Efficient Black-box Checking of Snapshot Isolation in Databases

Kaile Huang, Si Liu, Zhenge Chen,

Hengfeng Wei, David Basin, Haixiang Li, Anqun Pan

hfwei@nju.edu.cn

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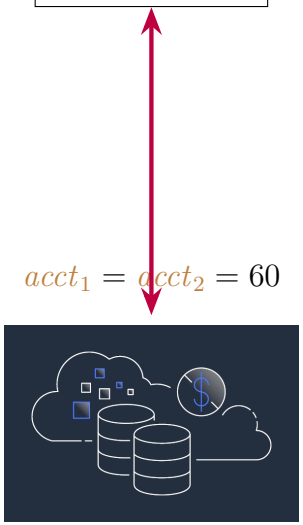
Transaction and Isolation Level

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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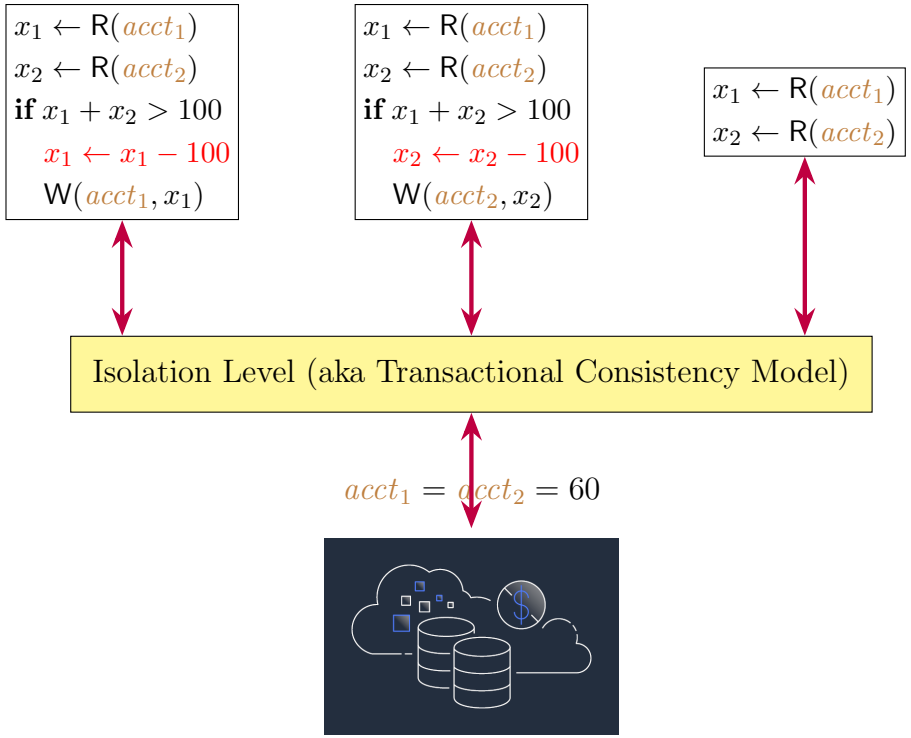
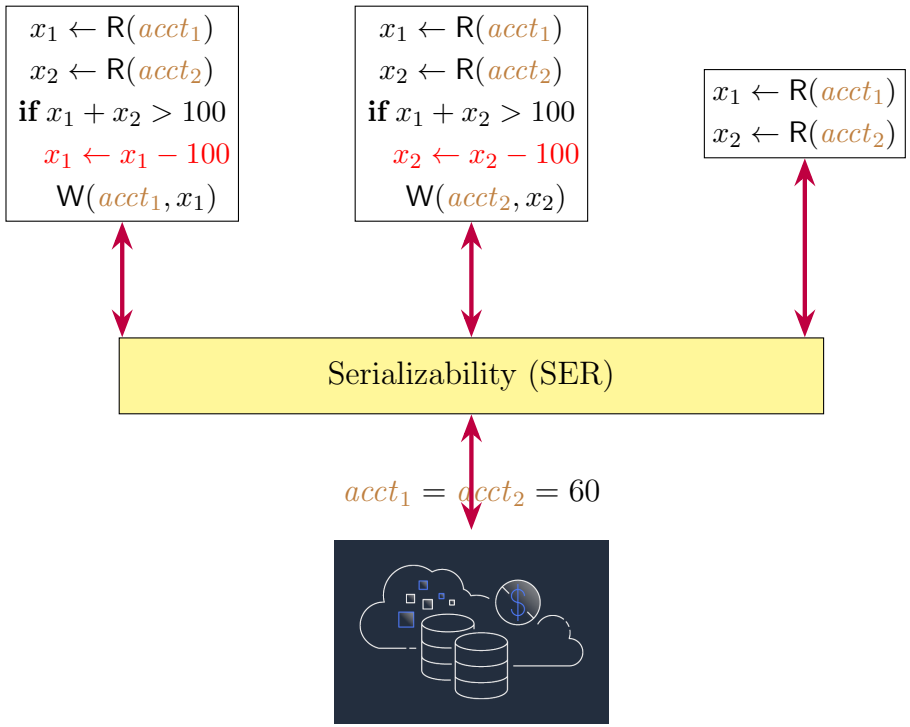


The isolation levels specify how they are isolated from each other.

