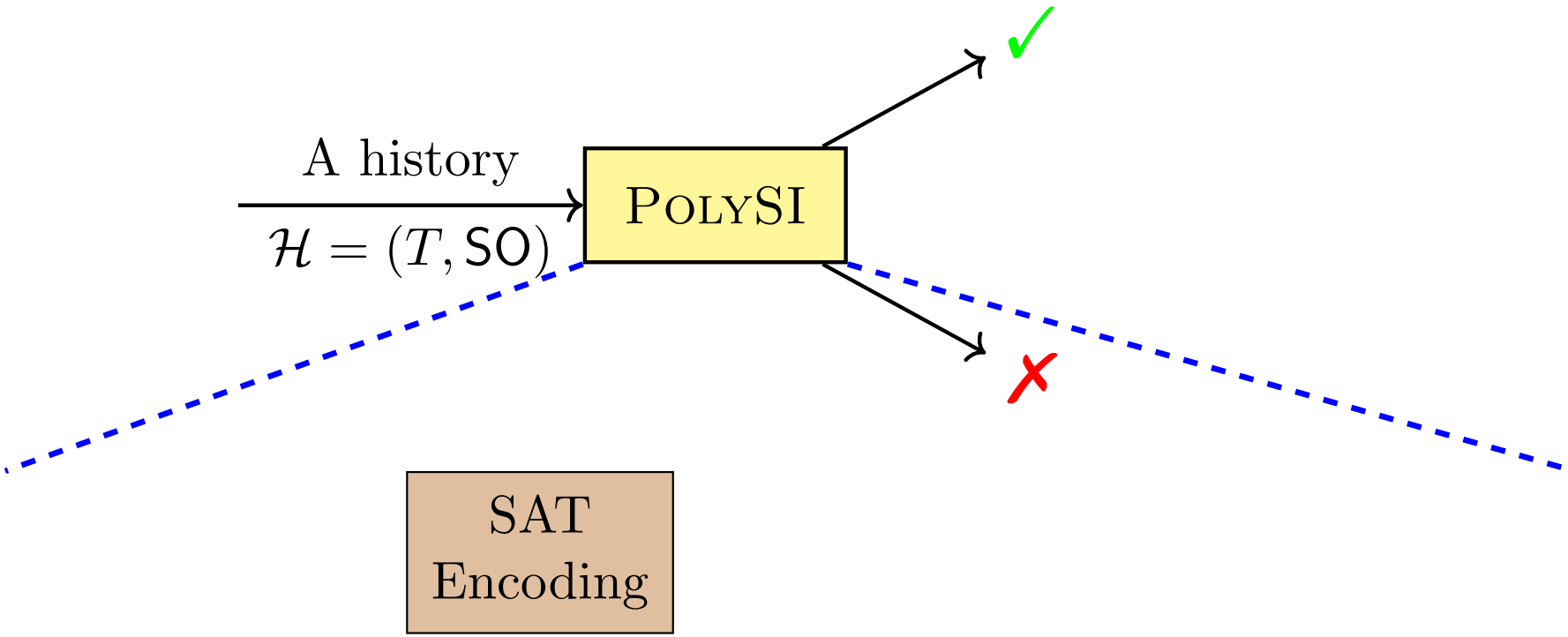
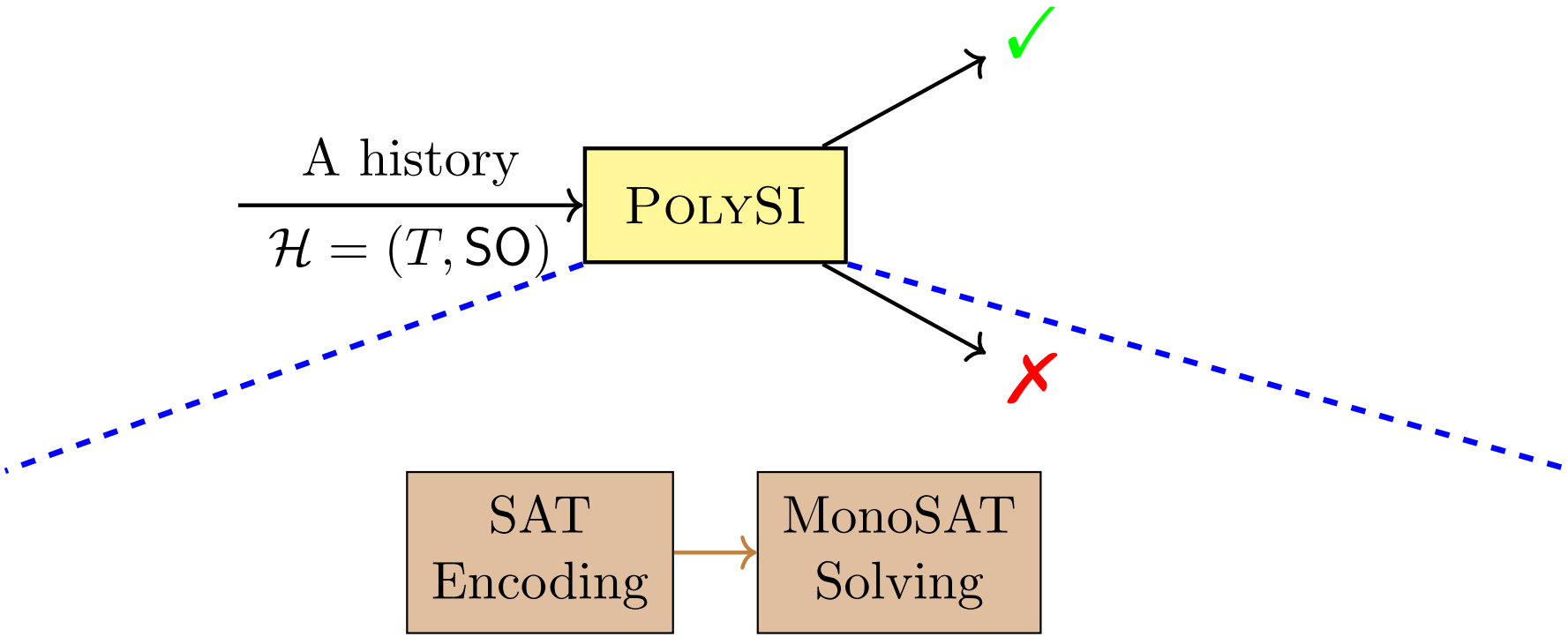


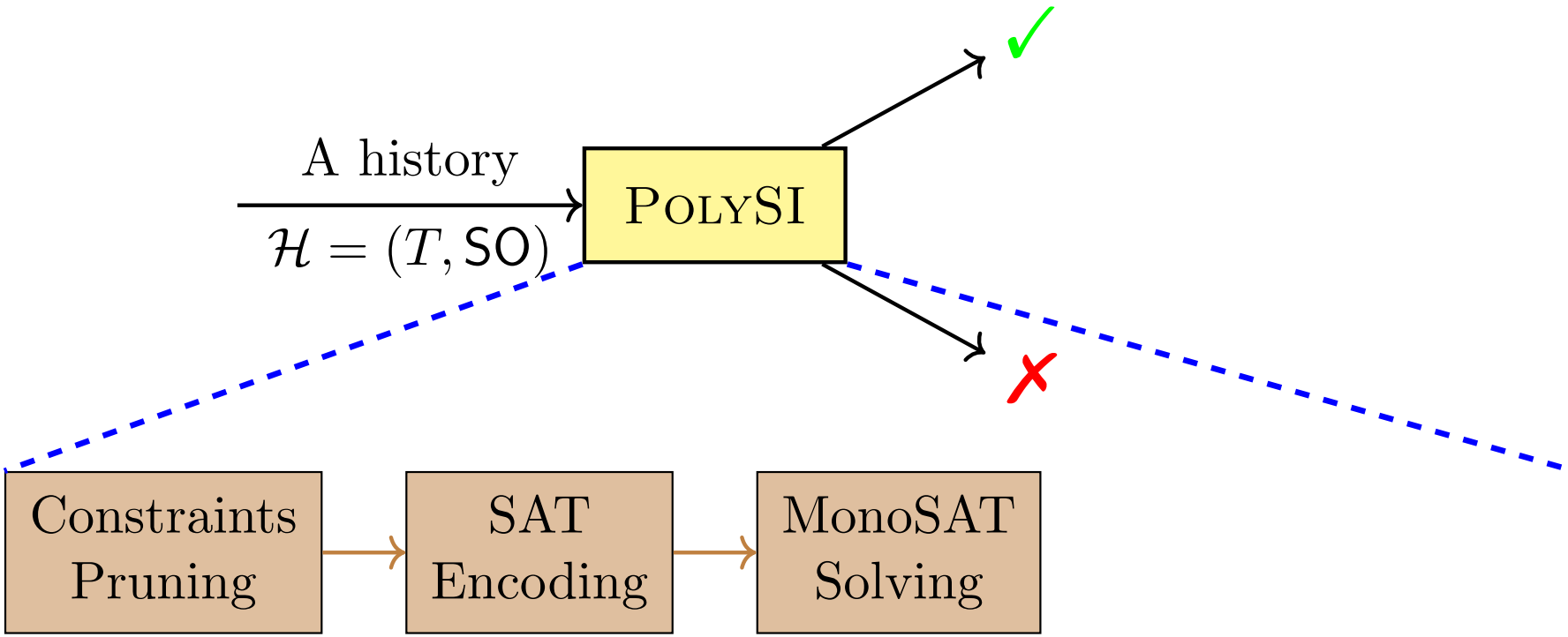
Sound & Complete: polygraph-based characterization of SI

Contribution: the PolySI Checker



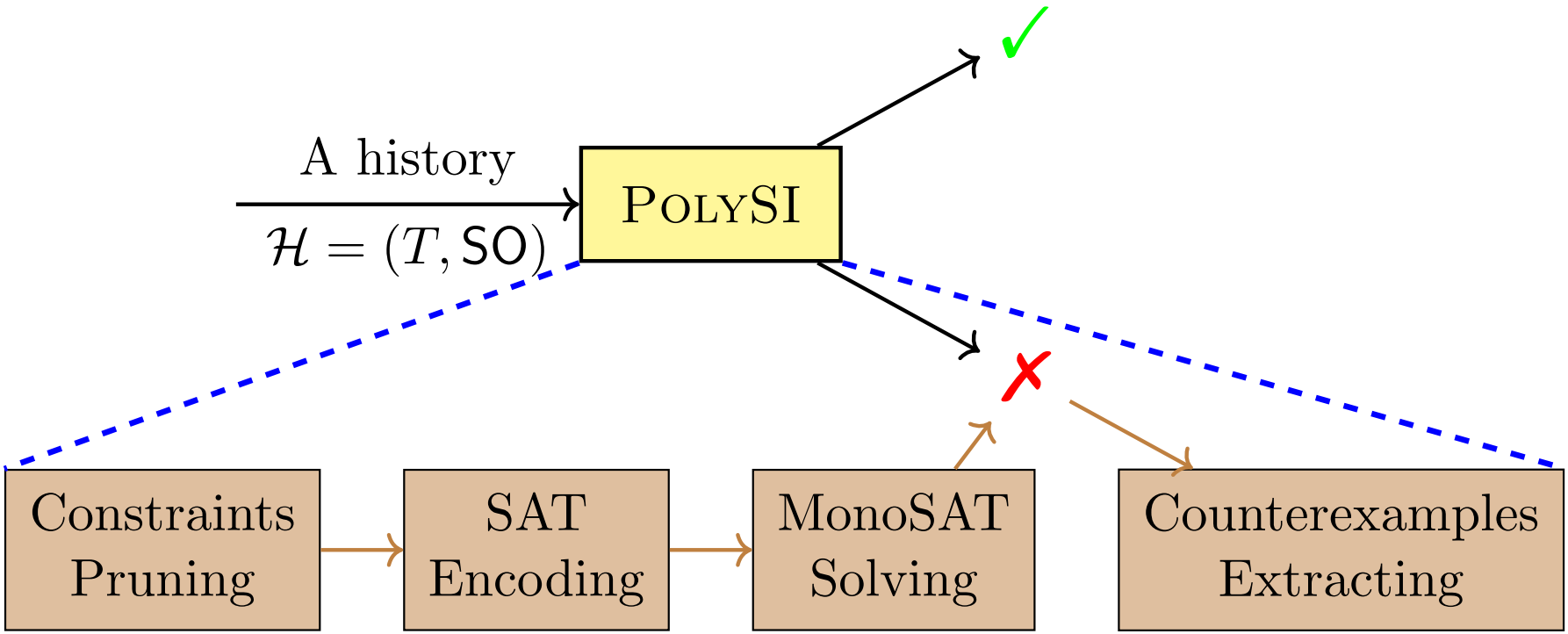
Efficient: utilizing MonoSAT solver optimized for graph problems

Contribution: the PolySI Checker



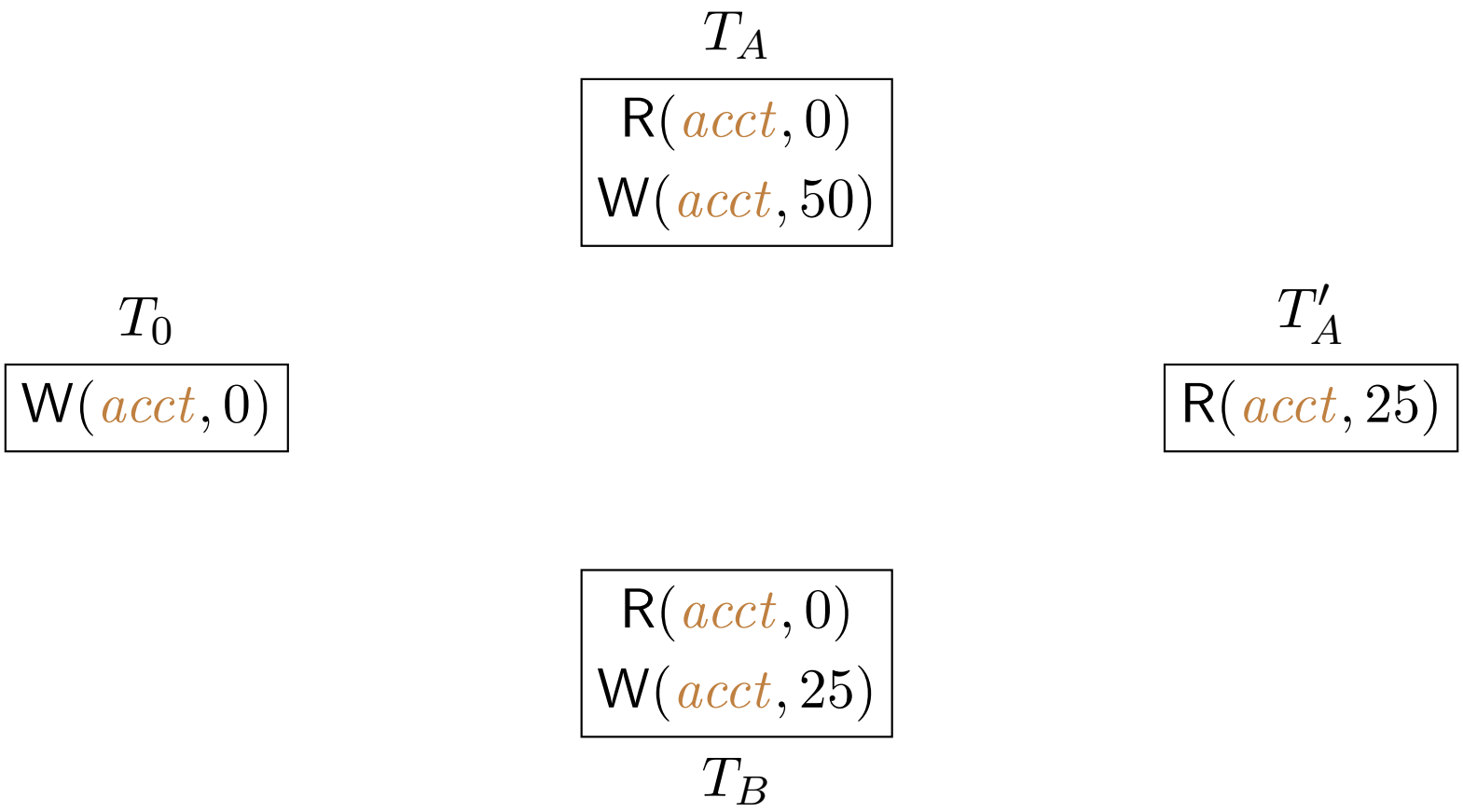
Efficient: domain-specific pruning before encoding

Contribution: the PolySI Checker



Informative: extract counterexamples from the unsatisifiable core

Dependency Graph-based Characterization of SI



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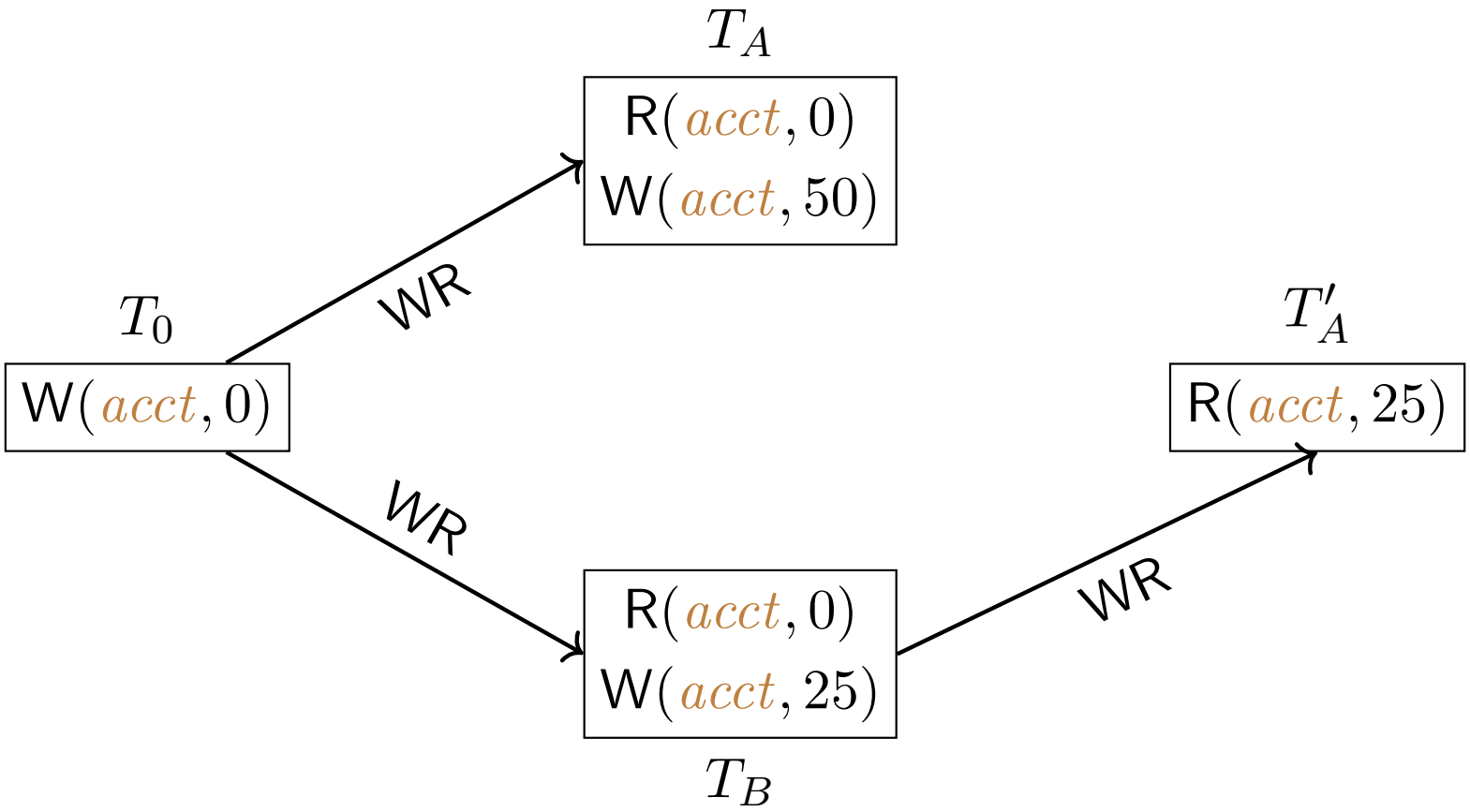