Serializability (SER)

All transactions appear to execute in some total order.



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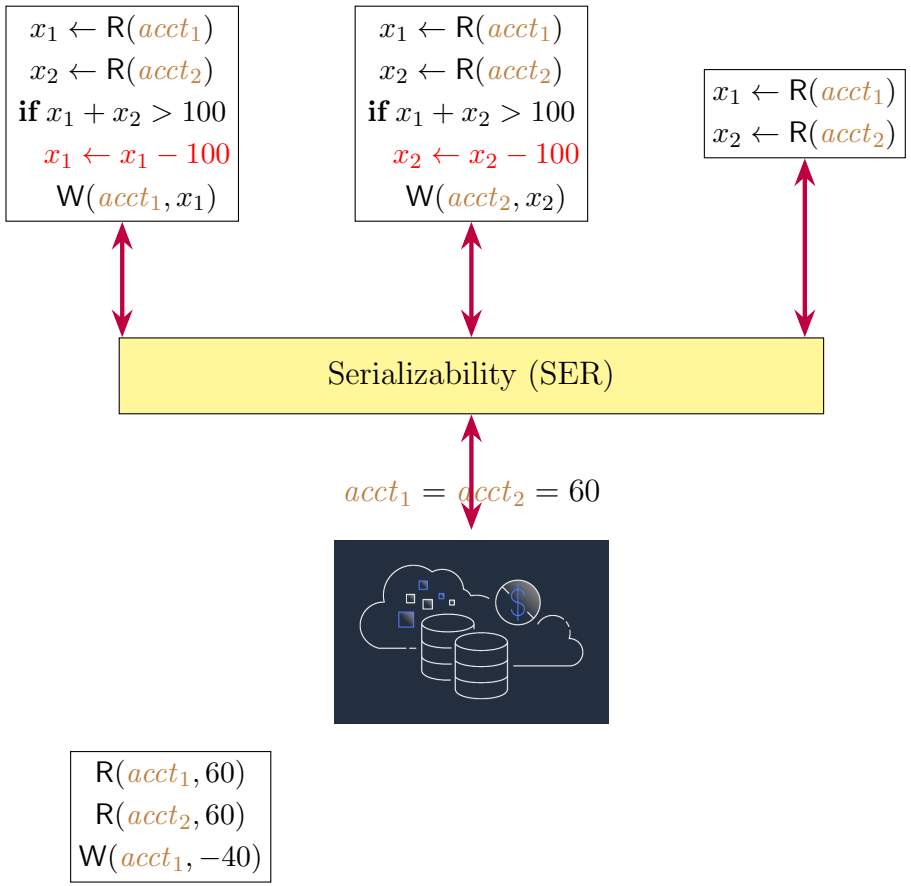