WR: "write-read" dependency capturing the "read-from" relation

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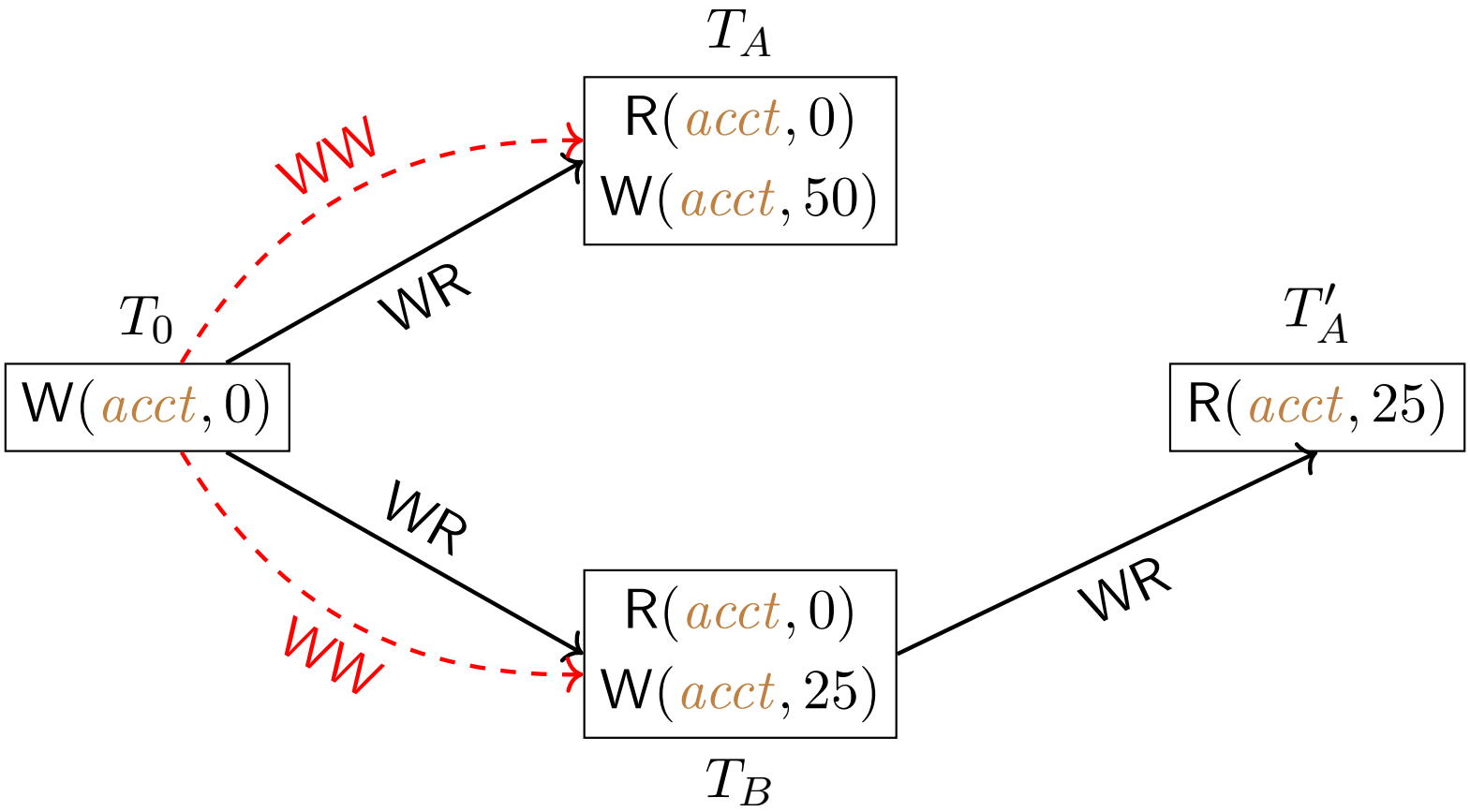
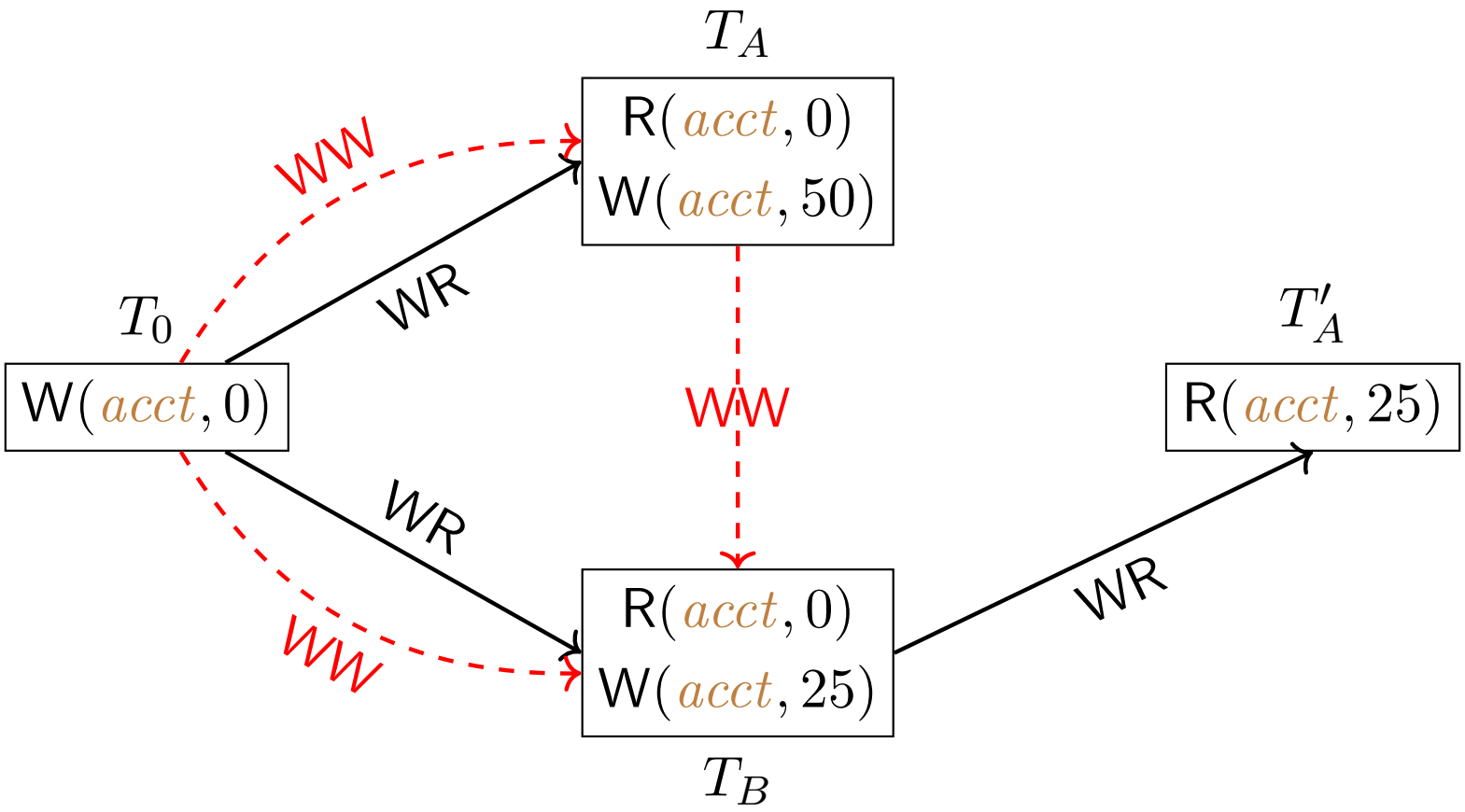


WW: "write-write" dependency capturing the version order

Dependency Graph-based Characterization of SI

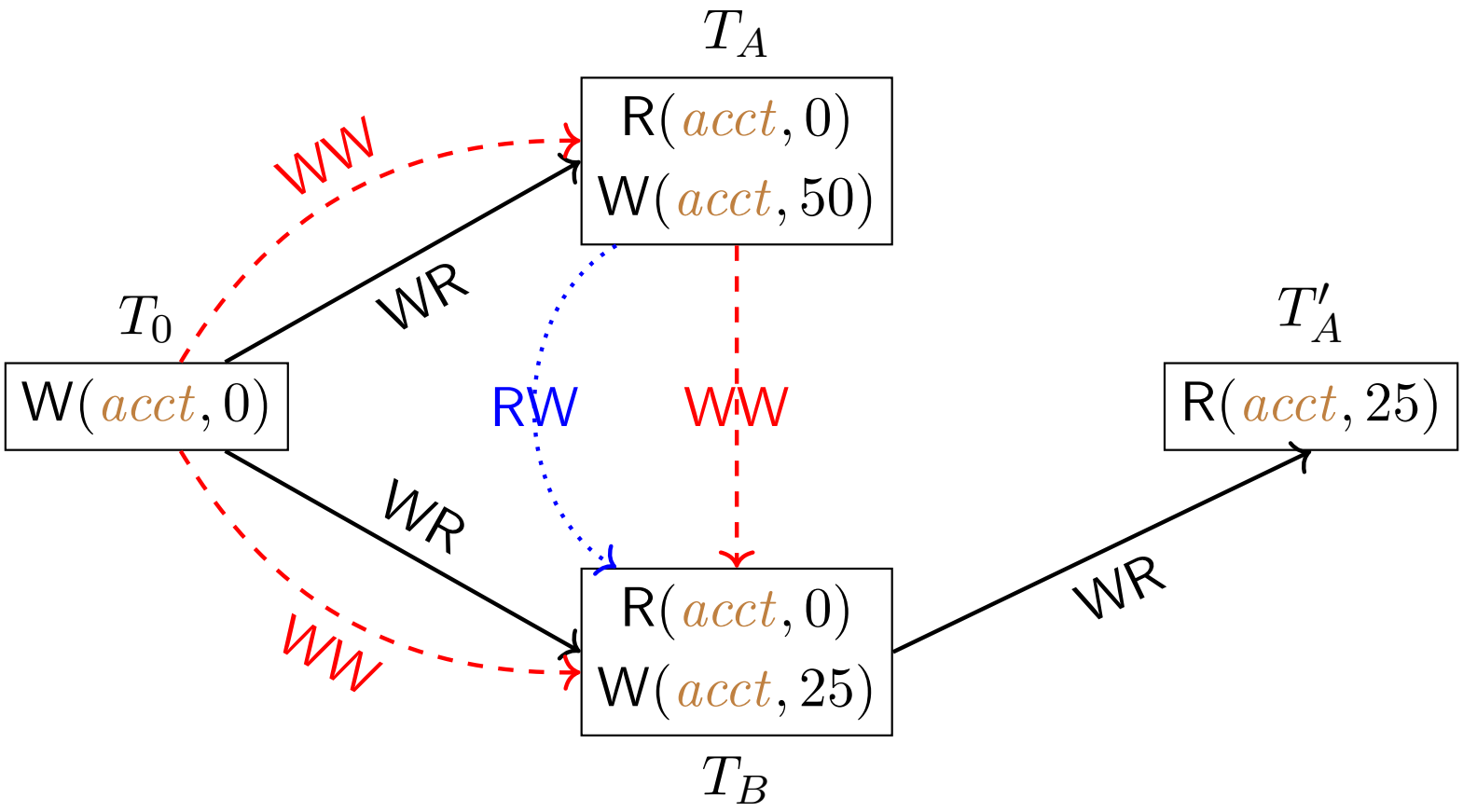
Suppose that $T_A \xrightarrow{\mathsf{WW}} T_B$



WW: "write-write" dependency capturing the version order

Dependency Graph-based Characterization of SI

$$T_0 \xrightarrow{\mathsf{WR}} T_A \wedge T_0 \xrightarrow{\mathsf{WW}} T_B \implies T_A \xrightarrow{\mathsf{RW}} T_B$$



RW: "read-write" dependency capturing the overwritten relation

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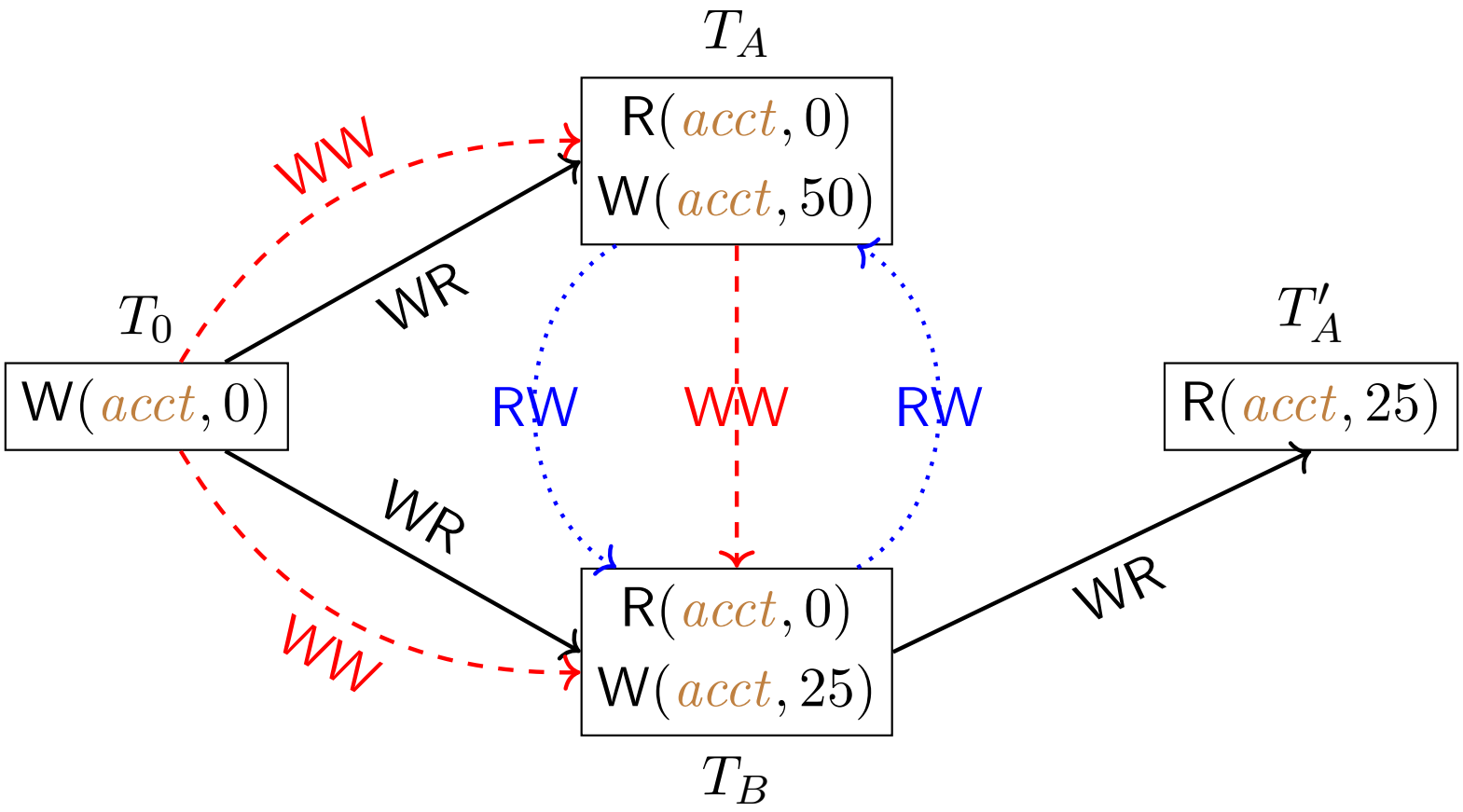

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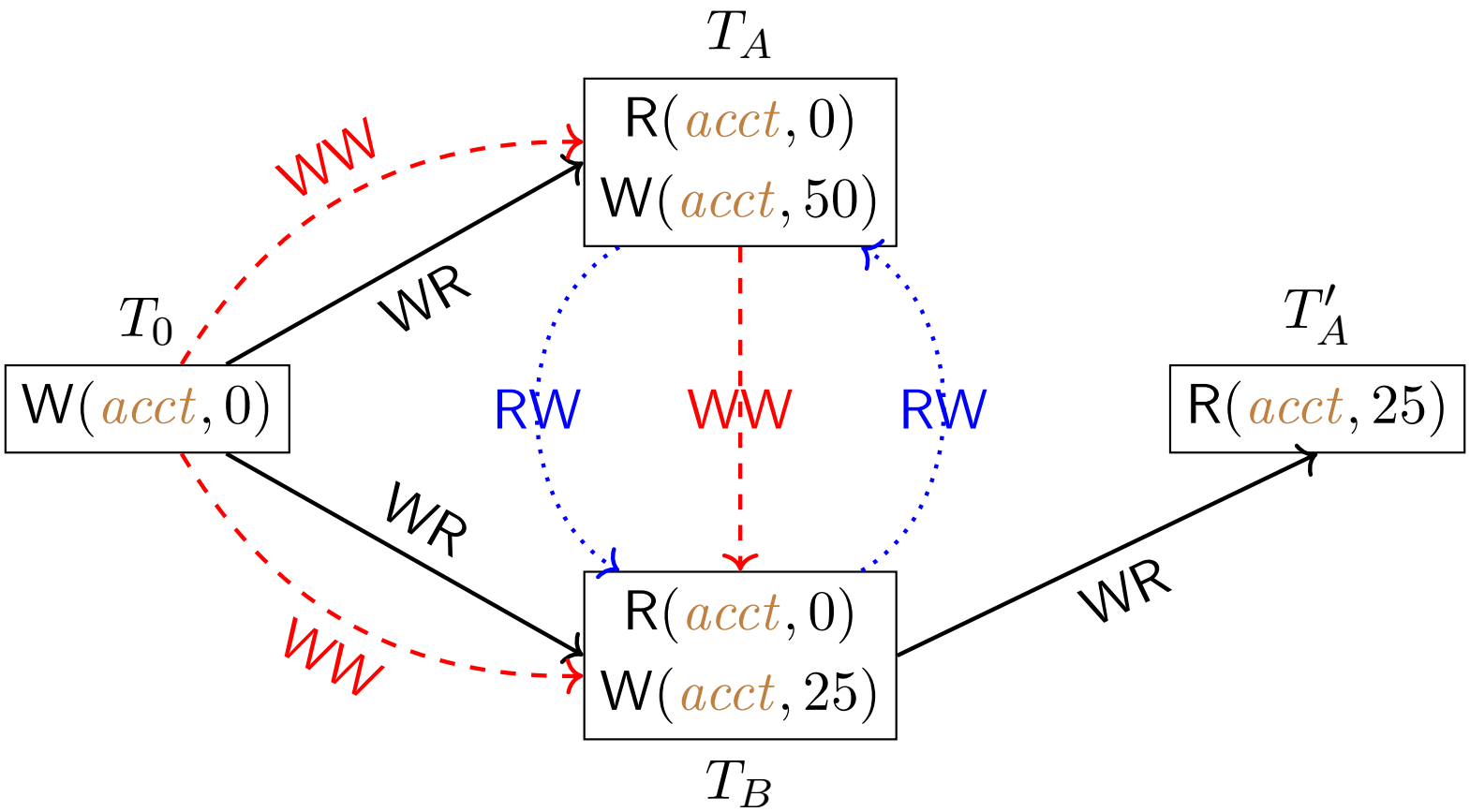

undesired cycle: $T_A \xrightarrow{\text{WW}} T_B \xrightarrow{\text{RW}} T_A$

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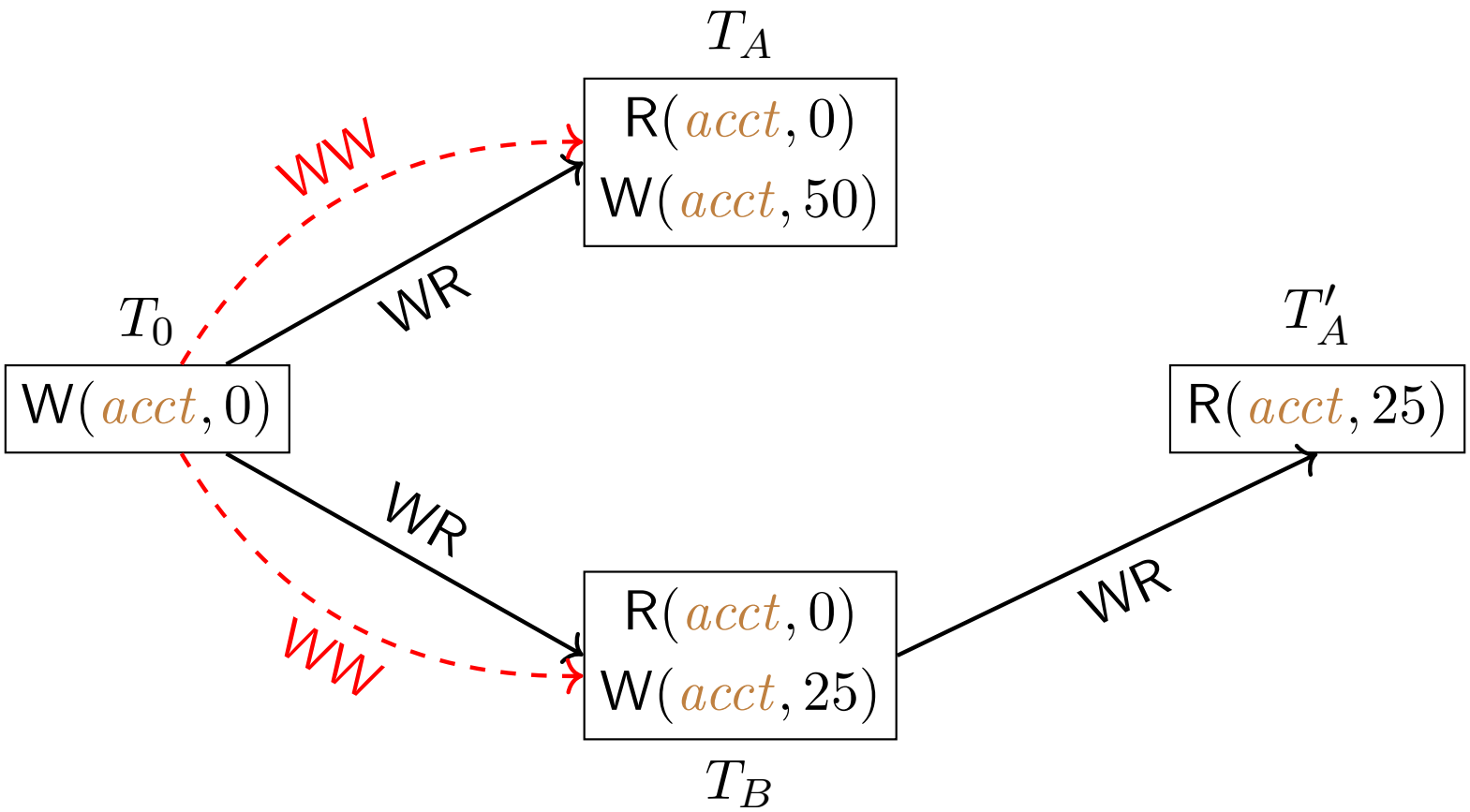

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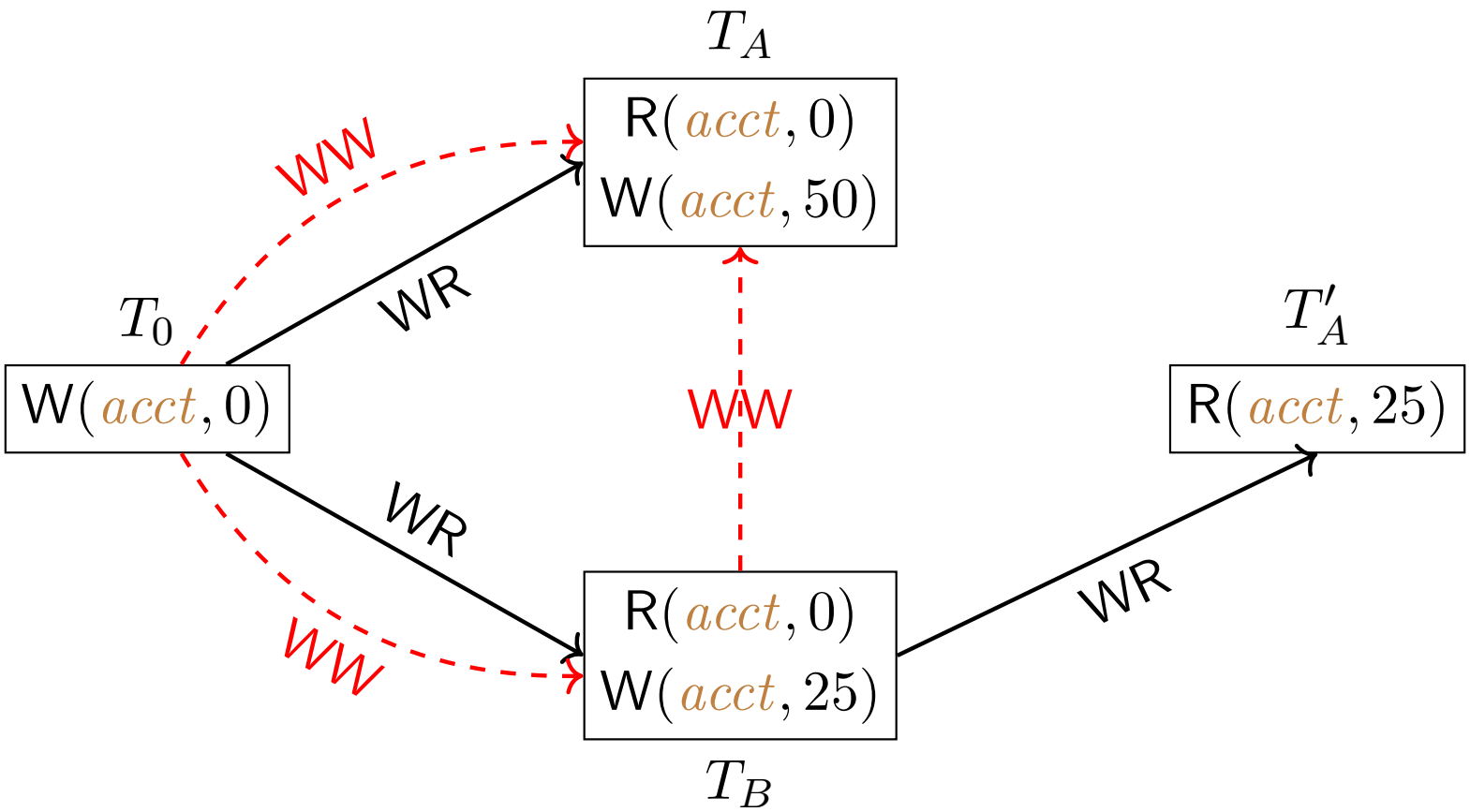
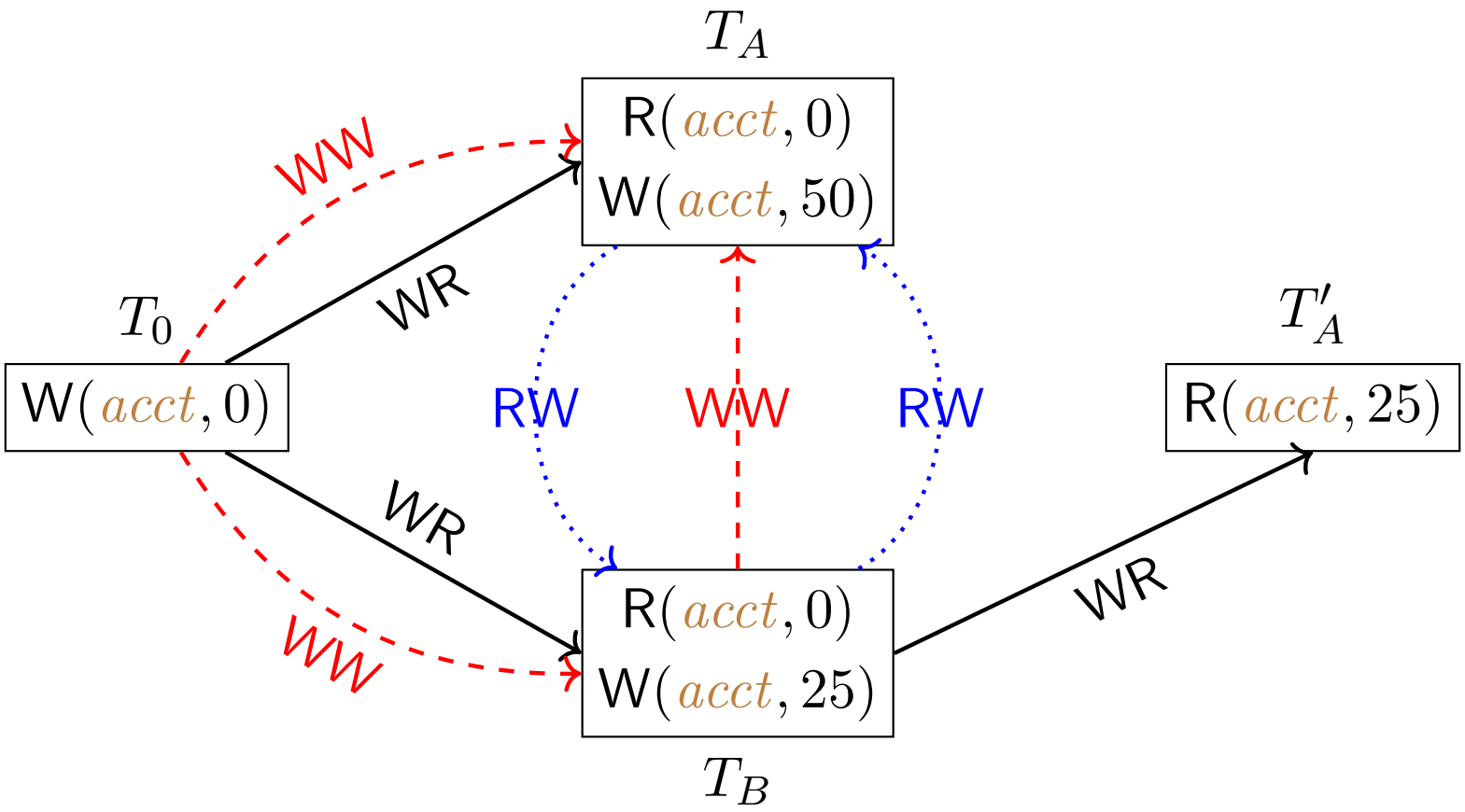