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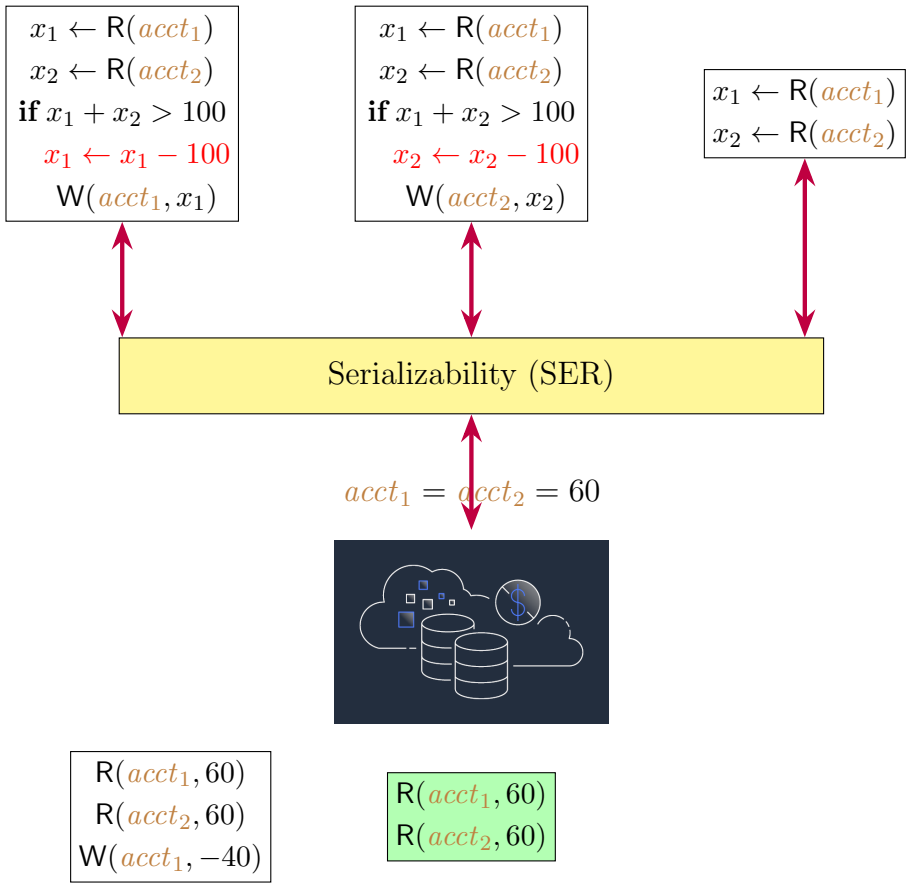

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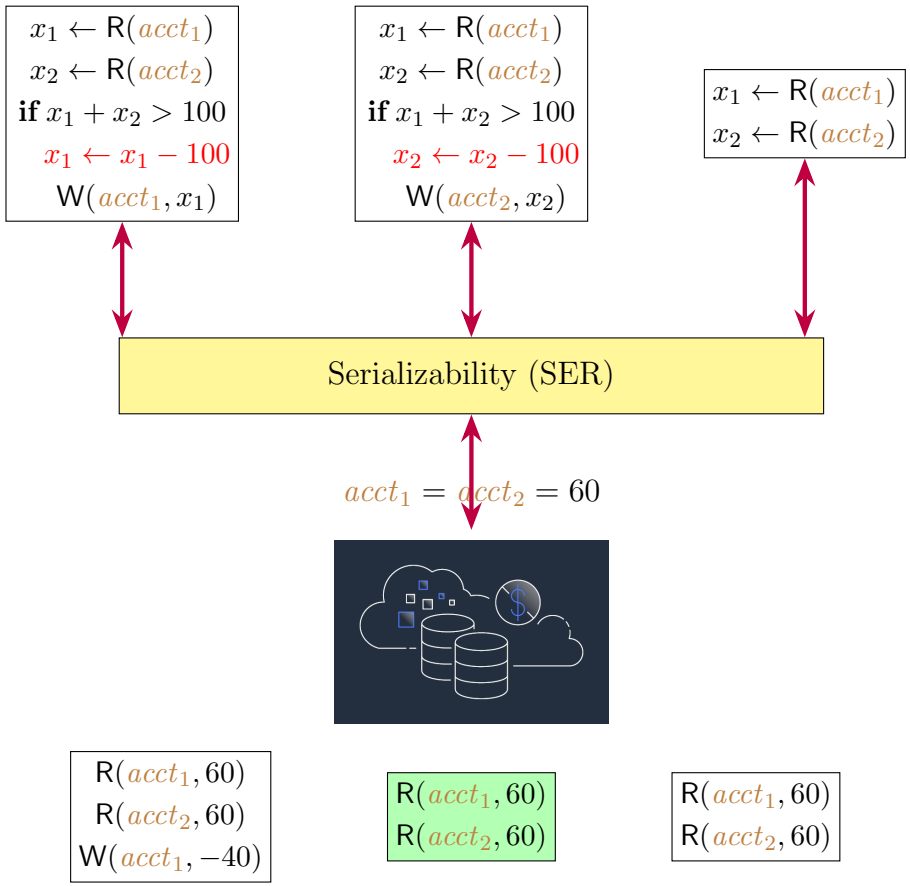