Dependency Graph-based Characterization of SI

Suppose that $T_B \xrightarrow{\text{WW}} T_A$



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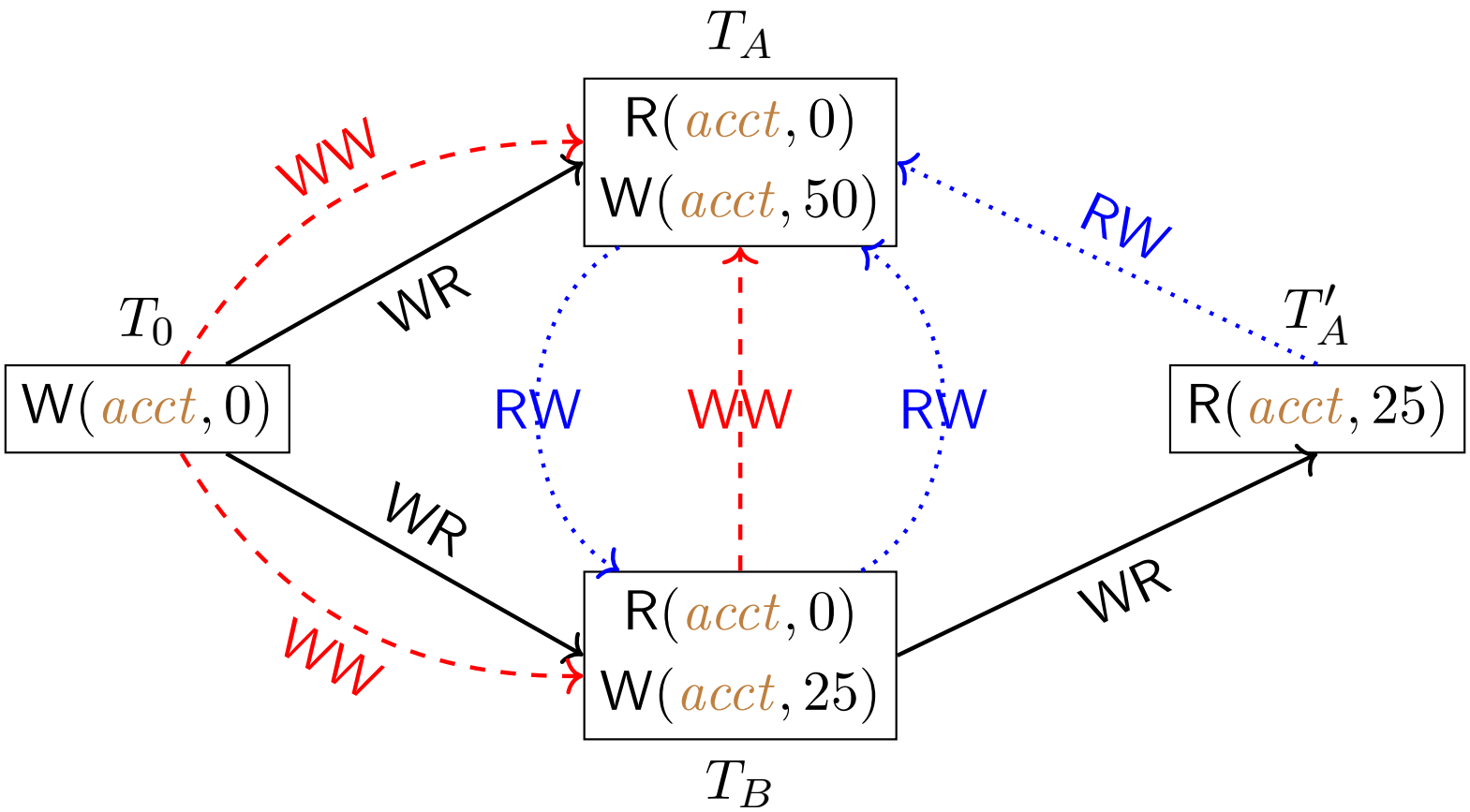

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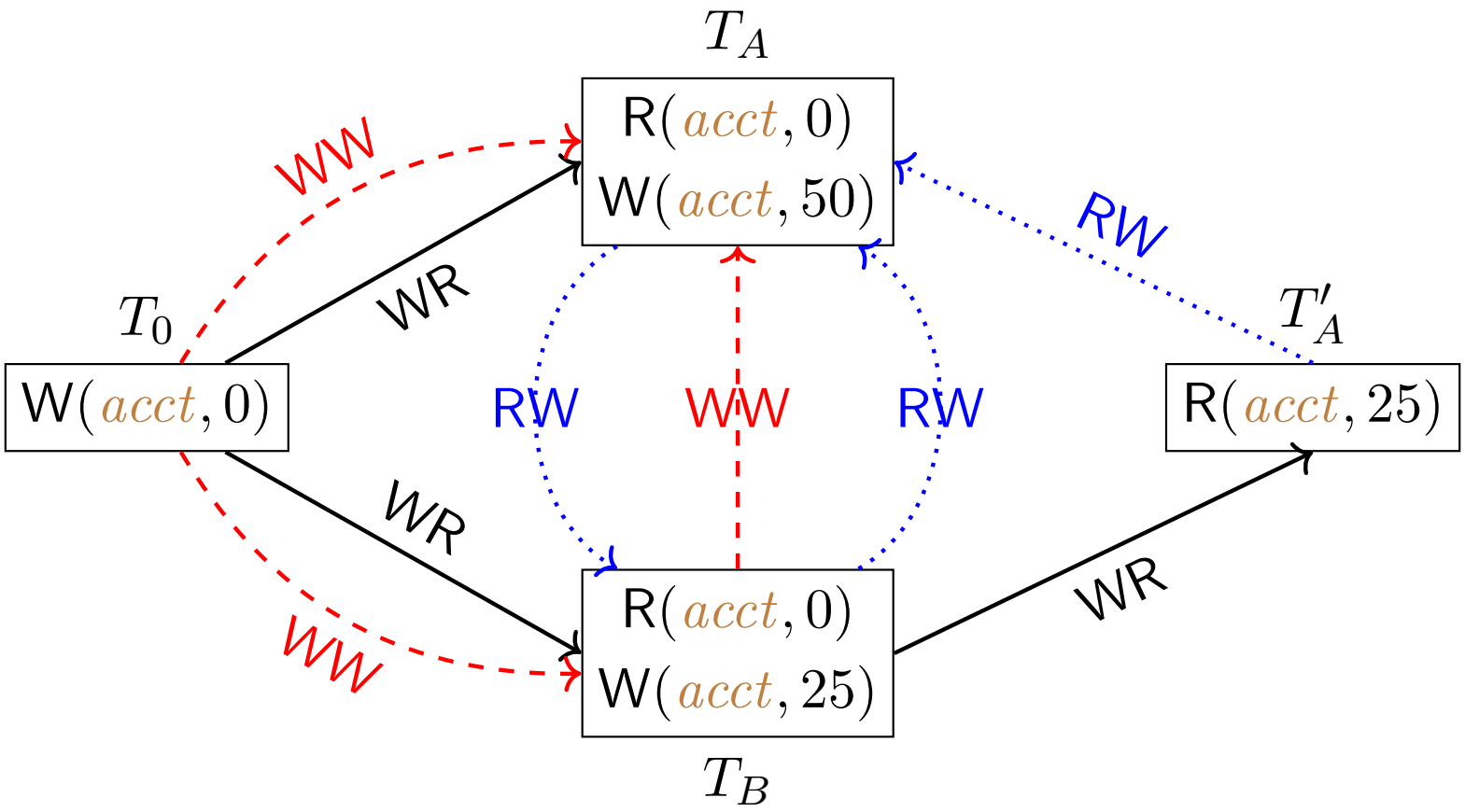
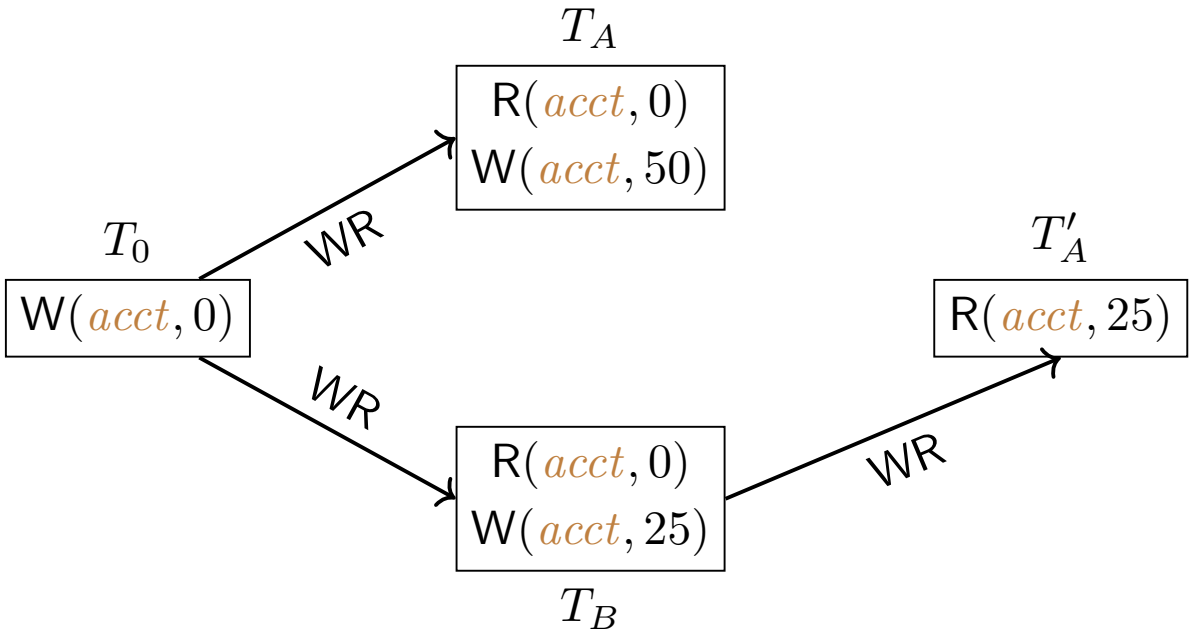


undesired cycle: $T_B \xrightarrow{\text{WW}} T_A \xrightarrow{\text{RW}} T_B$

Dependency Graph-based Characterization of SI

We have considered both bases $T_A \xrightarrow{\mathsf{WW}} T_B$ and $T_B \xrightarrow{\mathsf{WW}} T_A$.



Either case leads to an undesired cycle.

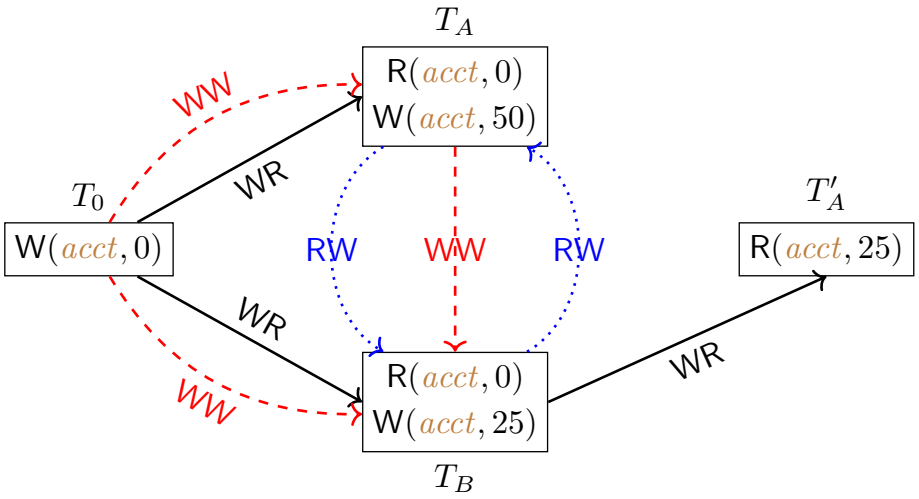
Therefore, it does not satisfy SI.

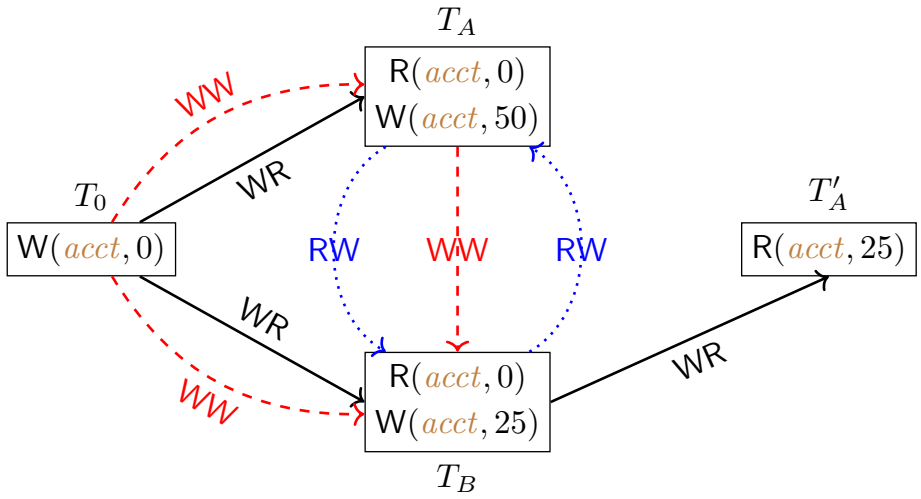
Dependency Graph-based Characterization of SI

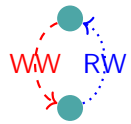
Theorem (Theorem 4.1 of [Cerone and Gotsman, 2018])

Informally, a history satisfies SI if only if there exists a dependency graph for it that contains only cycles (if any) with at least two adjacent RW *edges.*

Dependency Graph-based Characterization of SI





Every possible dependency graph contains an undesired 

cycle.

Dependency Graph-based Characterization of SI

Theorem (Theorem 4.1 of [Cerone and Gotsman, 2018])

For a history $\mathcal{H} = (T, \mathsf{SO})$,

$$\mathcal{H} \models \mathrm{SI} \iff \mathcal{H} \models \textsc{Int} \wedge$$
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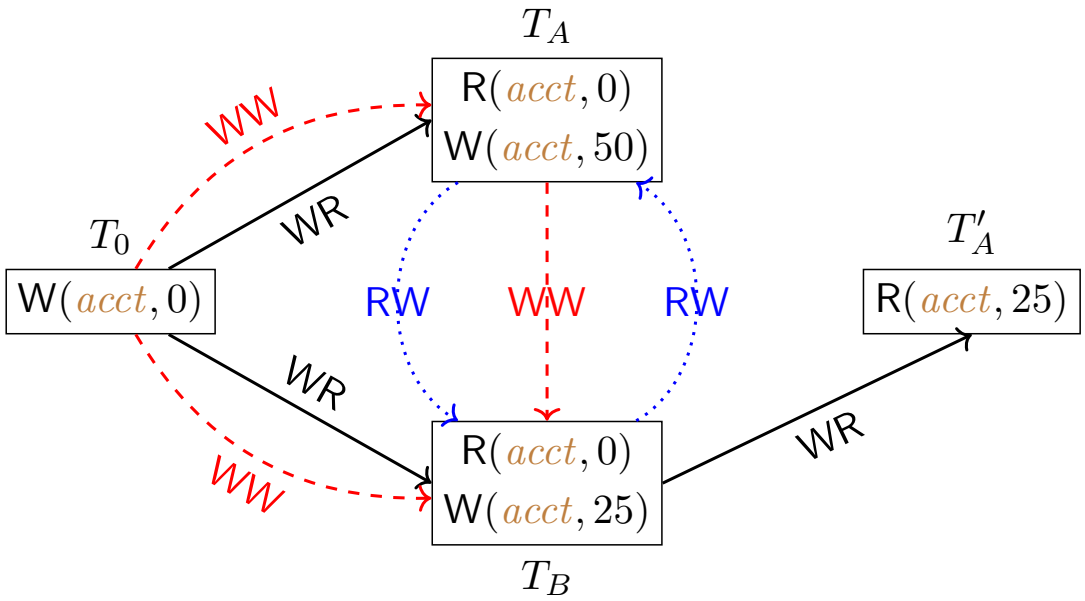

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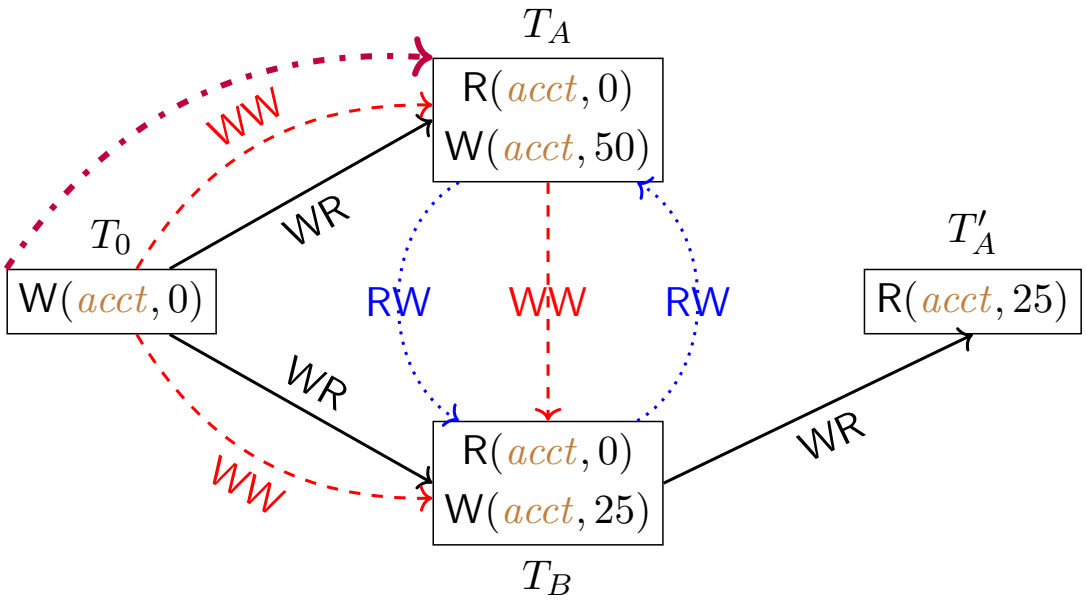

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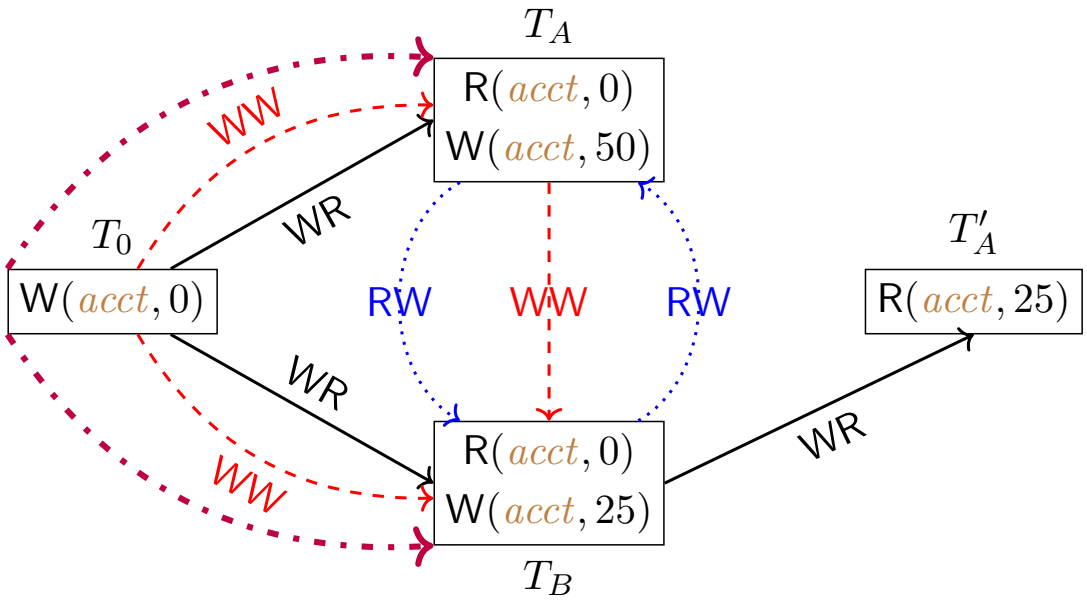