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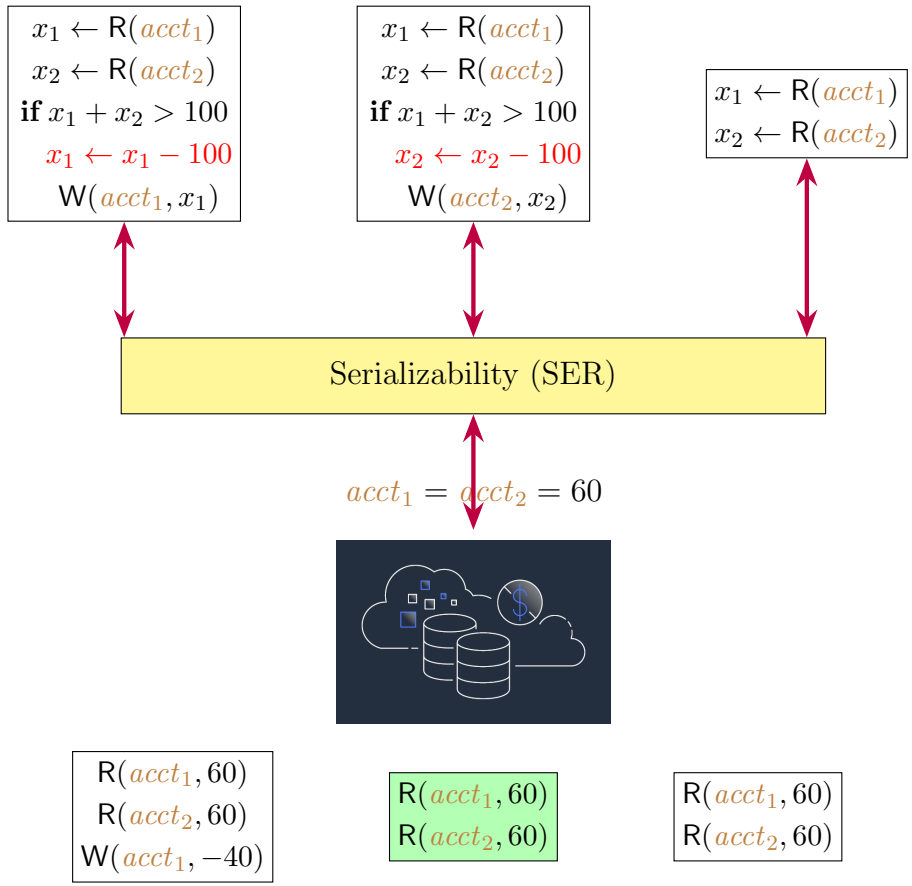
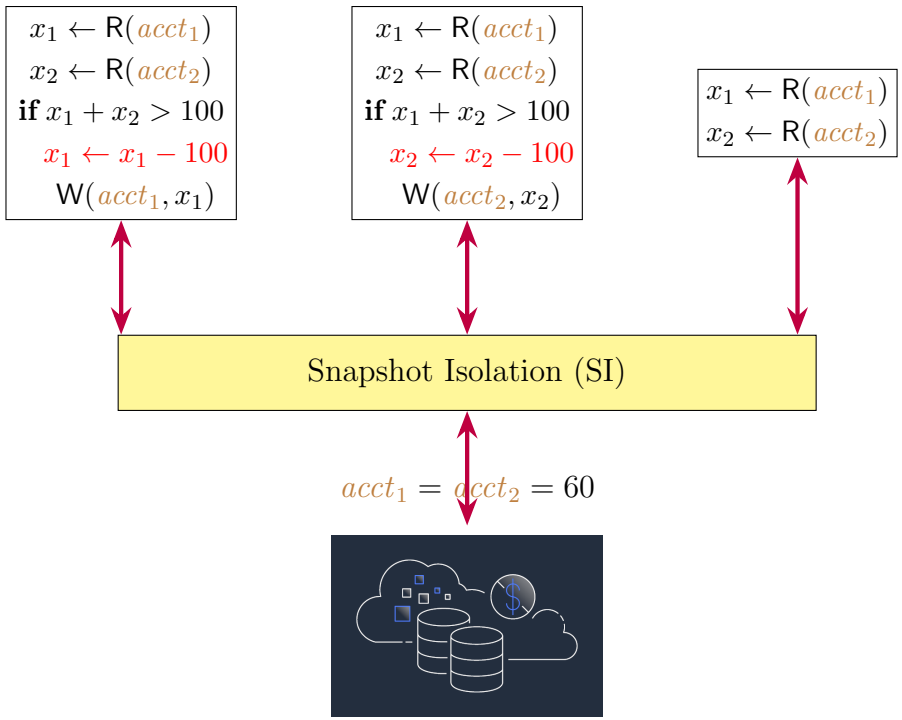


too expensive, especially for distributed transactions

Snapshot Isolation (SI)