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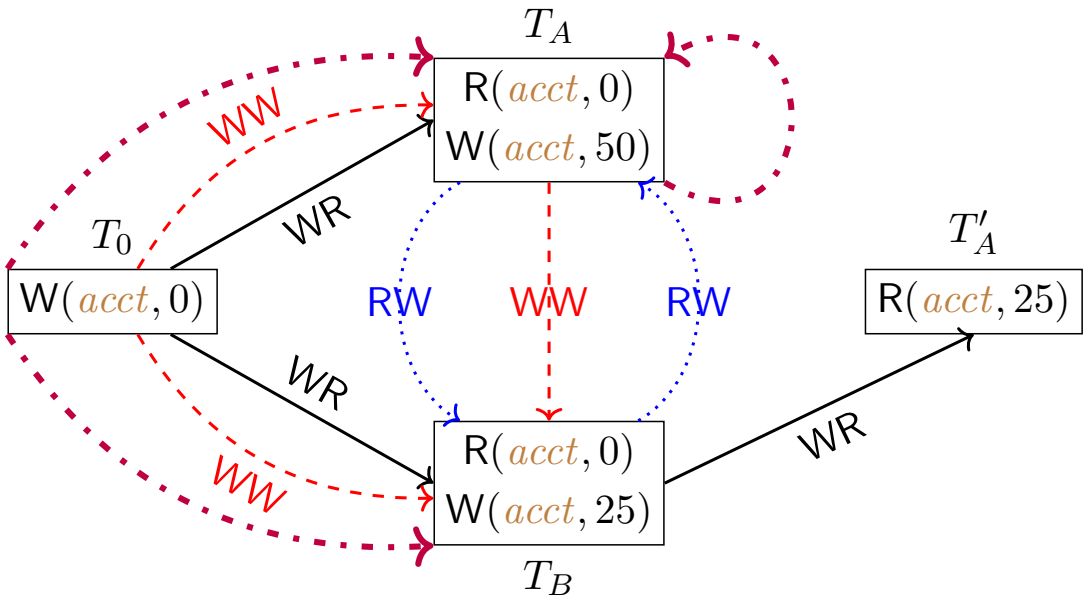

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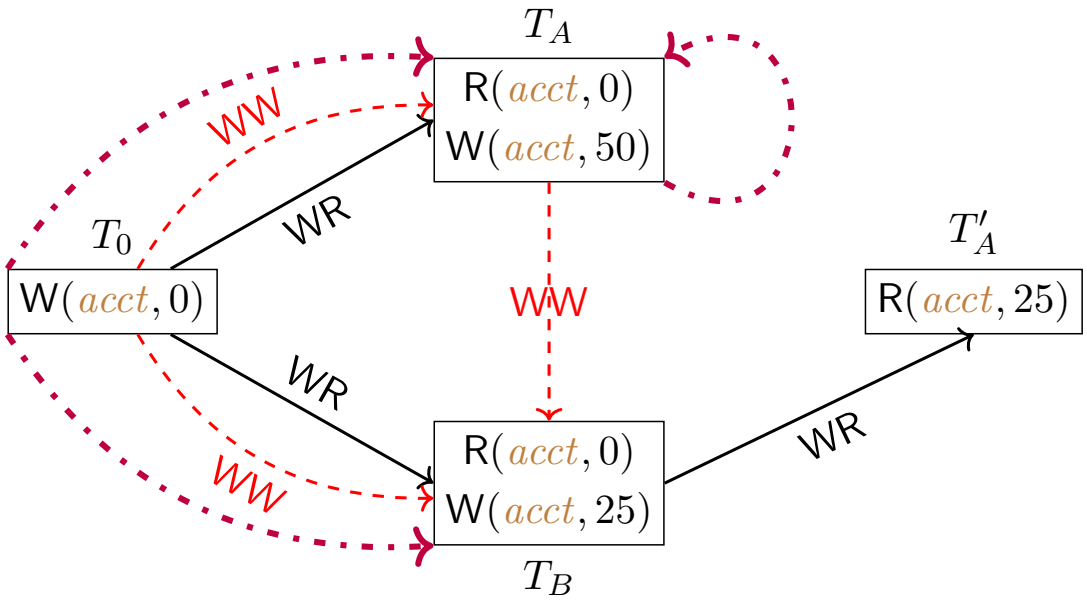
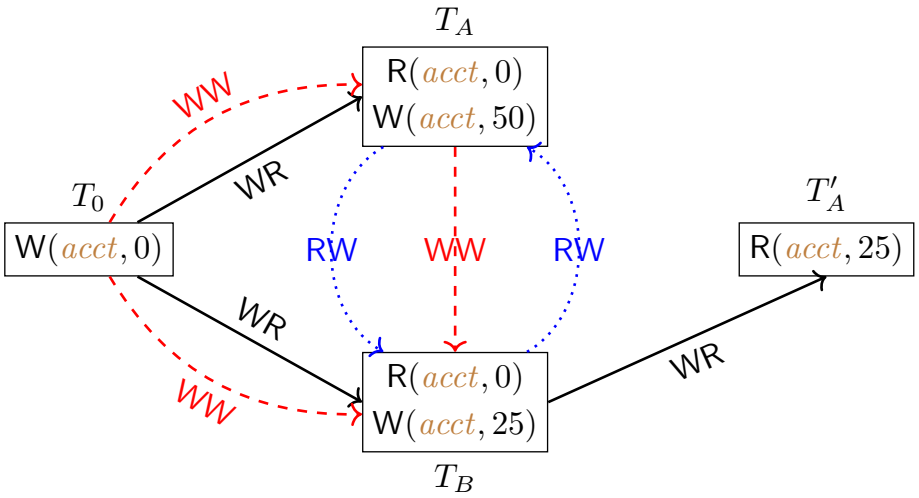
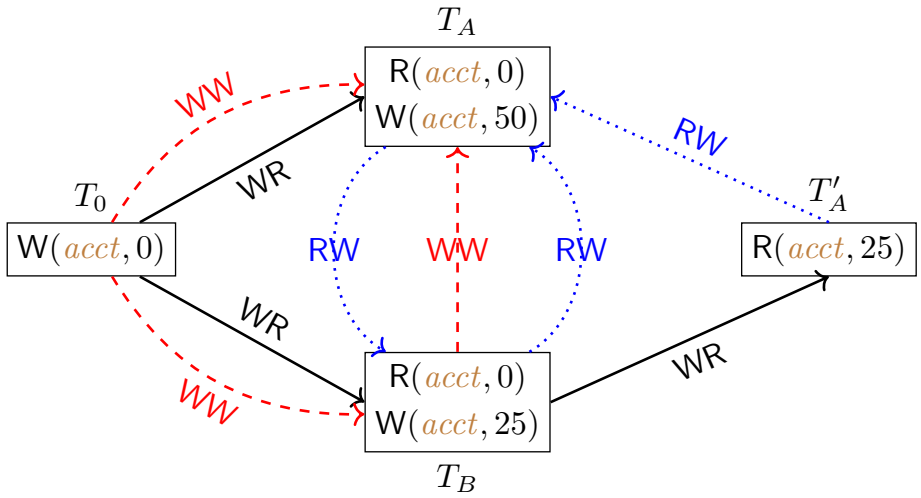


Dependency Graph-based Characterization of SI

$\mathcal{Q}$: How to capture and resolve all possible WW dependencies?





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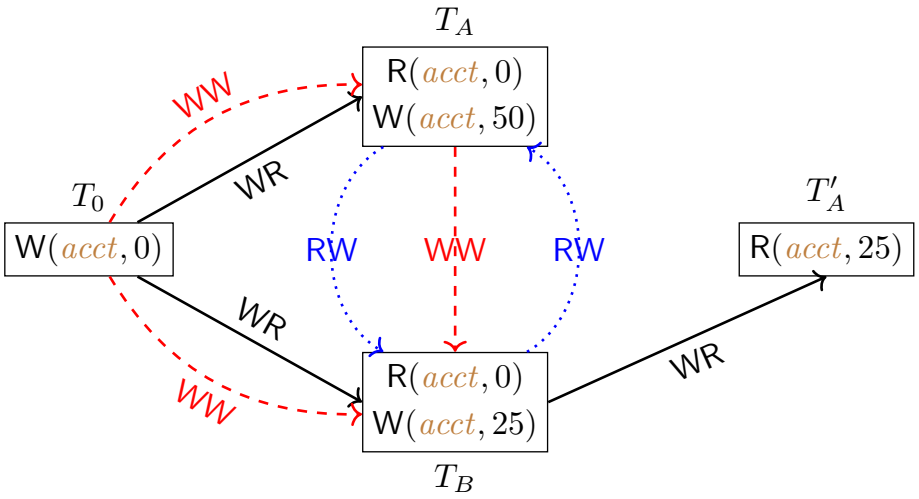
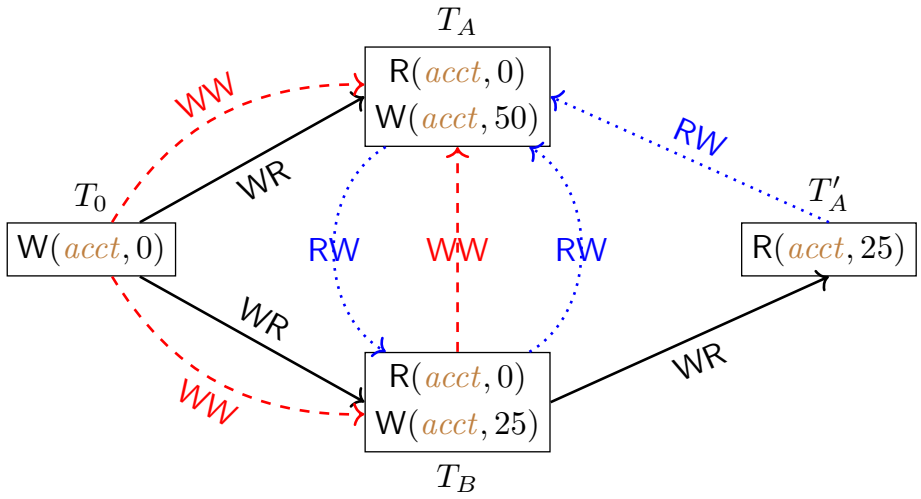
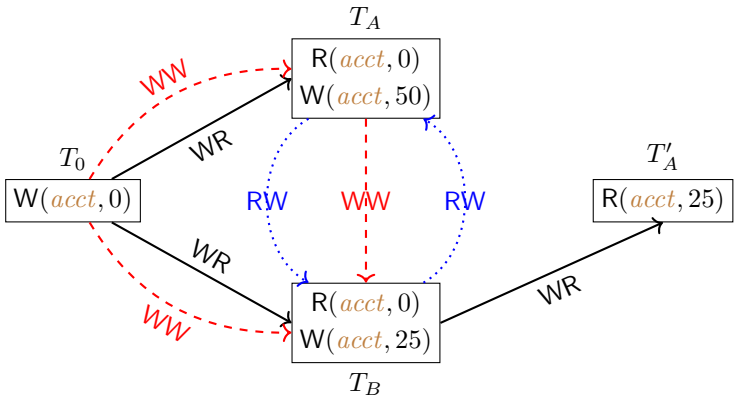


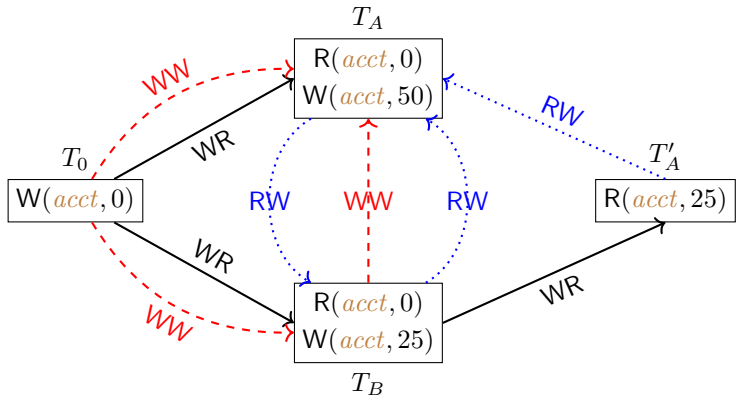


$\mathcal{A}$: encode them into SAT formulas based on (generalized) polygraphs and solve them using SAT solvers.

Polygraphs: A Family of Dependency Graphs

Consider the two cases of WW dependencies between T_A and T_B.





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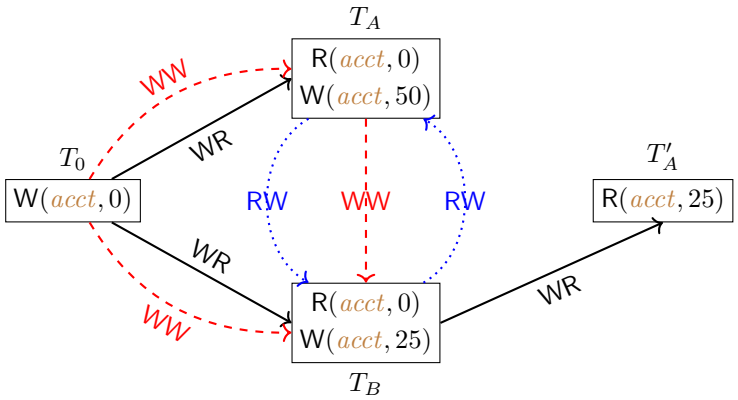

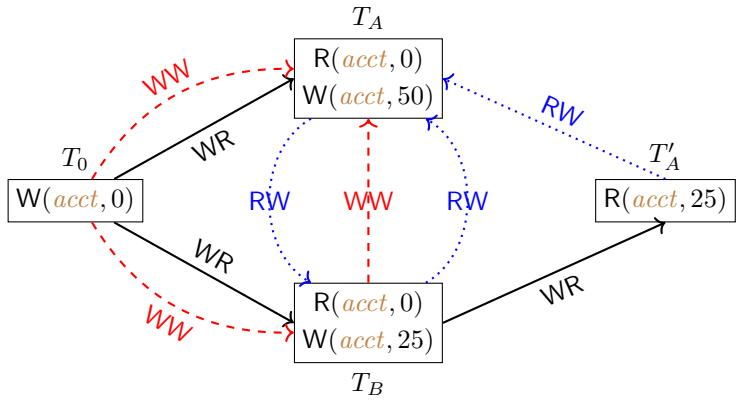

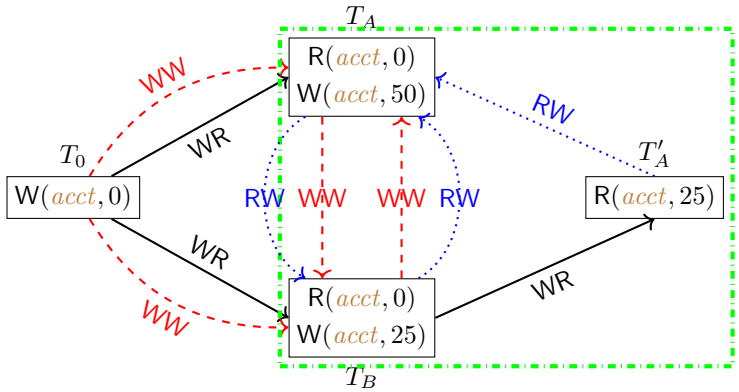

generalized polygraph:

Polygraphs: A Family of Dependency Graphs

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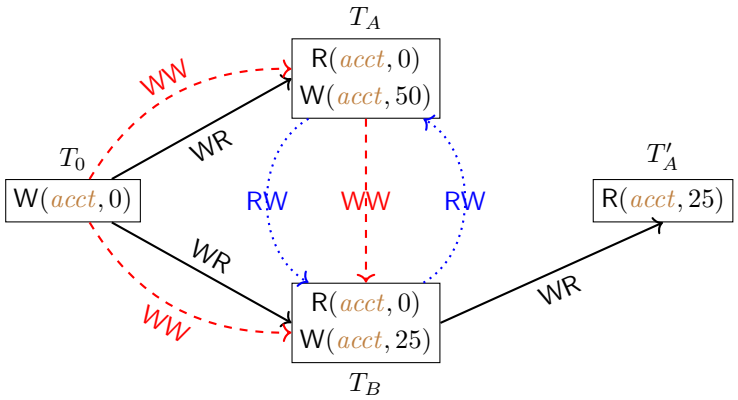
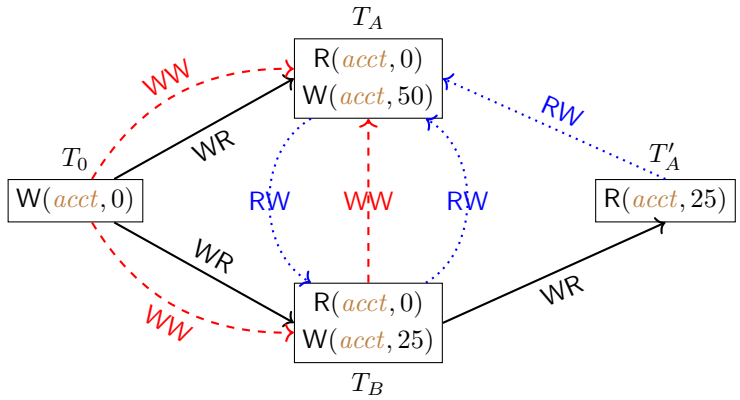
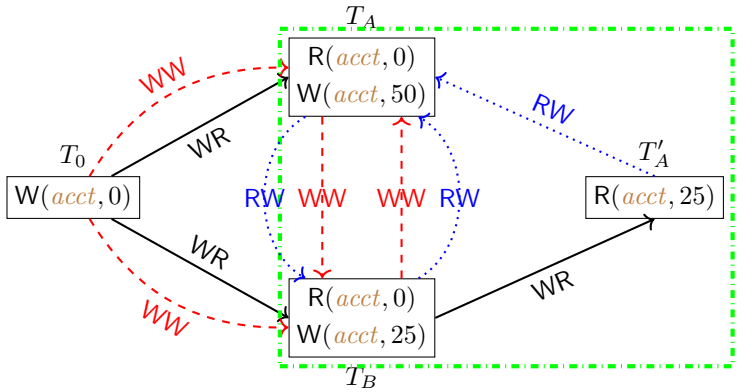


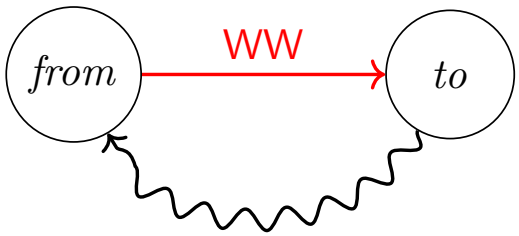


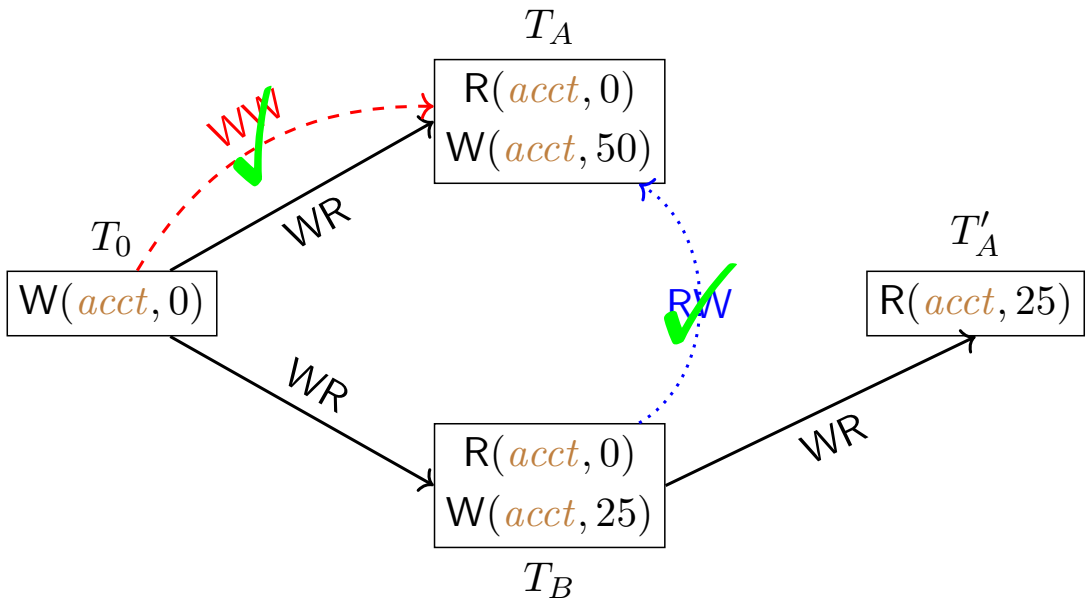


generalized polygraph:

$$\langle either \triangleq \{T_A \xrightarrow{\text{WW}} T_B\}, or \triangleq \{T_B \xrightarrow{\text{WW}} T_A, T'_A \xrightarrow{\text{RW}} T_A\}\rangle$$

PolySI: Pruning before Encoding (the WW case)





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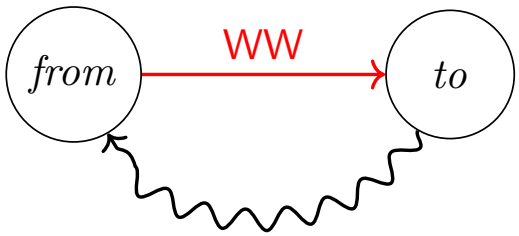
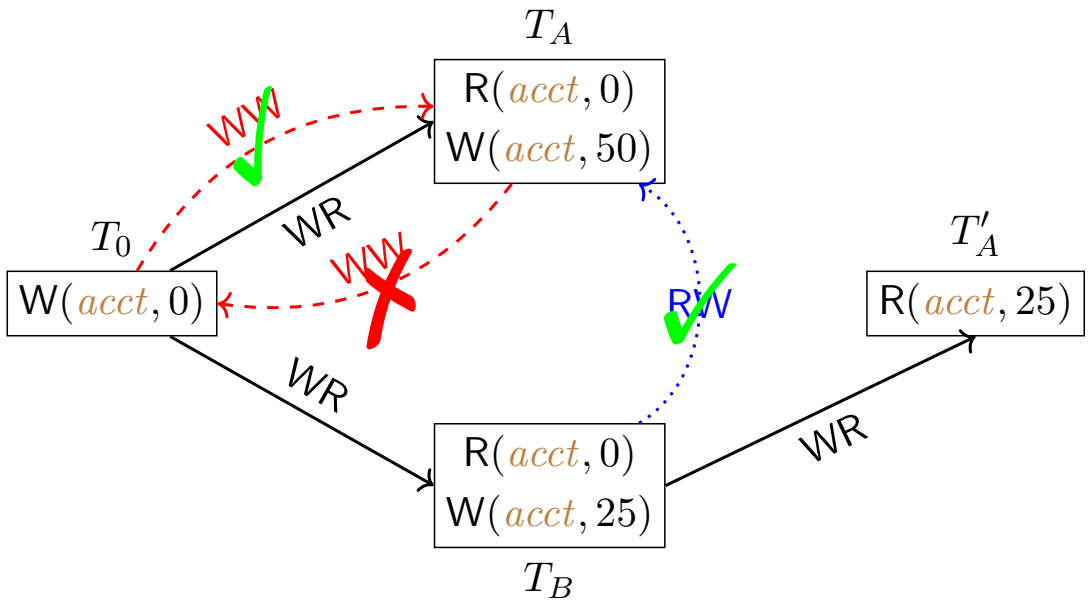
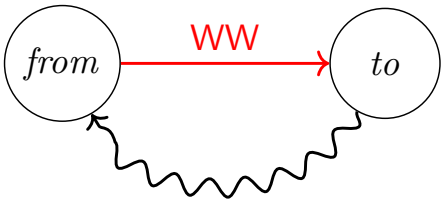
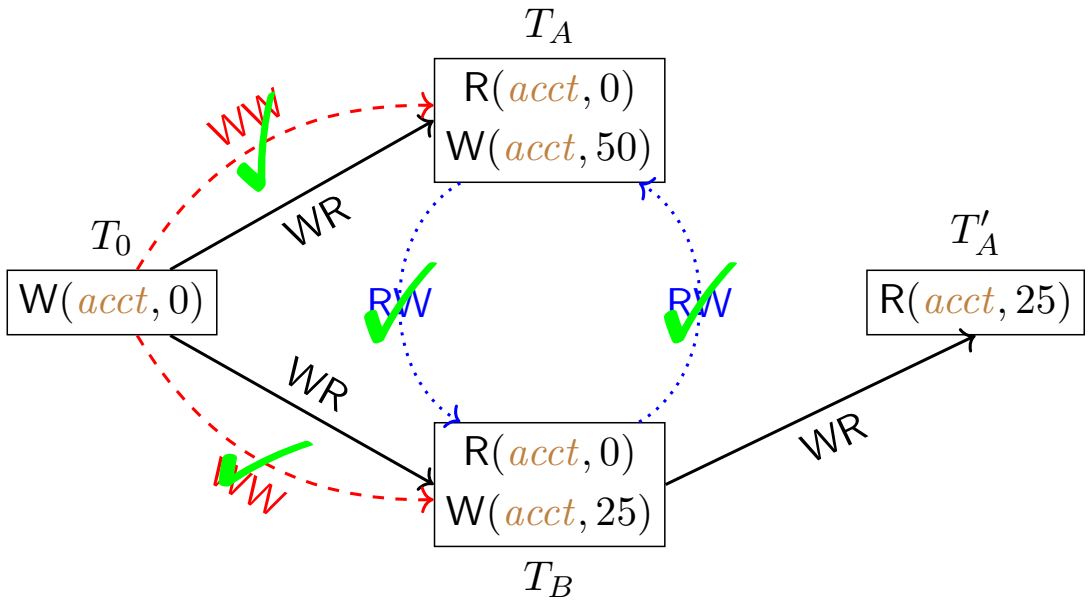




$T_A \xrightarrow{\text{WW}} T_0$ can be pruned due to the $T_A \xrightarrow{\text{WW}} T_0 \xrightarrow{\text{WR}} T_A$ cycle.