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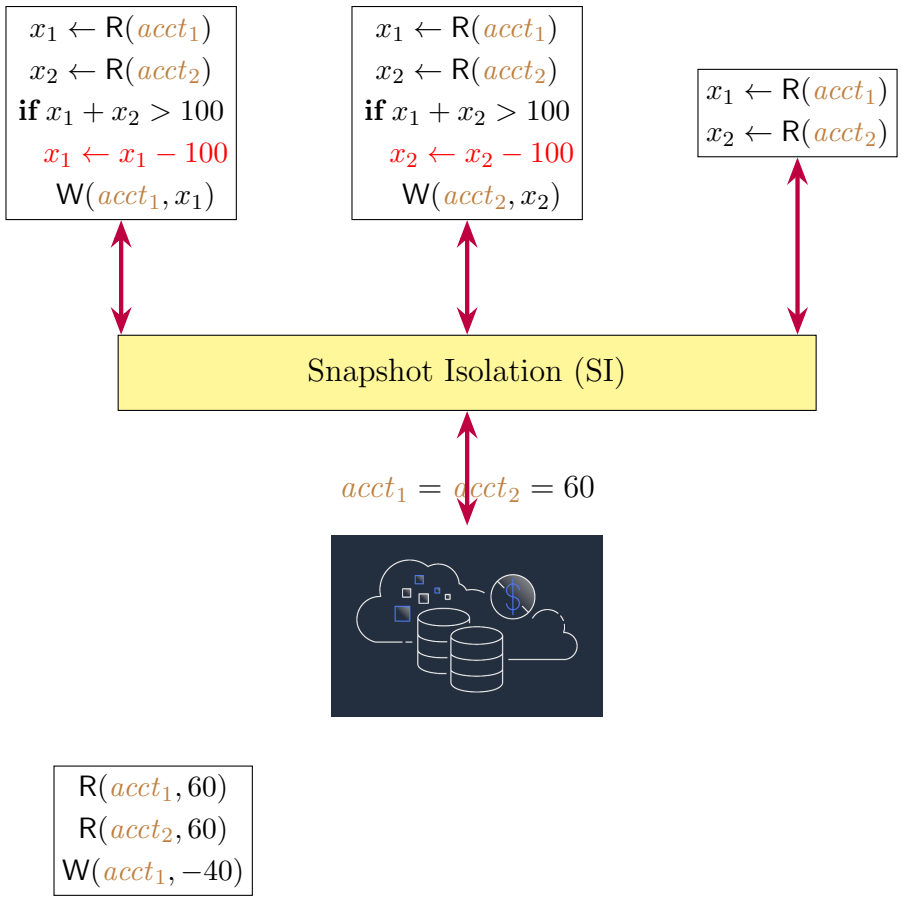

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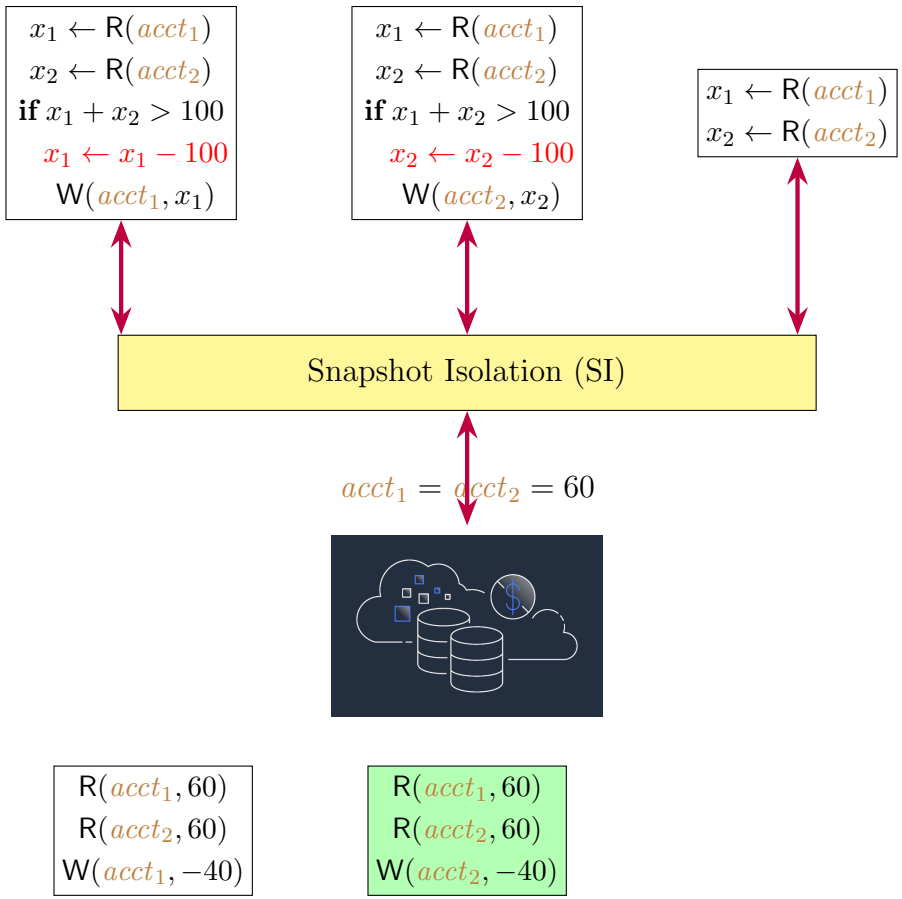

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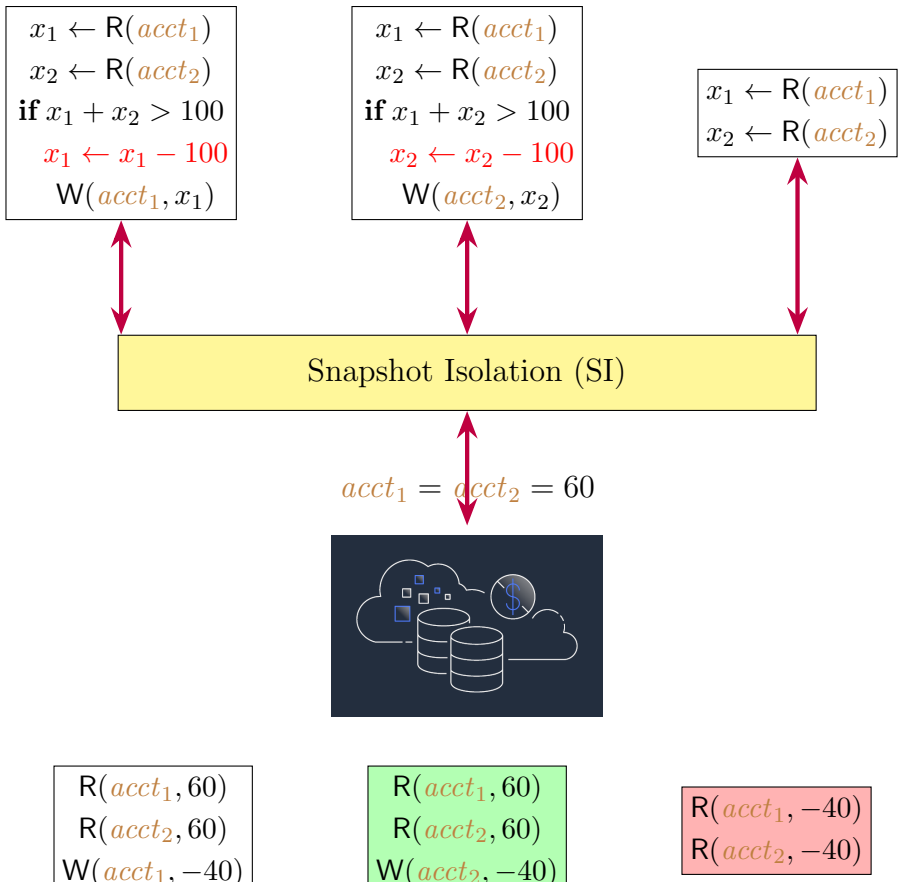