PolySI: Pruning before Encoding (the WW case)





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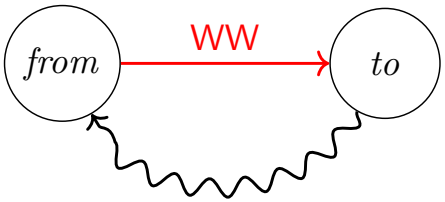

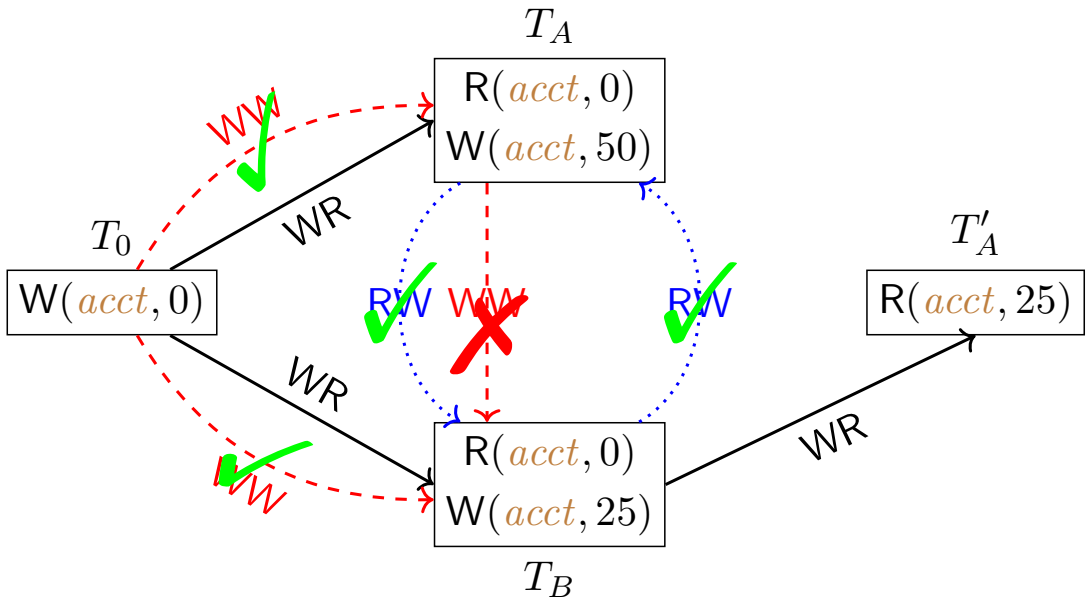

$T_A \xrightarrow{\text{WW}} T_B$ is pruned due to the $T_A \xrightarrow{\text{WW}} T_B \xrightarrow{\text{RW}} T_A$ cycle.

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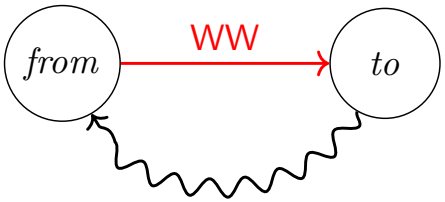

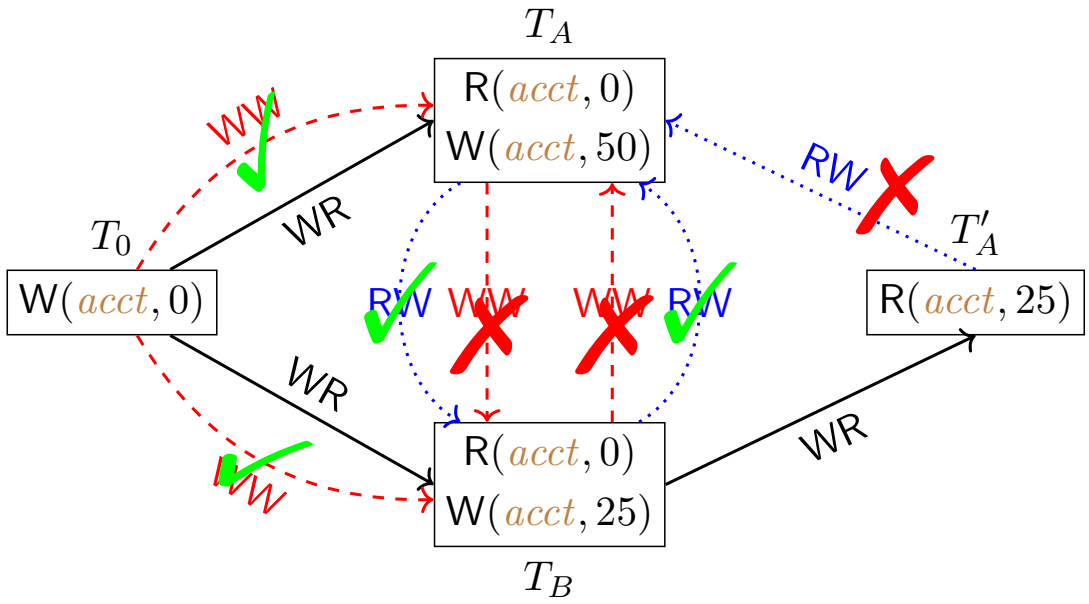

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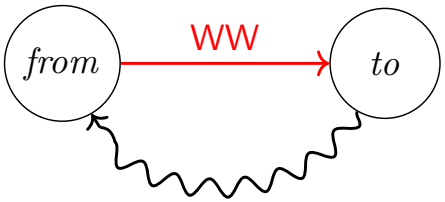

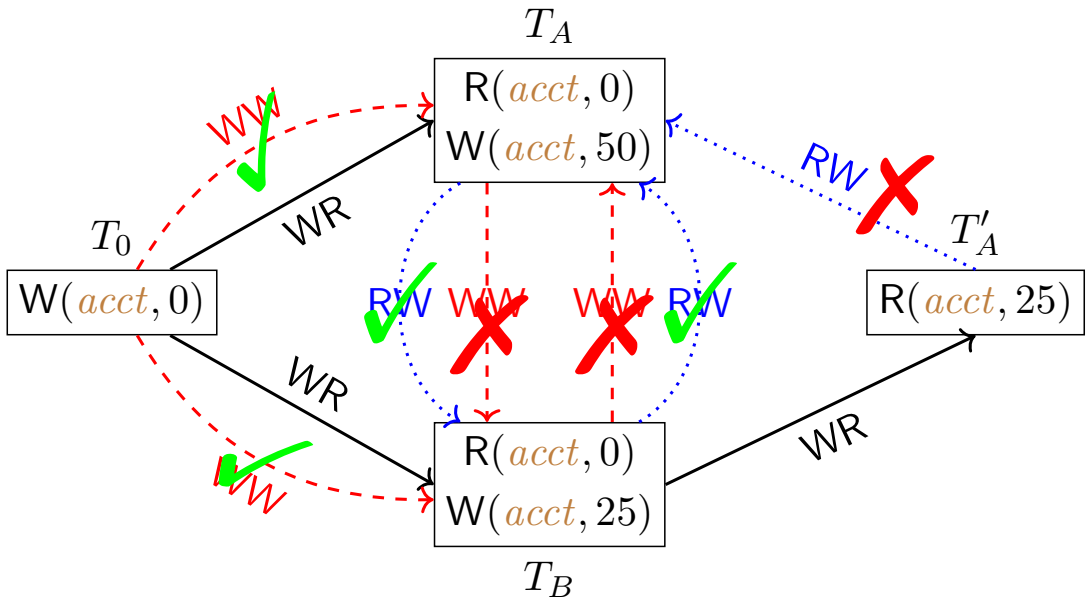

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Therefore, we are sure that the history does *not* satisfy SI.

PolySI: Pruning before Encoding (the RW case)

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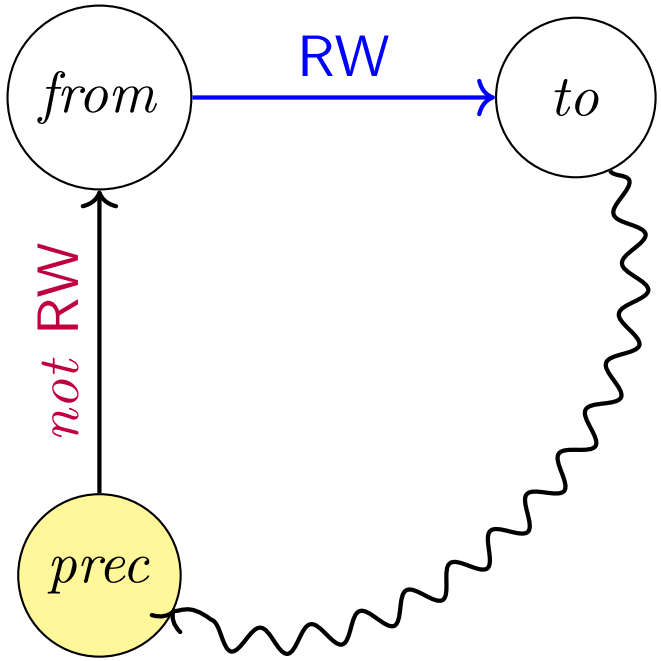

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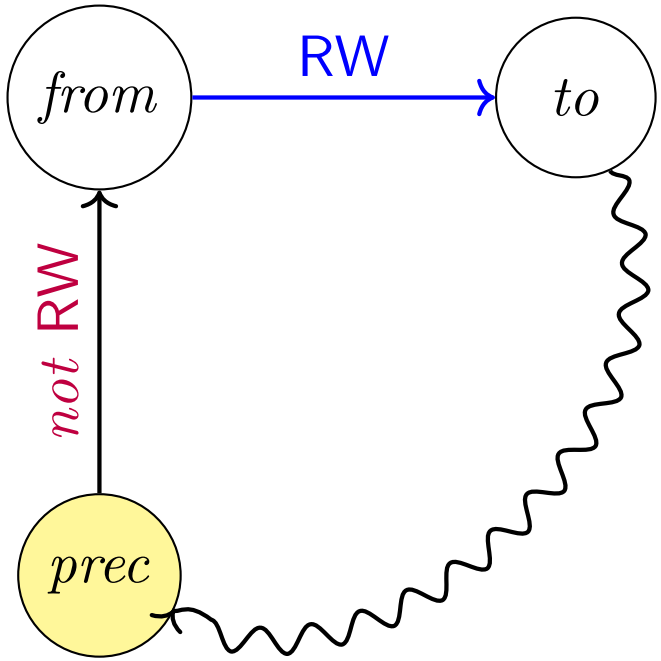

Theorem (Theorem 4.1 of [Cerone and Gotsman, 2018])

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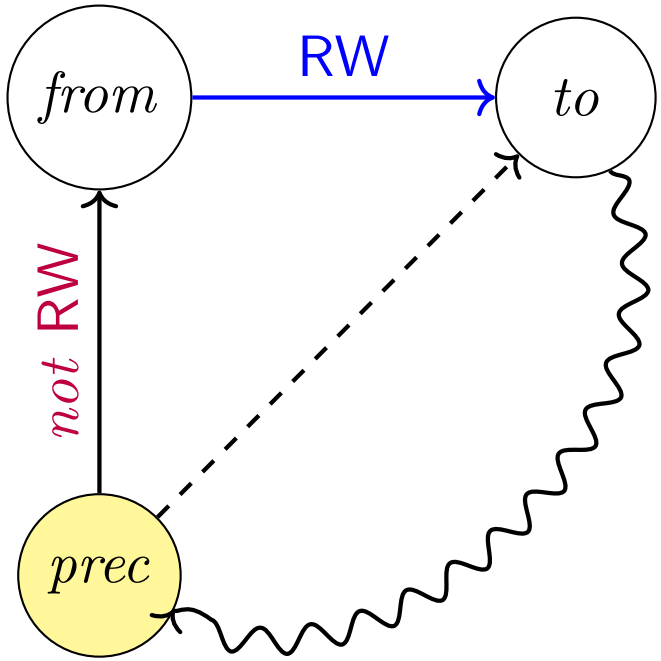

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PolySI: An Illustrating Example of "Long Fork"

T_0 $\boxed{\mathsf{W}(x, 0)\ \mathsf{W}(y, 0)}$

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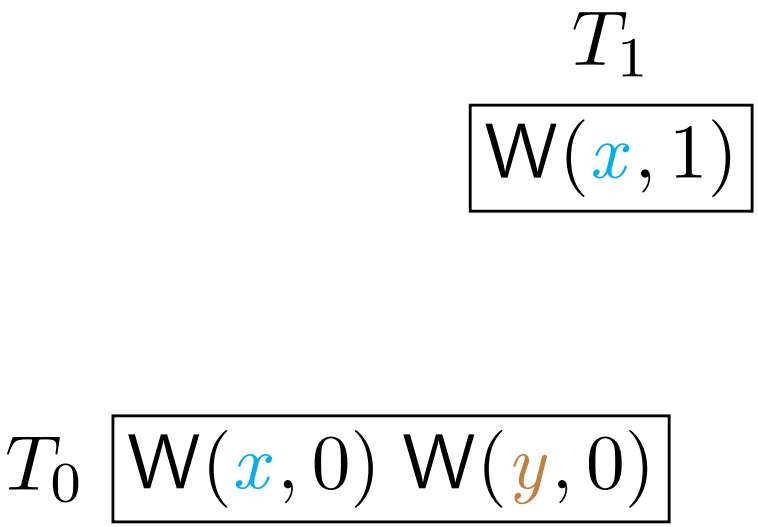

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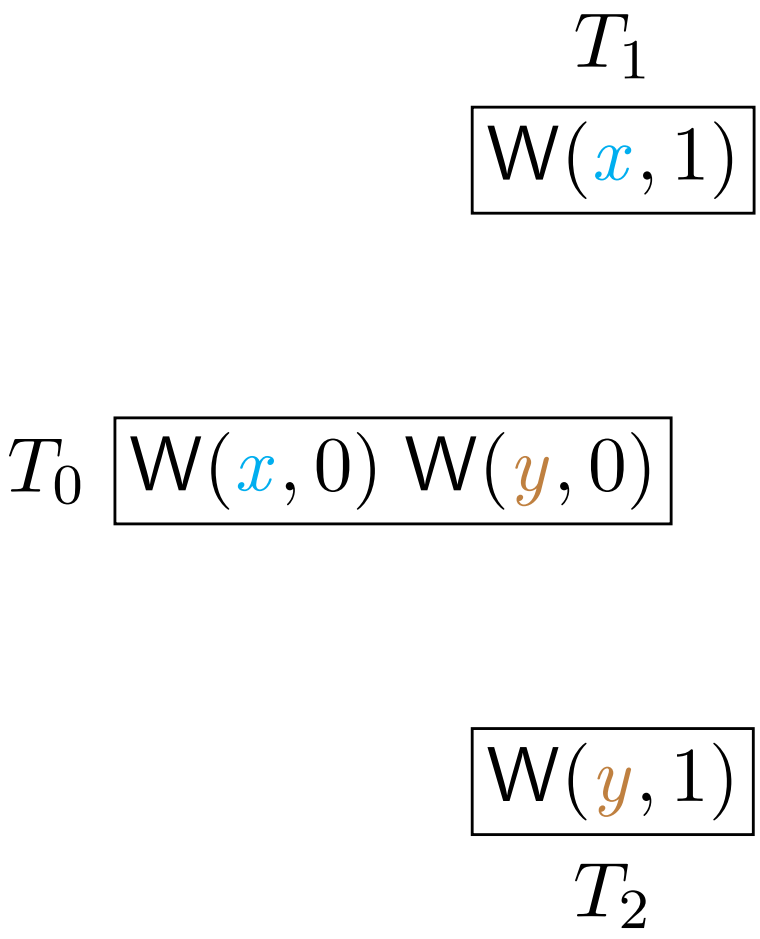

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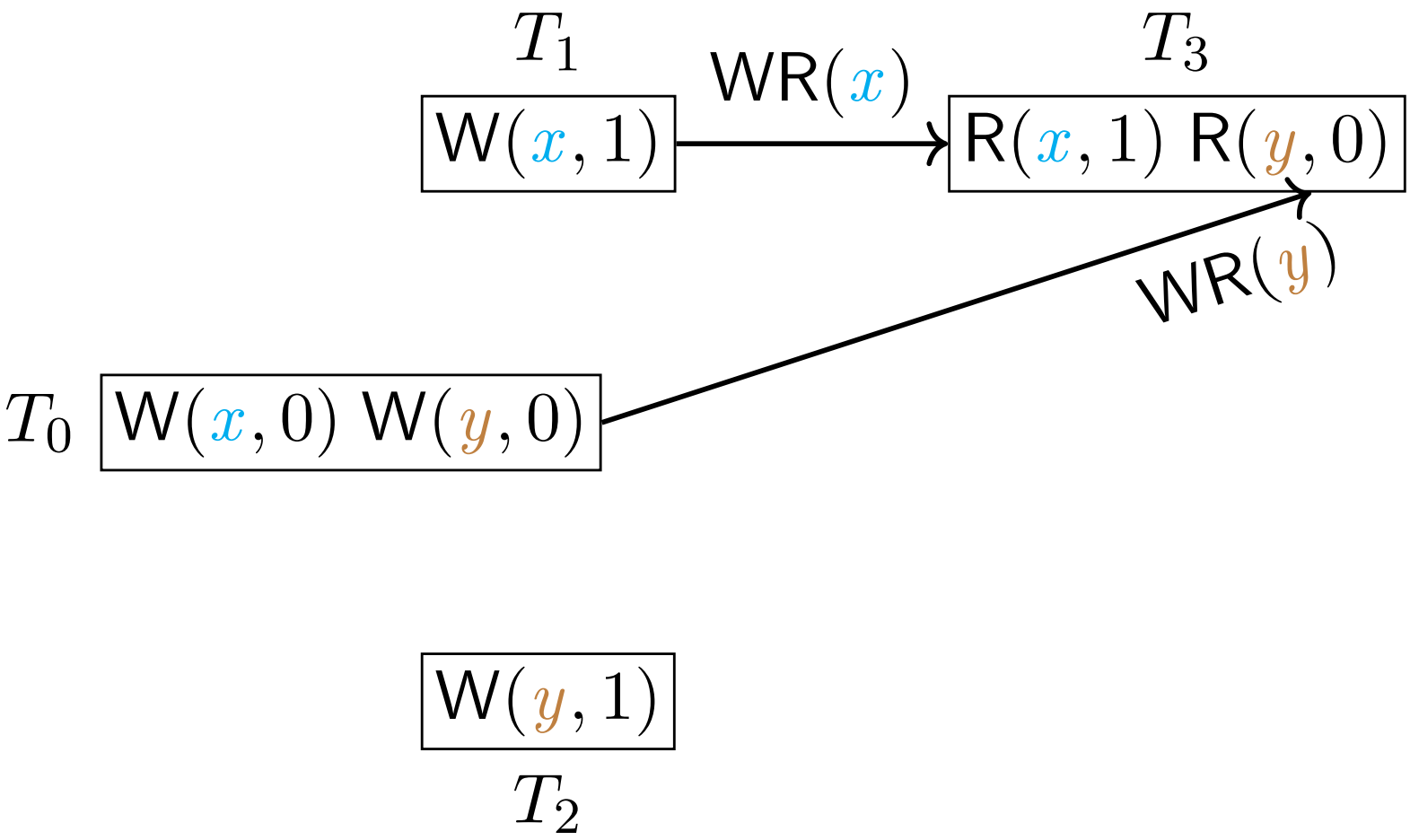

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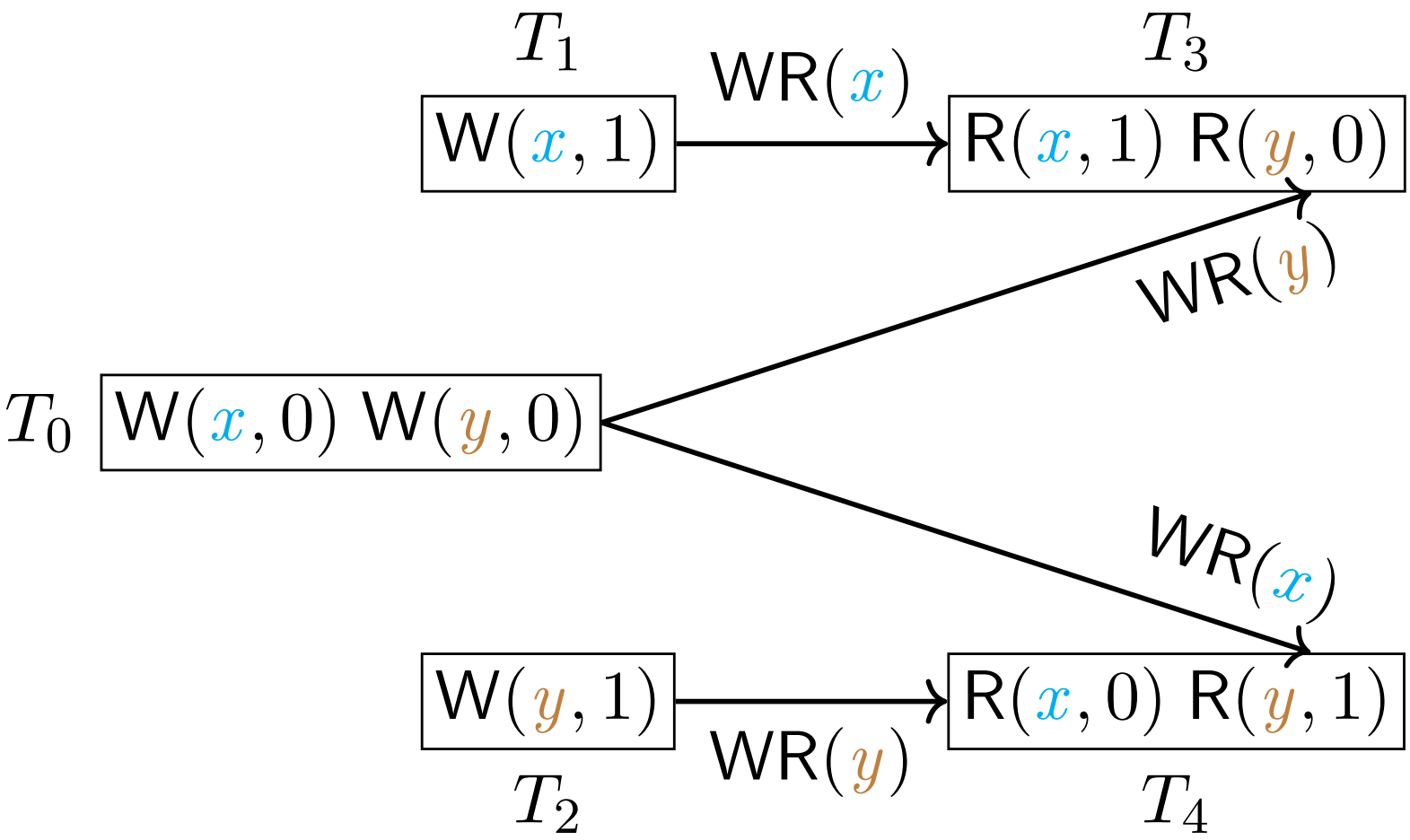