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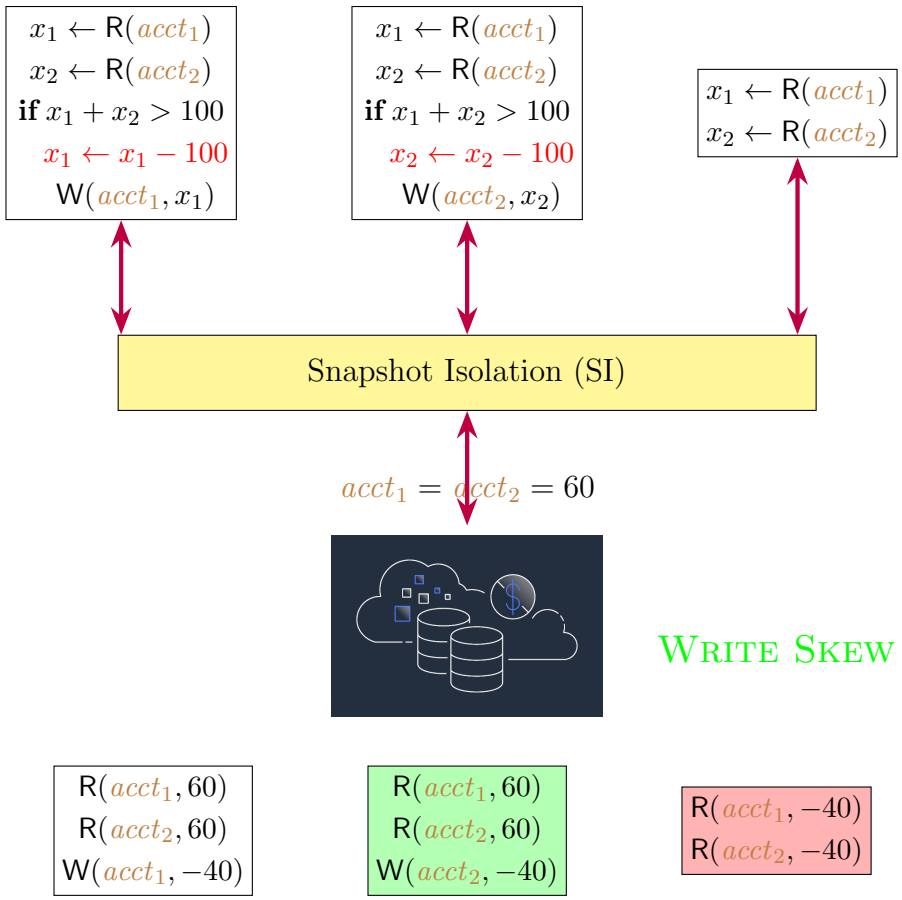

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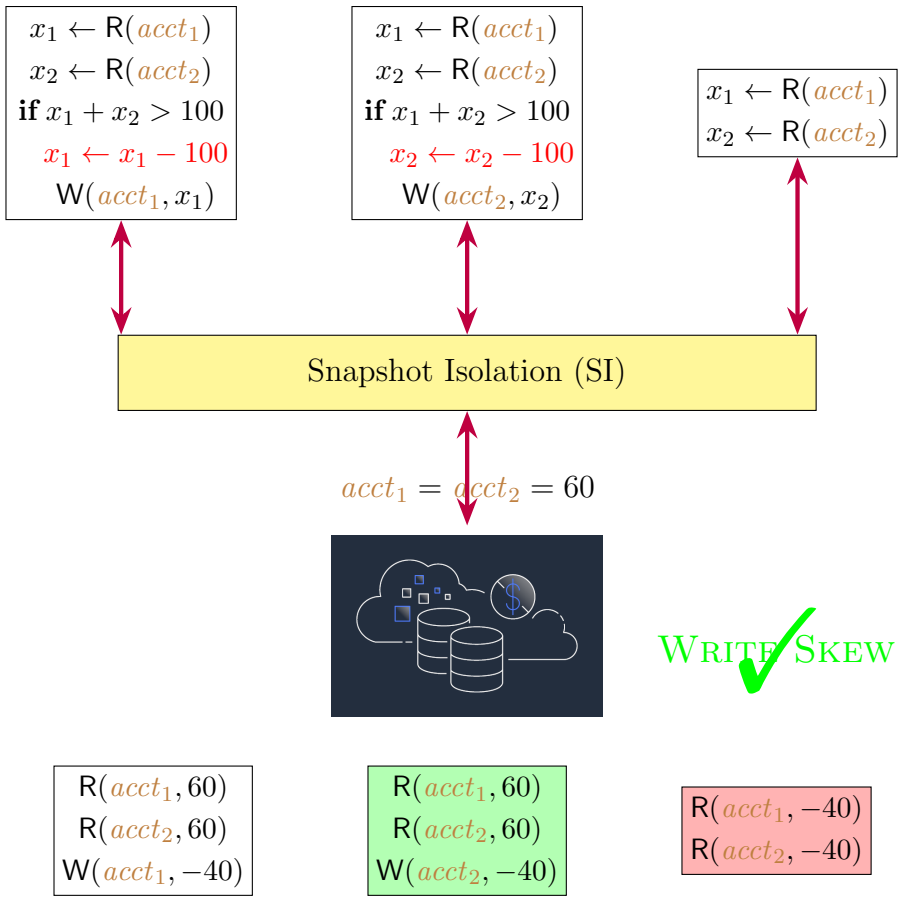