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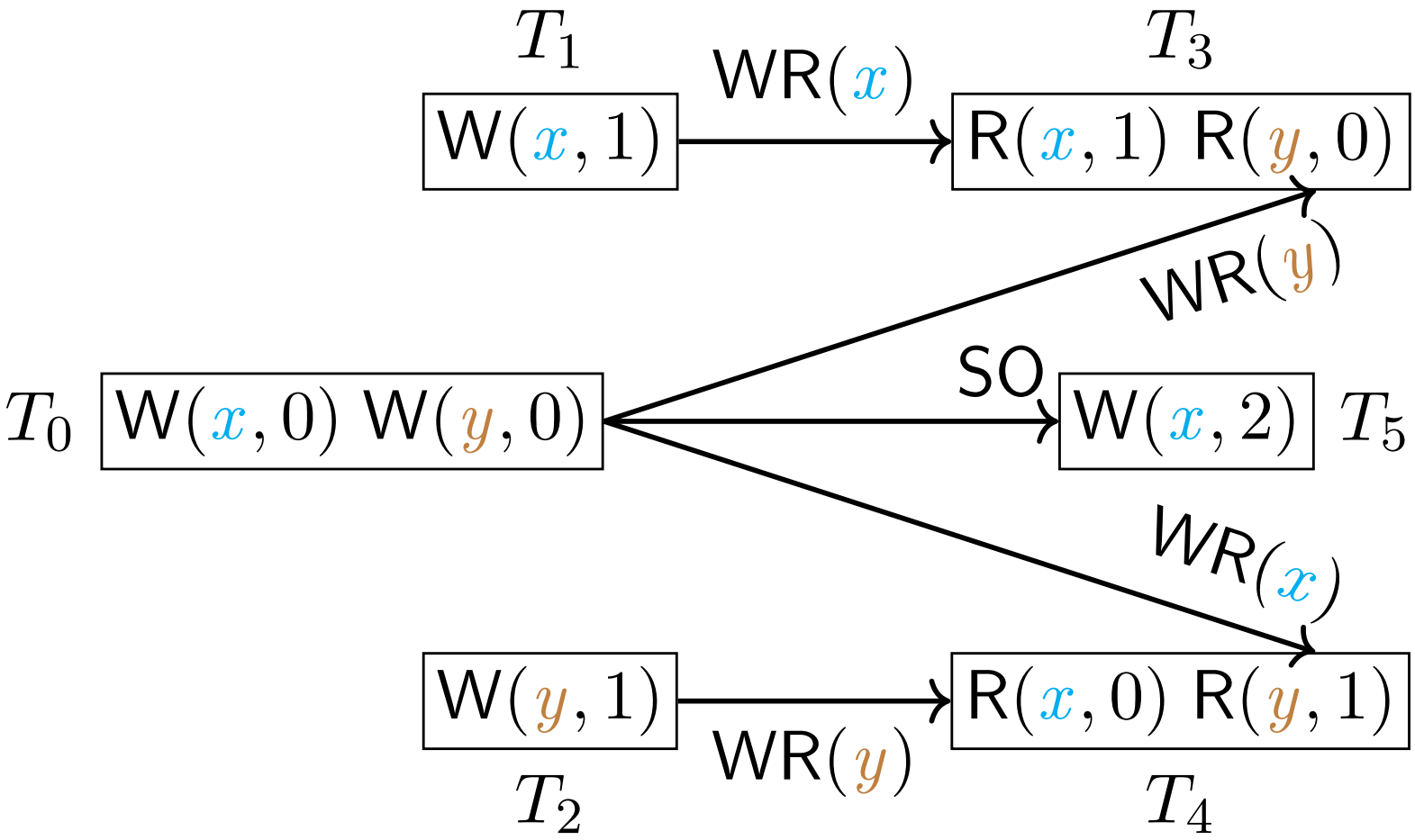
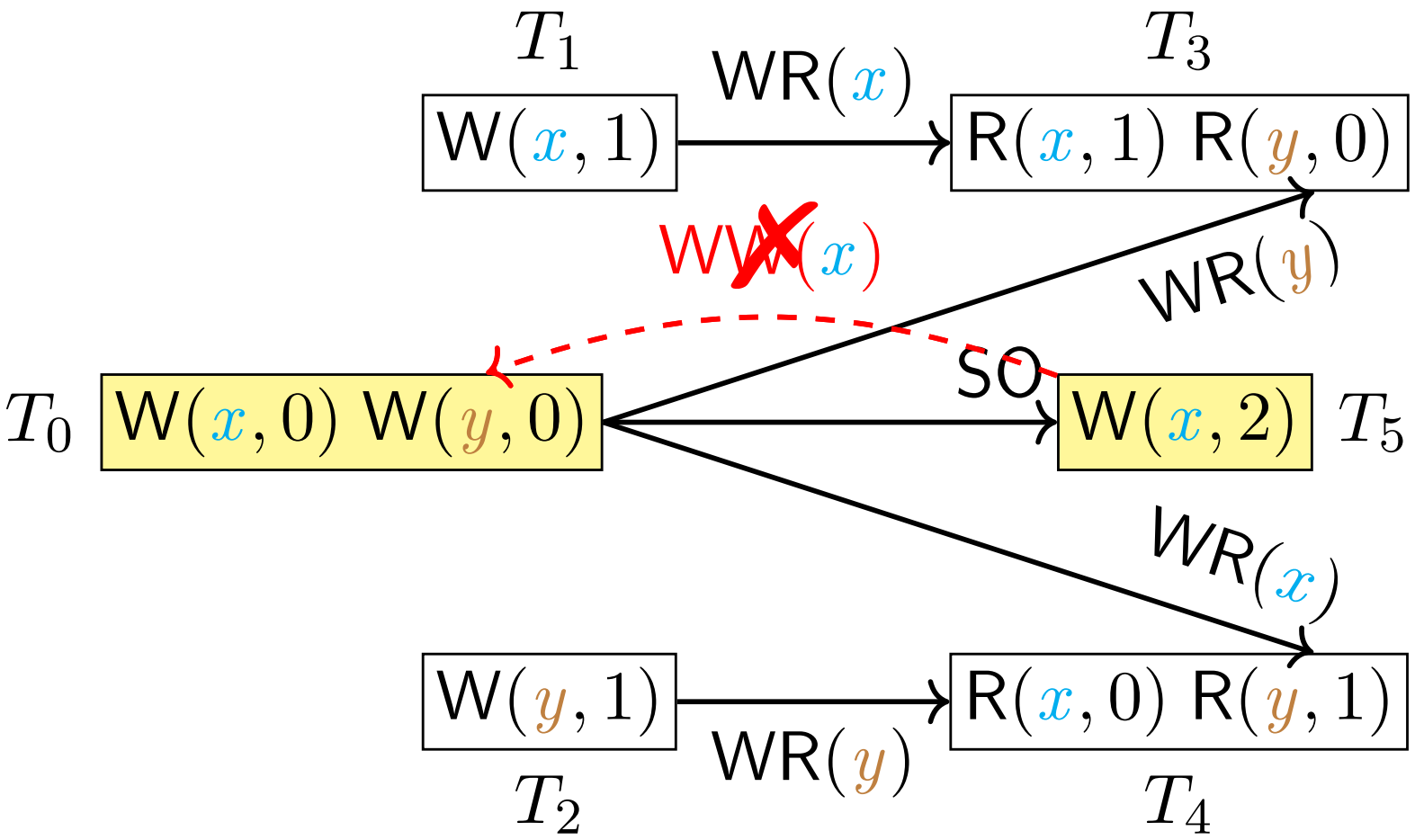


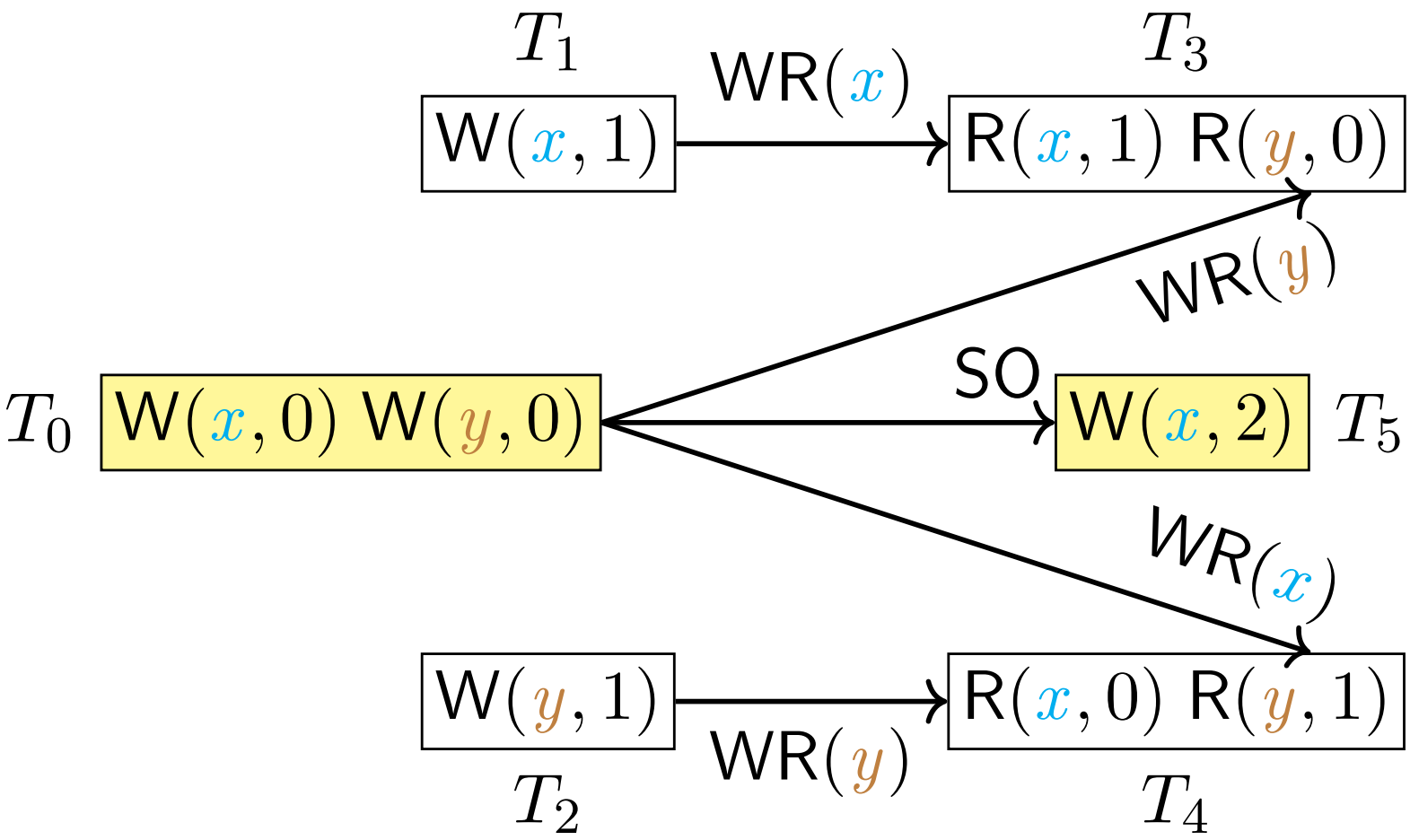
order between T_0, T_1, and T_5 (on x) and between T_0 and T_2 (on y)

PolySI: An Illustrating Example of "Long Fork"

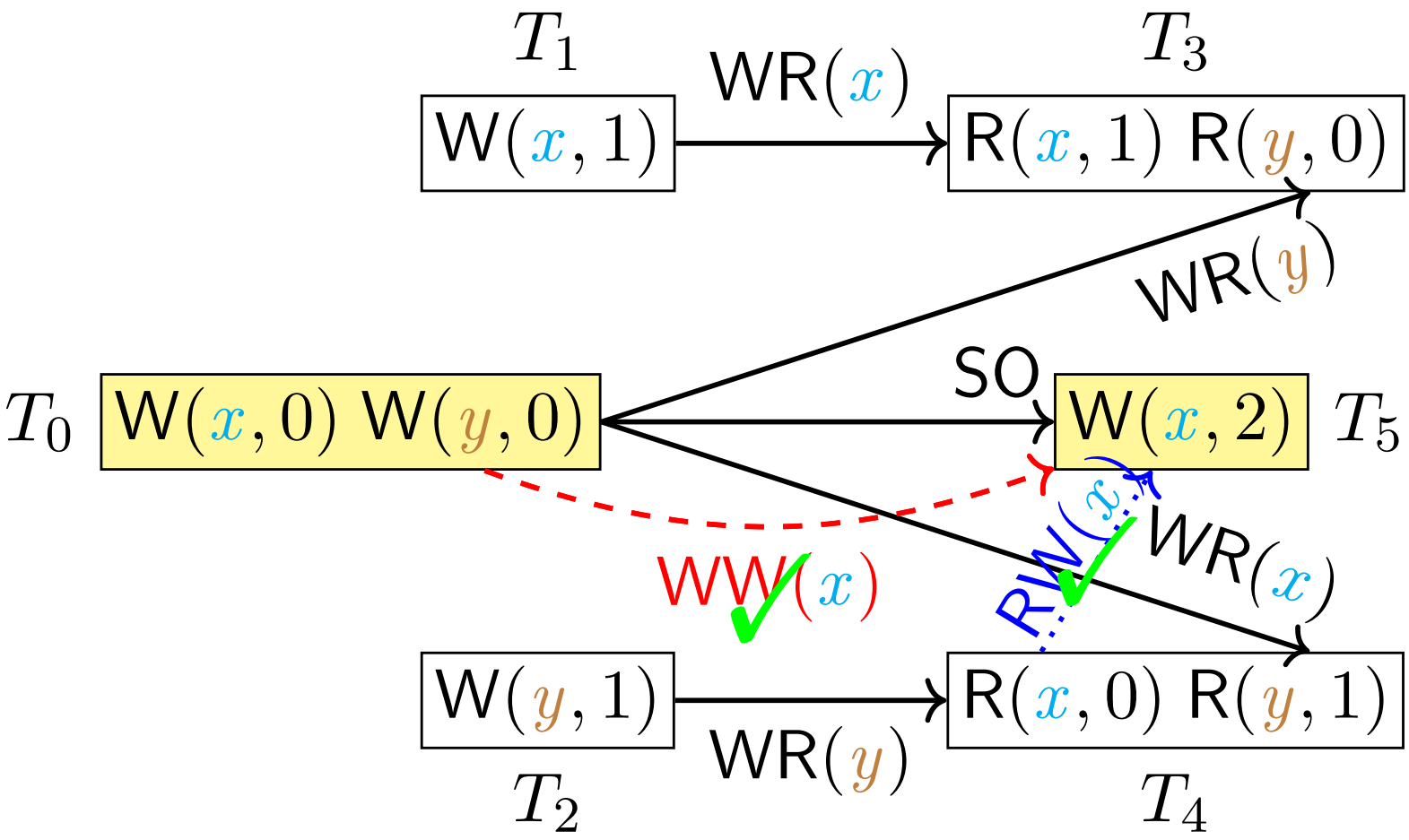


The $T_5 \xrightarrow{\mathsf{WW}(x)} T_0$ case is pruned due to $T_0 \xrightarrow{\mathsf{SO}} T_5 \xrightarrow{\mathsf{WW}(x)} T_0$.

PolySI: An Illustrating Example of "Long Fork"

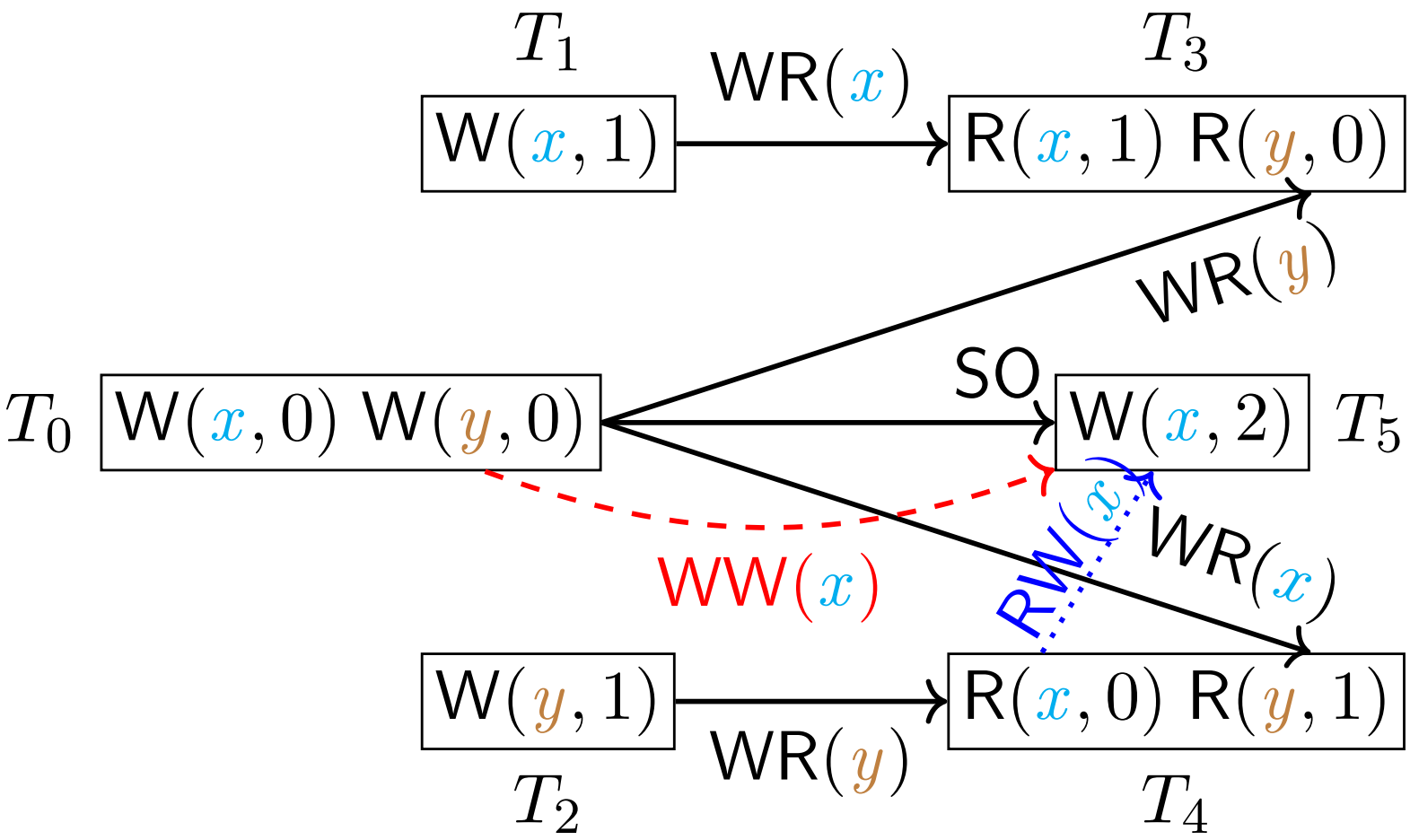


PolySI: An Illustrating Example of "Long Fork"

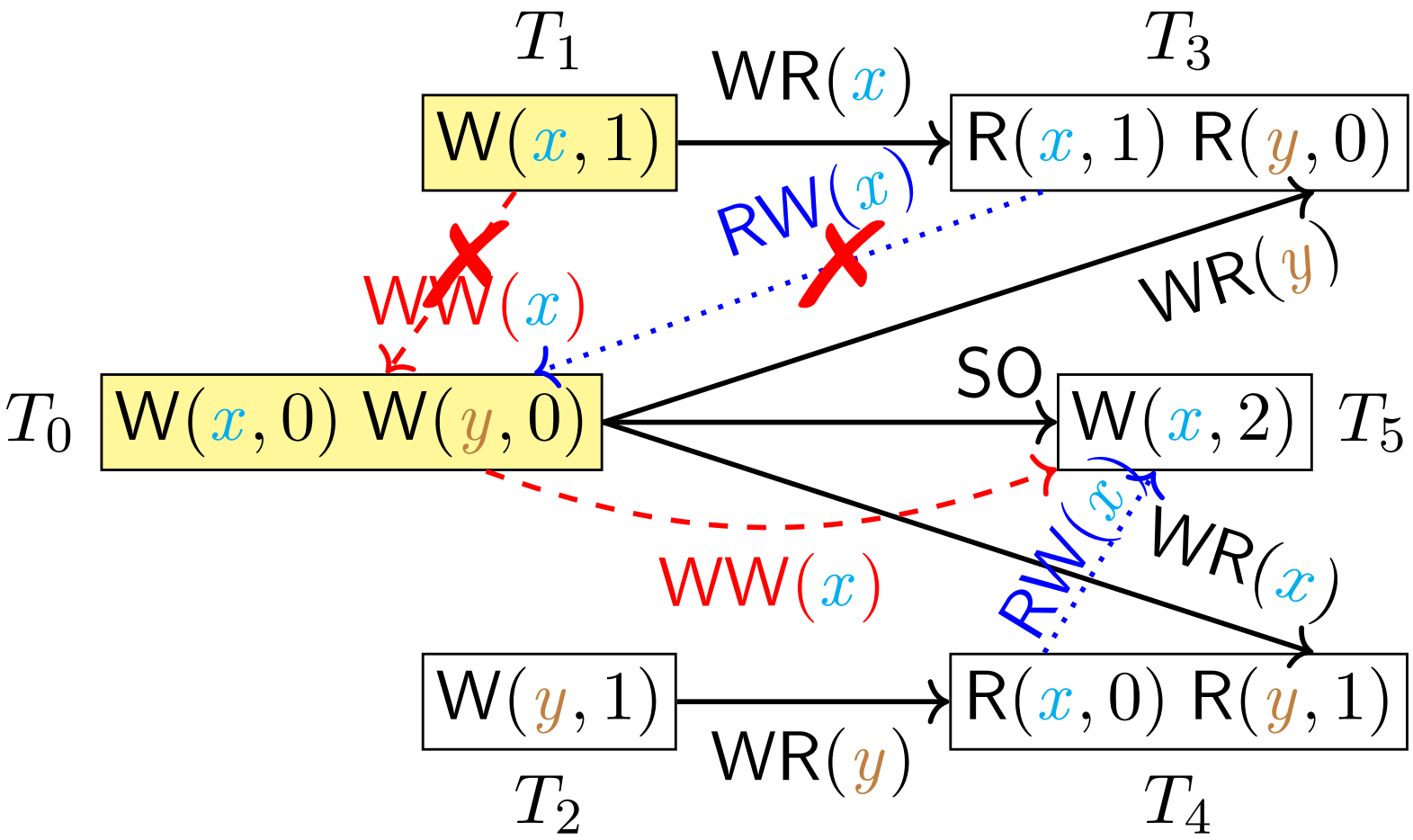


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_5$ case becomes known.

PolySI: An Illustrating Example of "Long Fork"

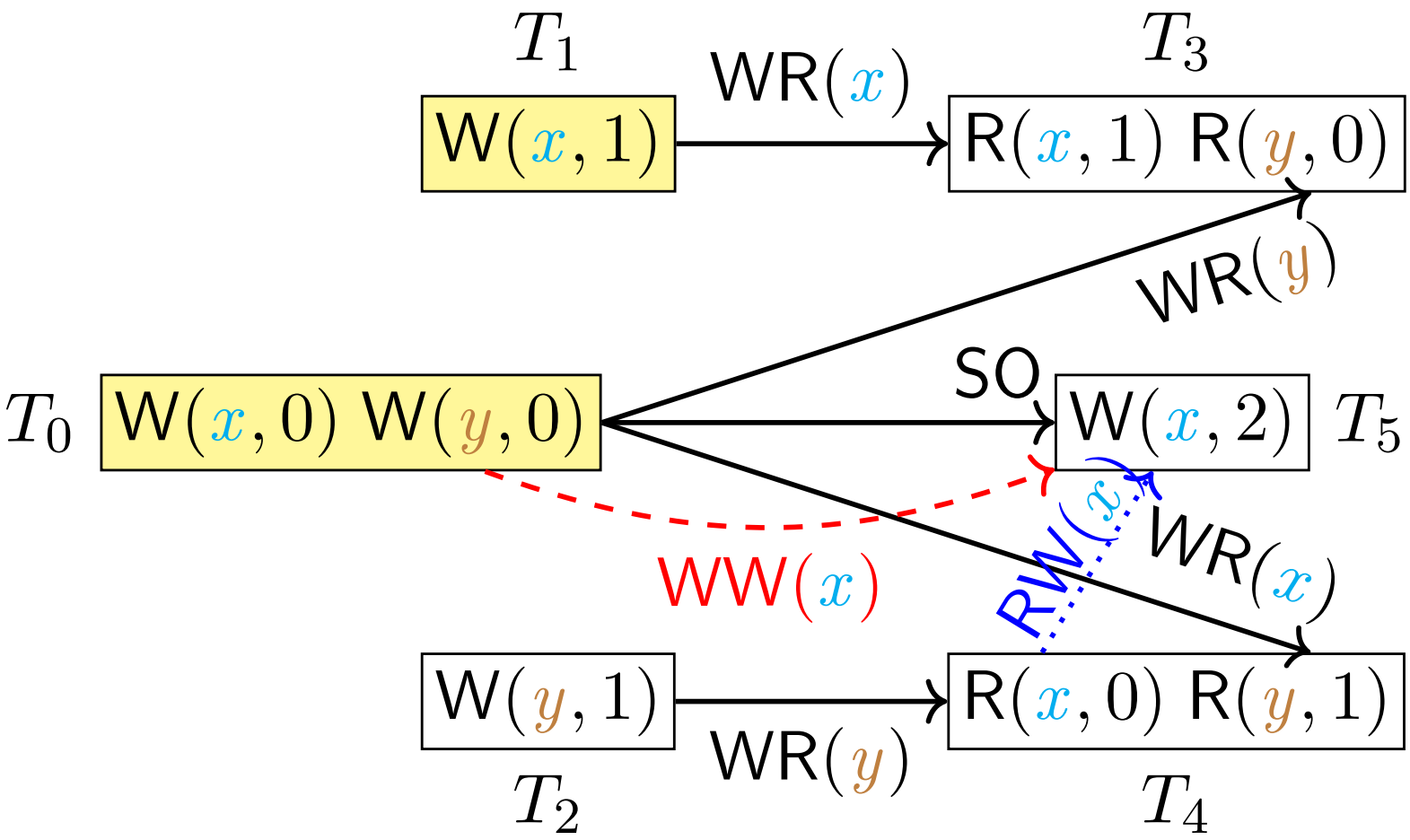


PolySI: An Illustrating Example of "Long Fork"

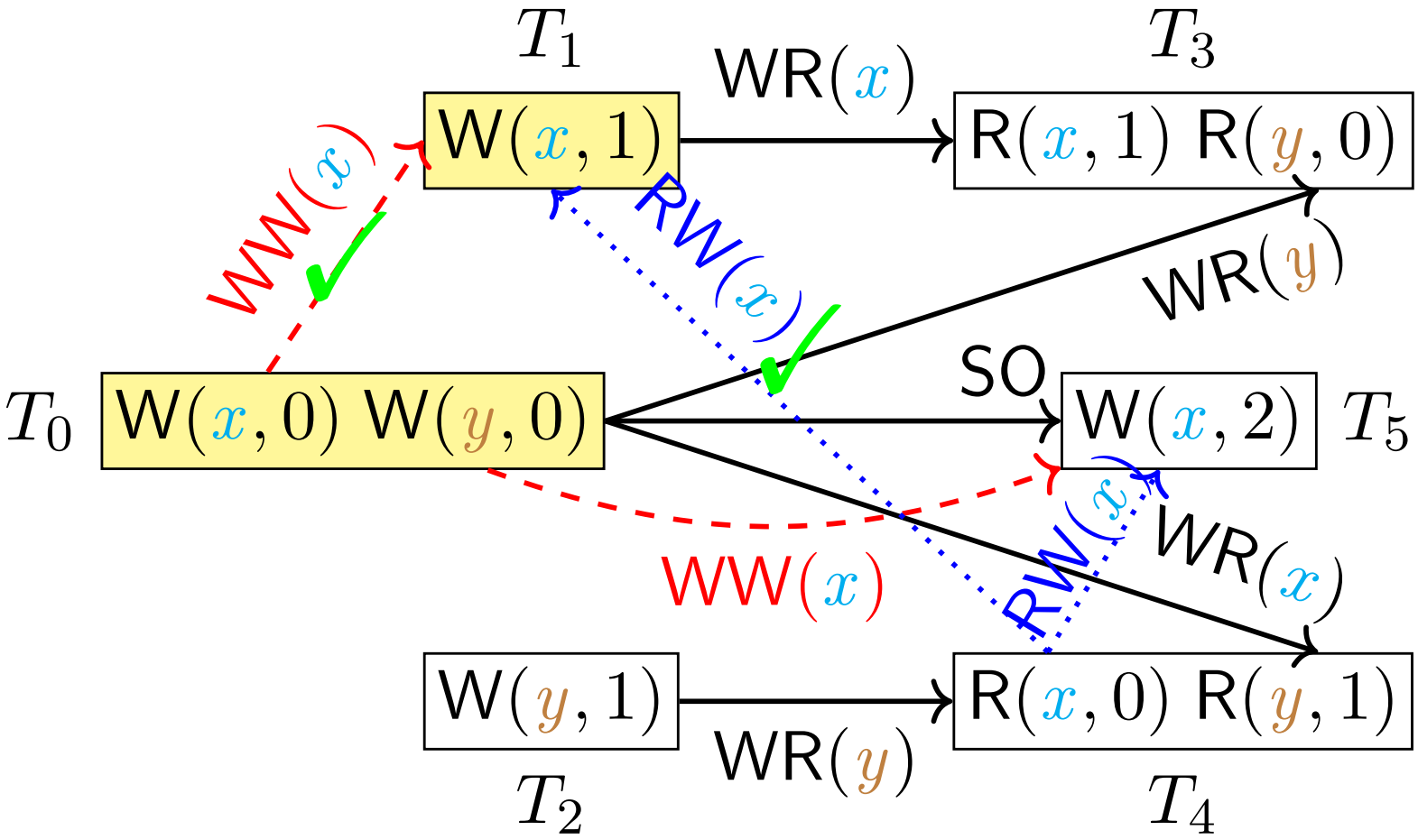


The $T_1 \xrightarrow{\mathsf{WW}(x)} T_0$ case is pruned due to $T_3 \xrightarrow{\mathsf{RW}(x)} T_0 \xrightarrow{\mathsf{WR}(y)} T_3$.

PolySI: An Illustrating Example of "Long Fork"

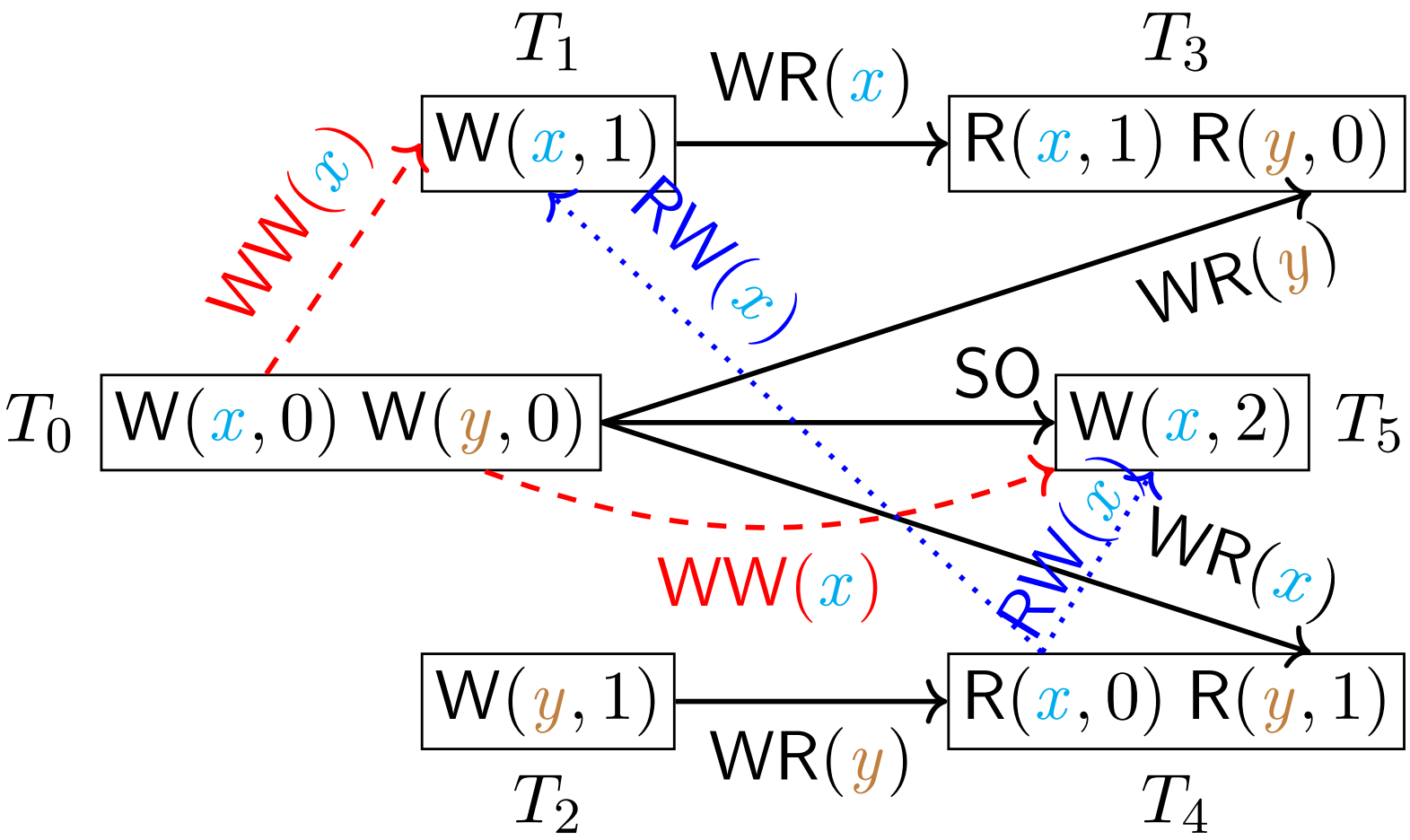


PolySI: An Illustrating Example of "Long Fork"

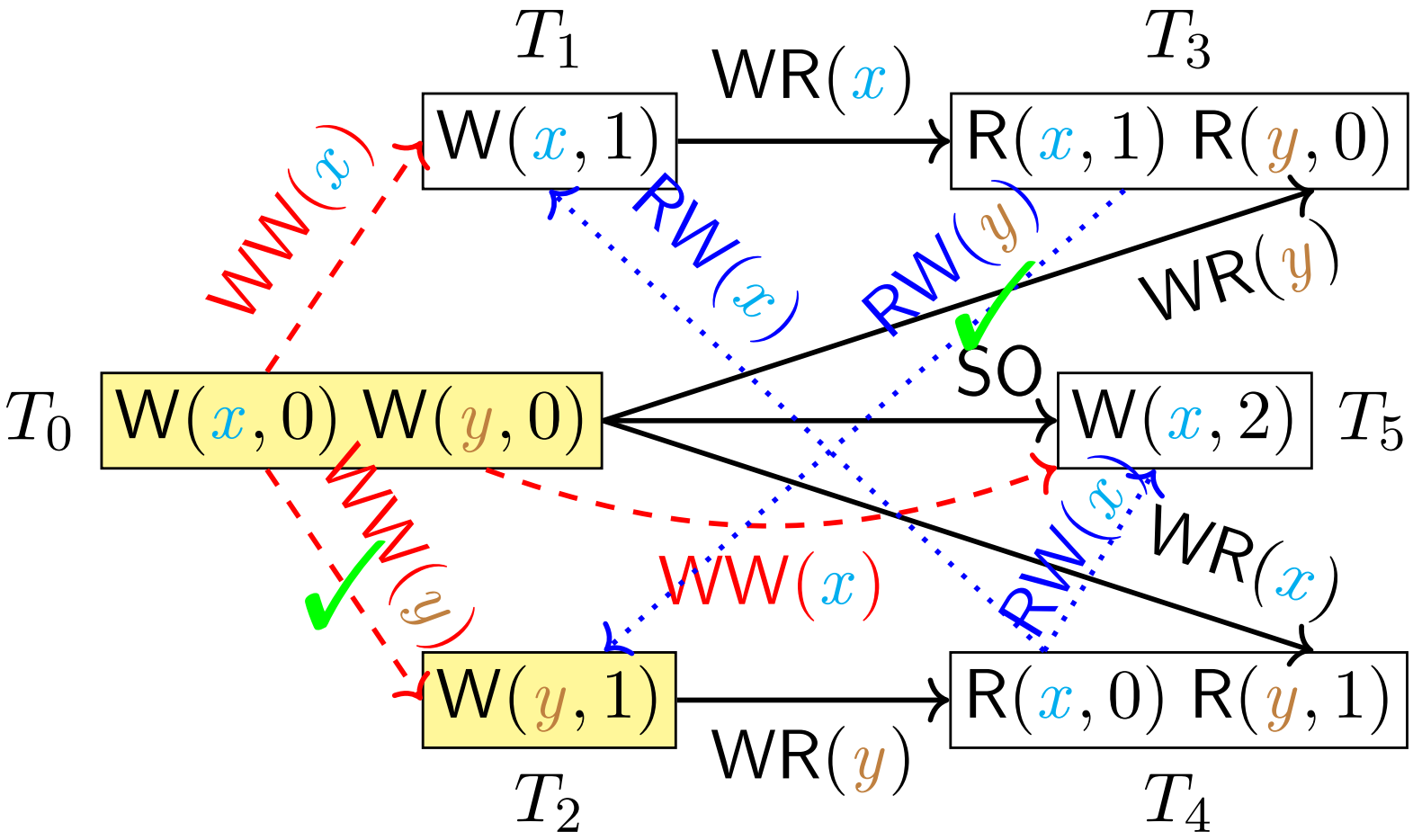


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_1$ case becomes known.

PolySI: An Illustrating Example of "Long Fork"



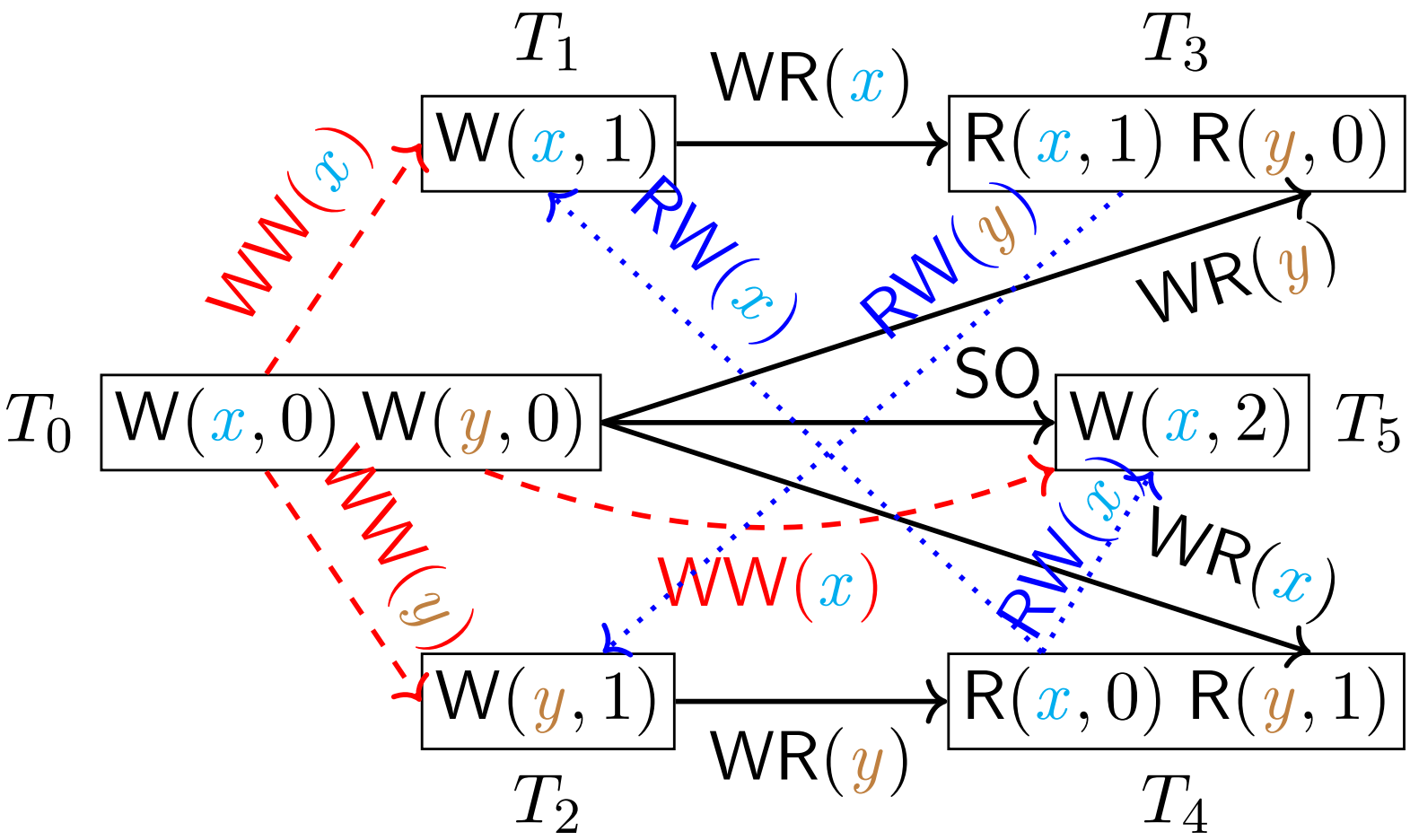
PolySI: An Illustrating Example of "Long Fork"



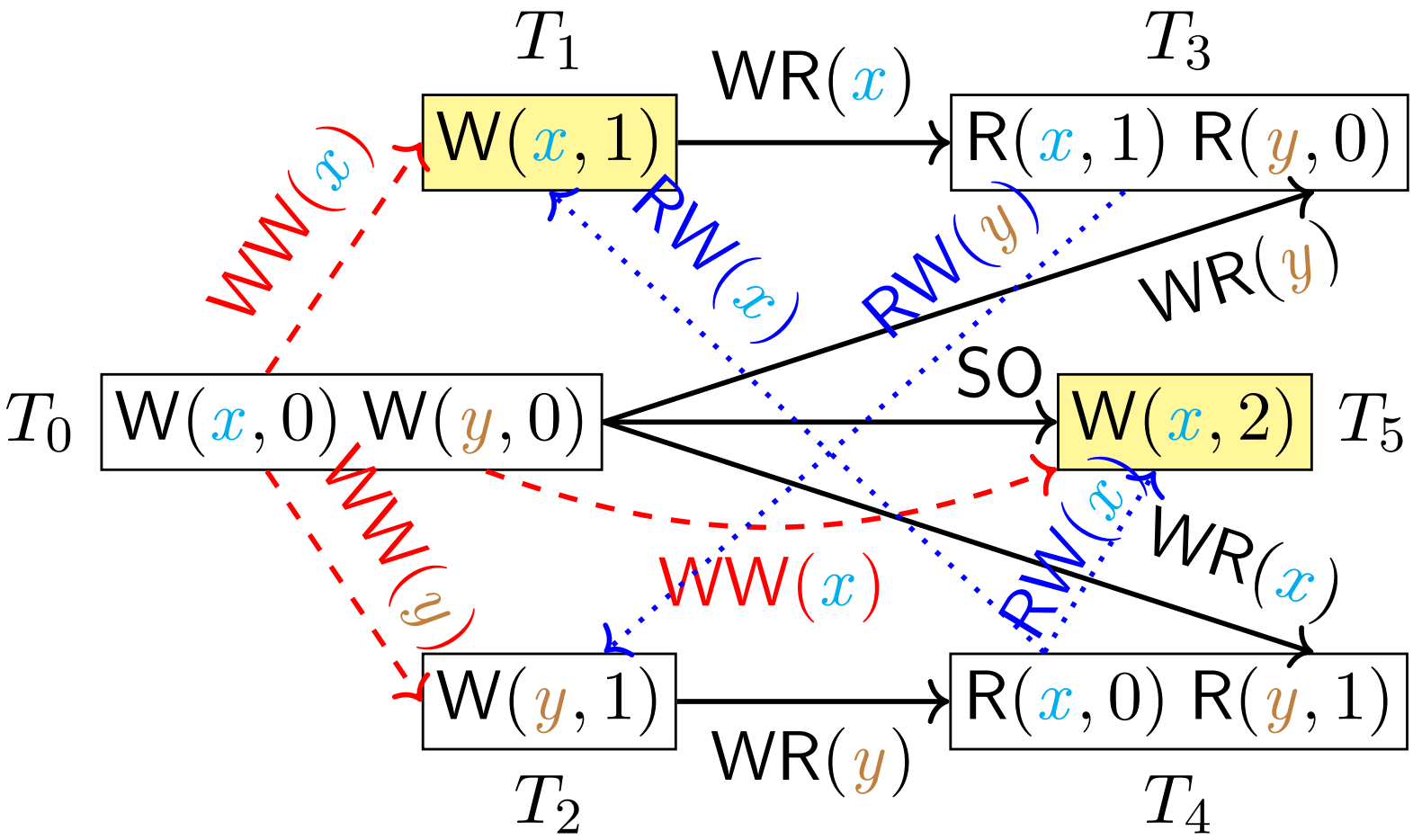
The $T_2 \xrightarrow{\mathsf{WW}(y)} T_0$ case is pruned,

while the $T_0 \xrightarrow{\mathsf{WW}(y)} T_2$ case becomes known.

PolySI: An Illustrating Example of "Long Fork"

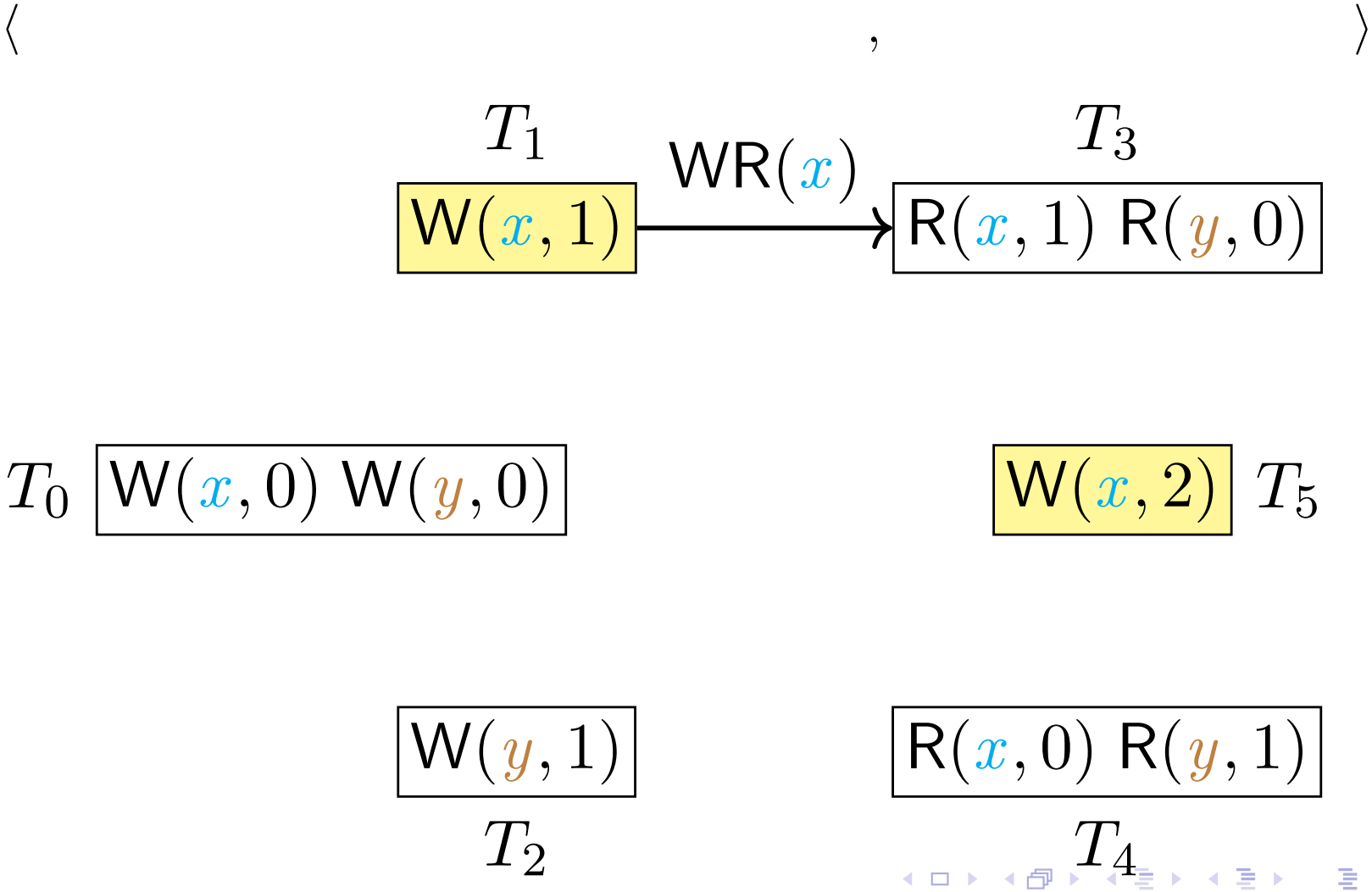


PolySI: An Illustrating Example of "Long Fork"



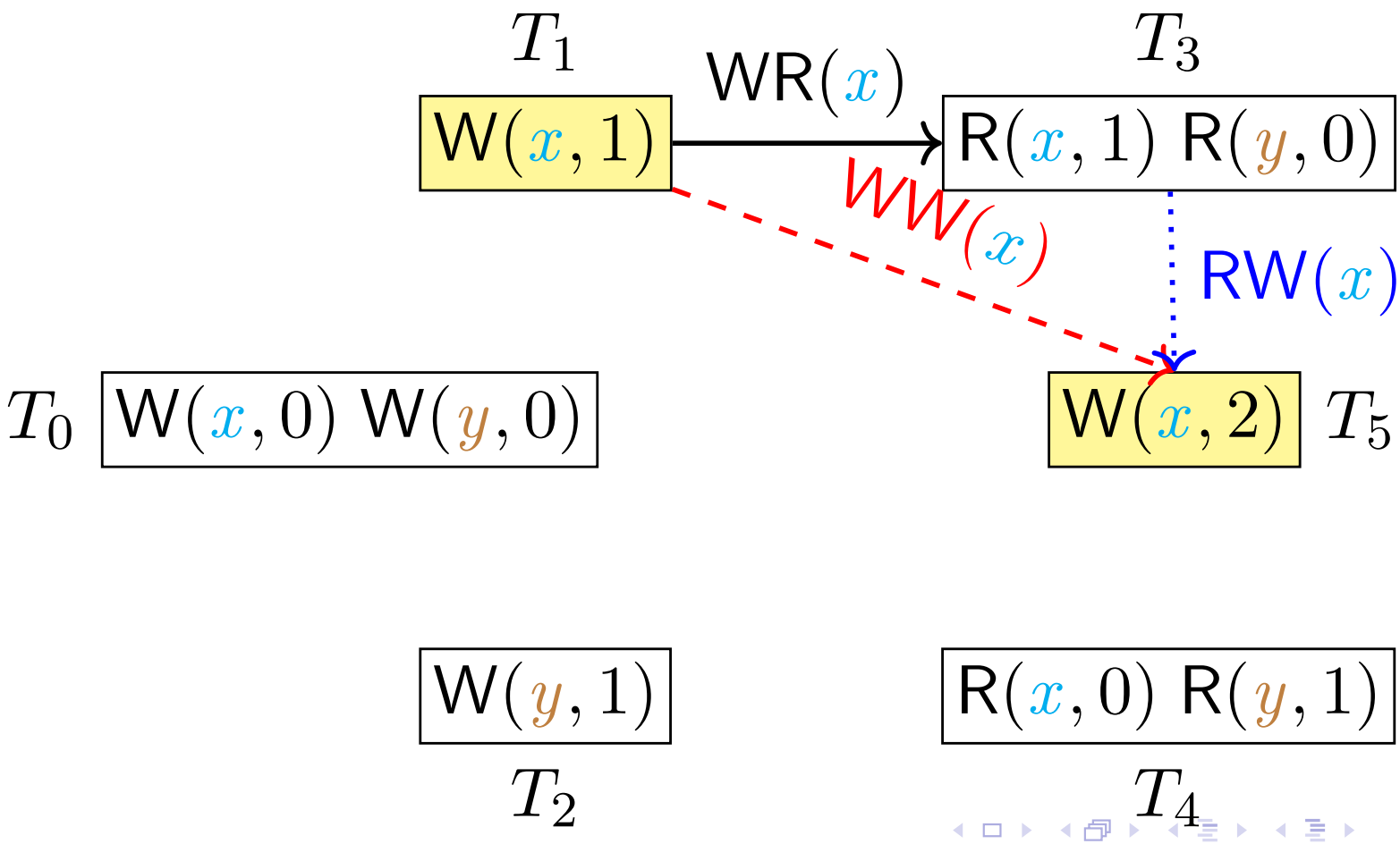
The order between T_1 and T_5 is still uncertain after pruning.

PolySI: An Illustrating Example of "Long Fork"



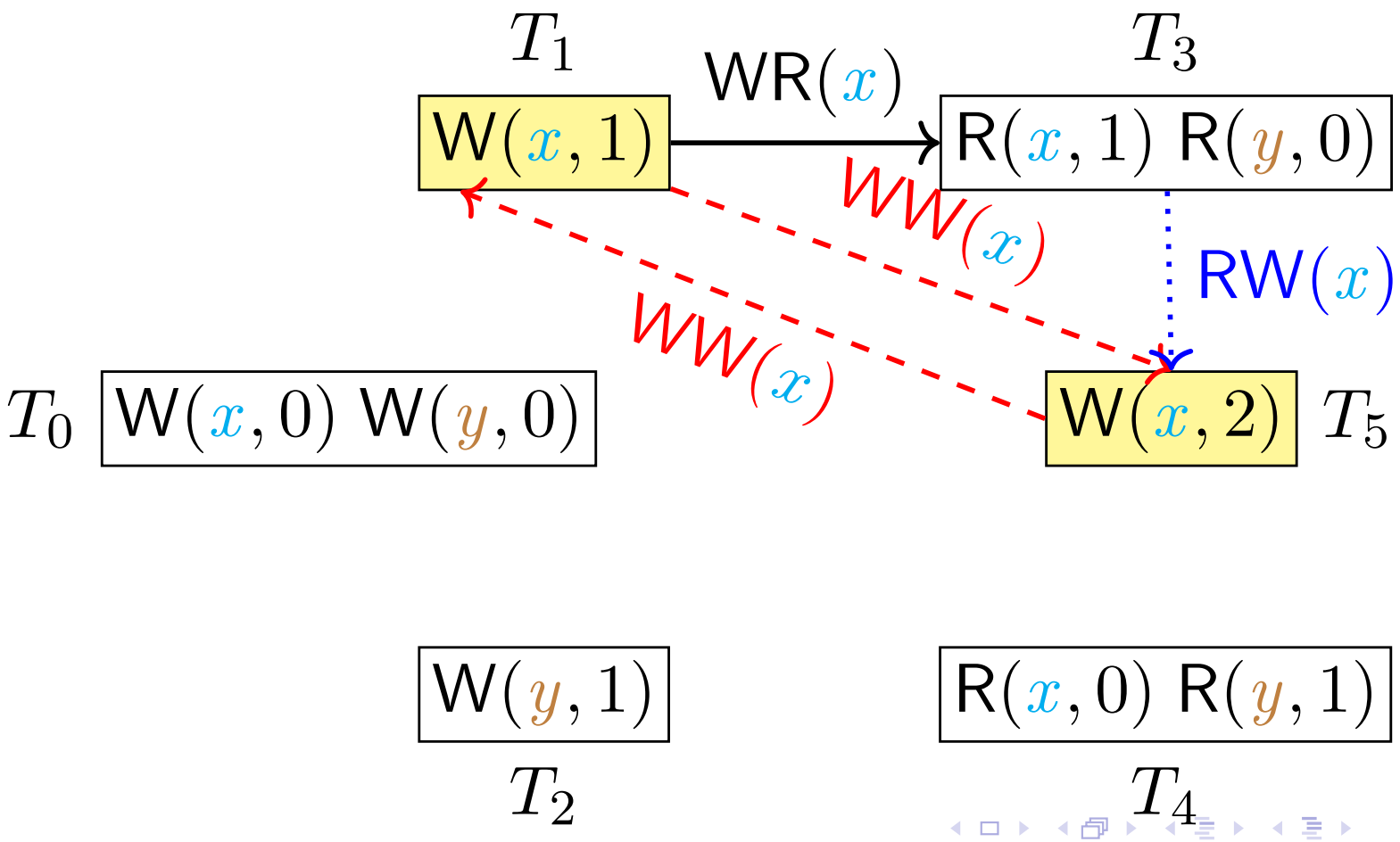
PolySI: An Illustrating Example of "Long Fork"

$\langle either = \{T_1 \xrightarrow{\mathsf{WW}(x)} T_5, T_3 \xrightarrow{\mathsf{RW}(x)} T_5\}, \quad \rangle$



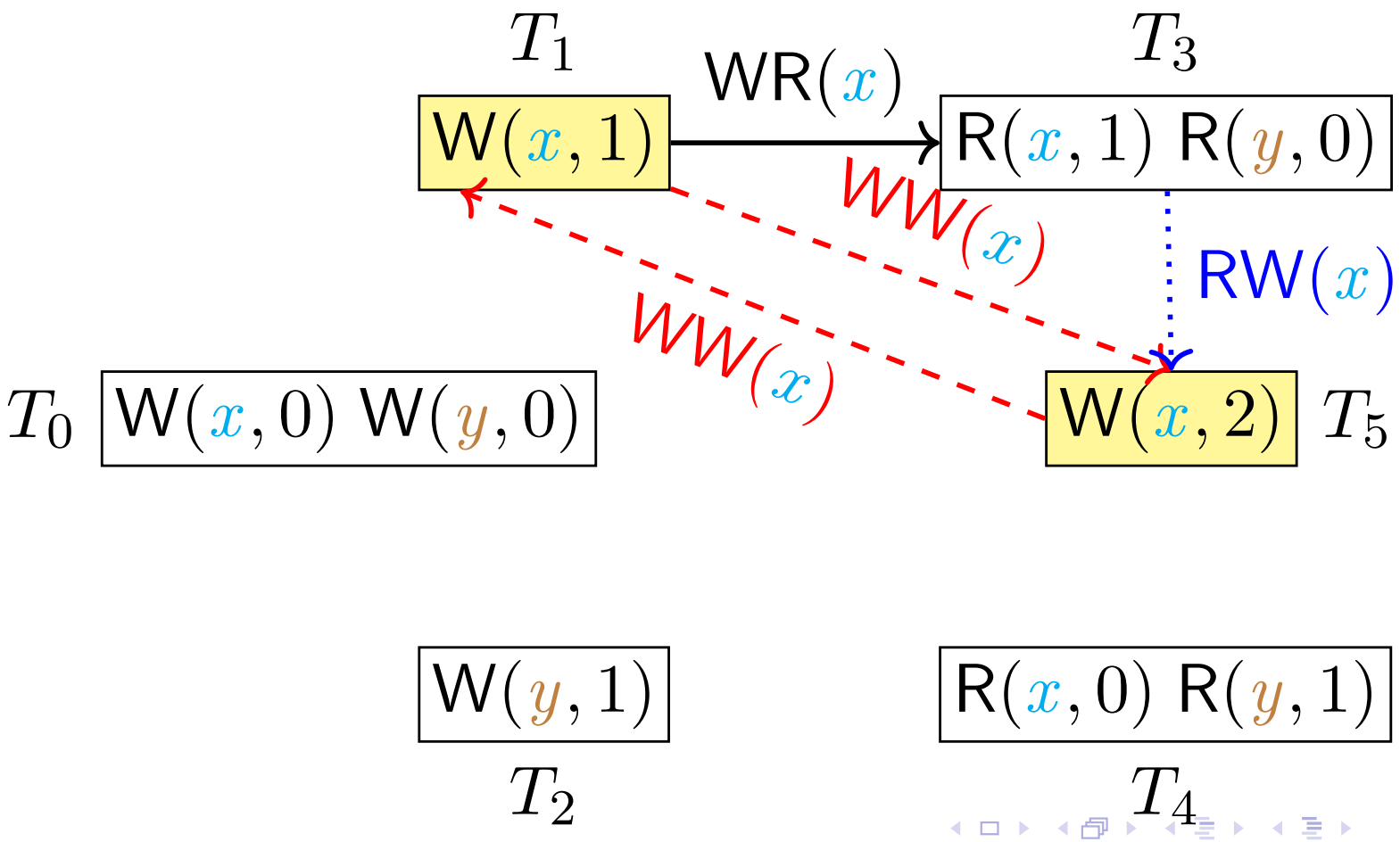
PolySI: An Illustrating Example of "Long Fork"

$$\langle either = \{T_1 \xrightarrow{\mathsf{WW}(x)} T_5, T_3 \xrightarrow{\mathsf{RW}(x)} T_5\}, or = \{T_5 \xrightarrow{\mathsf{WW}(x)} T_1\}\rangle$$



PolySI: An Illustrating Example of "Long Fork"

$$\langle either = \{T_1 \xrightarrow{\mathsf{WW}(x)} T_5, T_3 \xrightarrow{\mathsf{RW}(x)} T_5\}, or = \{T_5 \xrightarrow{\mathsf{WW}(x)} T_1\}\rangle$$



PolySI: An Illustrating Example of "Long Fork"

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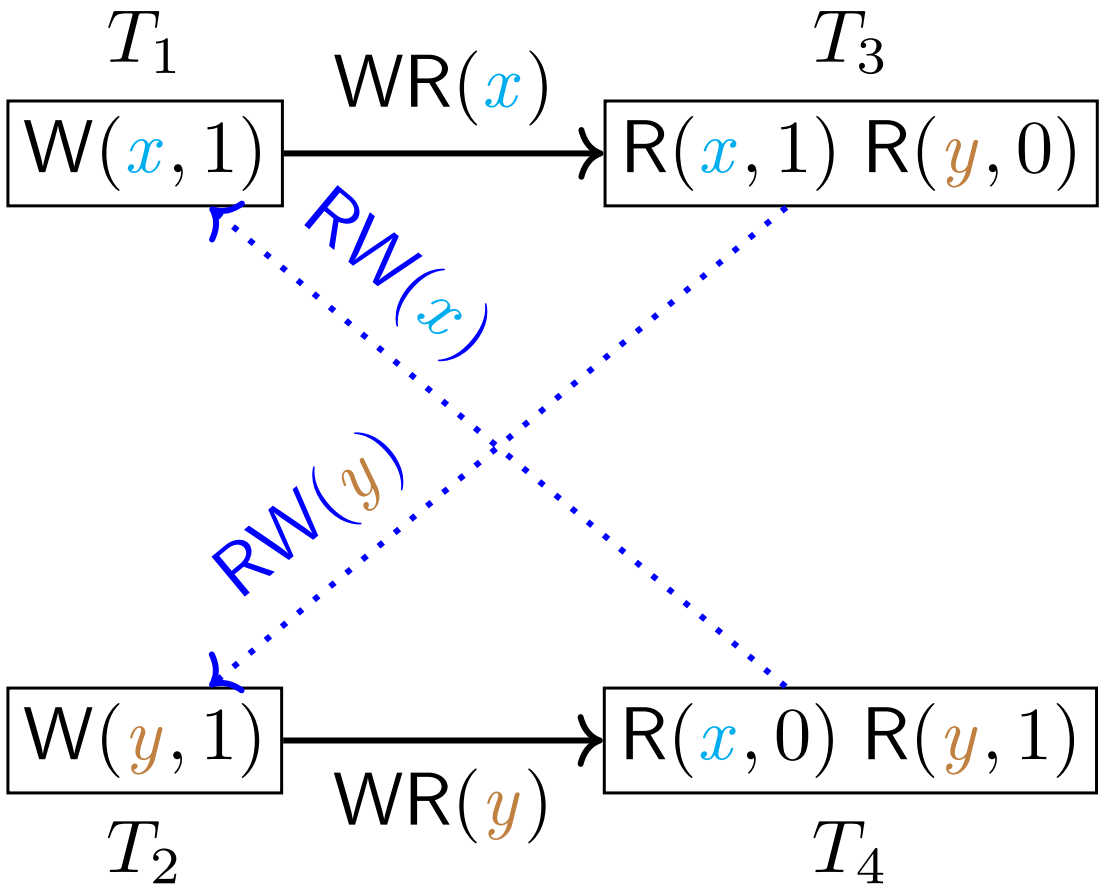


The undesired cycle for "long fork" found by MonoSAT.

Experimental Evaluation

(1) *Effective:* Can PolySI find SI violations in production databases?

(2) *Informative:* Can PolySI provide understandable counterexamples for SI violations?

(3) *Efficient:* How efficient is PolySI? Is it scalable?

Workloads, Benchmarks, and Setup

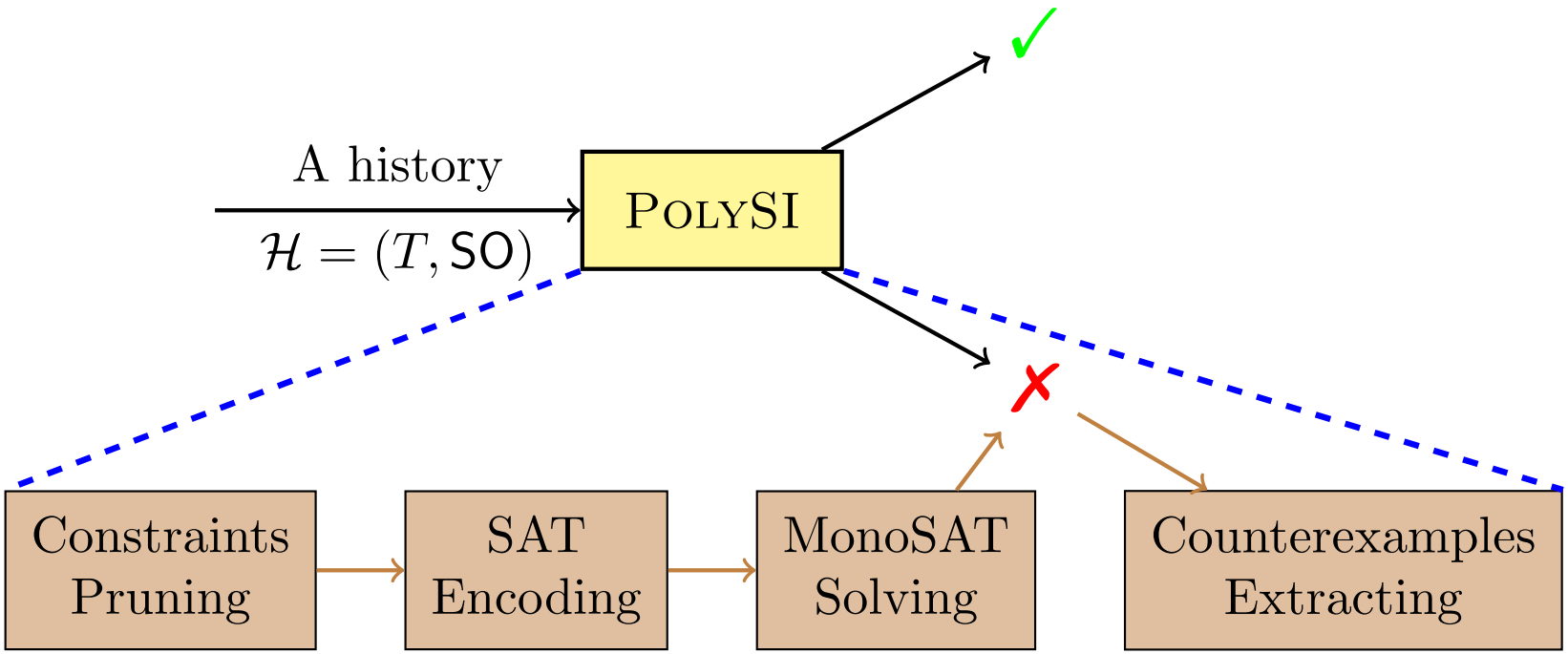
Finding SI Violations

Understanding Violations

Performance

Scalability

Conclusion


A history
$\mathcal{H} = (T, \mathsf{SO})$
PolySI
Constraints Pruning
SAT Encoding
MonoSAT Solving
Counterexamples Extracting

Hengfeng Wei (hfwei@nju.edu.cn)


Cerone, Andrea and Alexey Gotsman (Jan. 2018). "Analysing Snapshot Isolation". In: *J. ACM* 65.2. ISSN: 0004-5411. DOI: 10.1145/3152396. URL: https://doi.org/10.1145/3152396.