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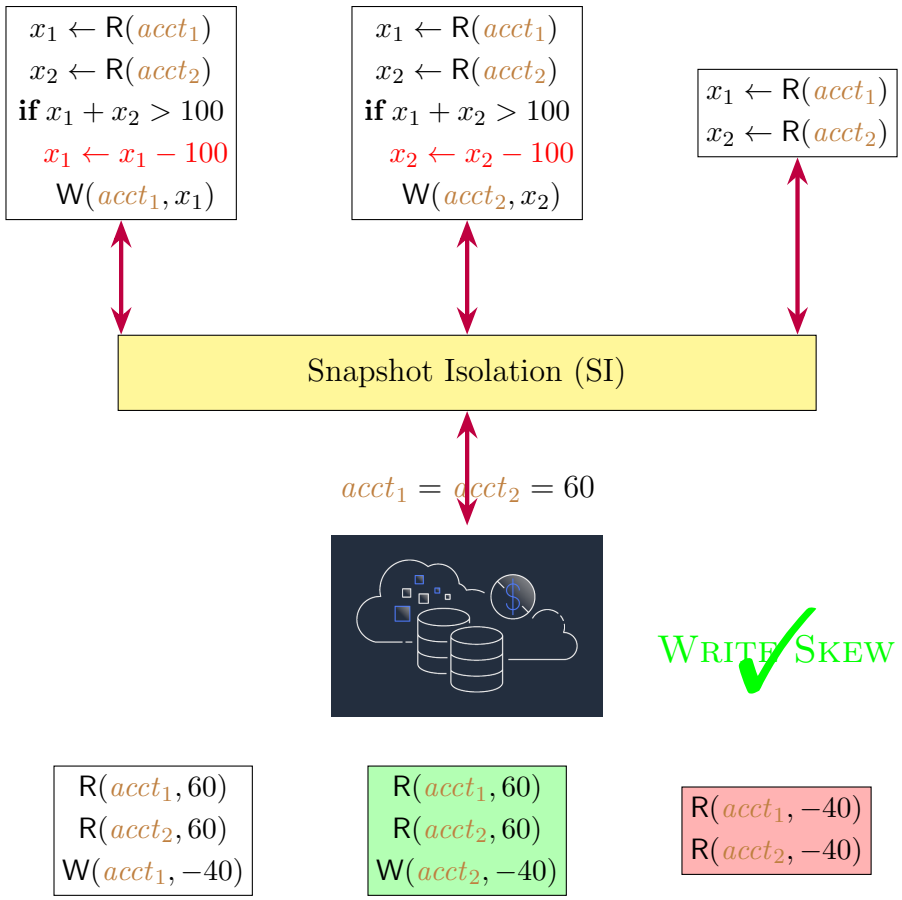

Snapshot Read: Each transaction reads data from a *snapshot* of committed data valid as of the (logical) time the transaction started.

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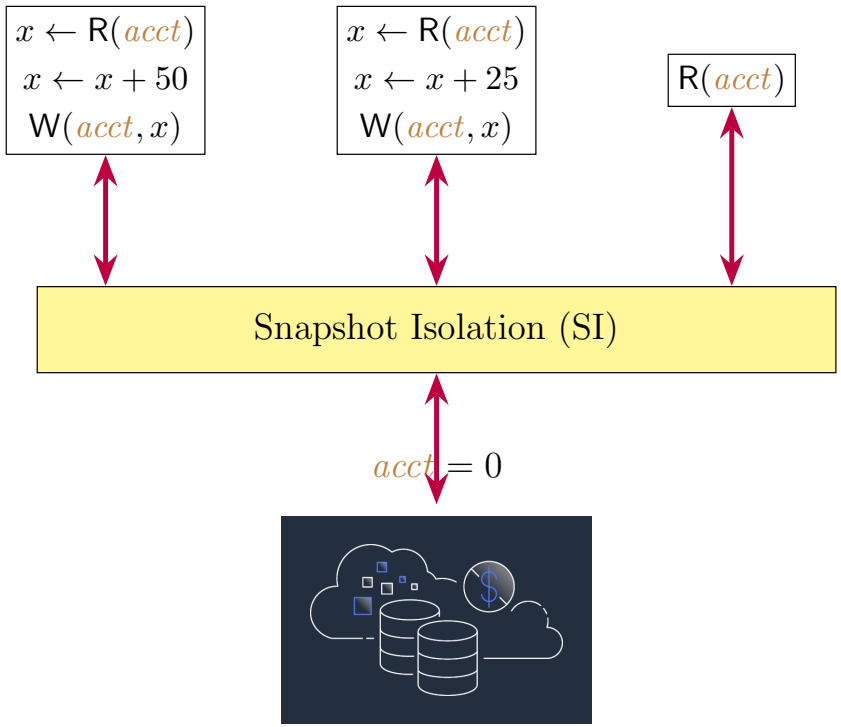

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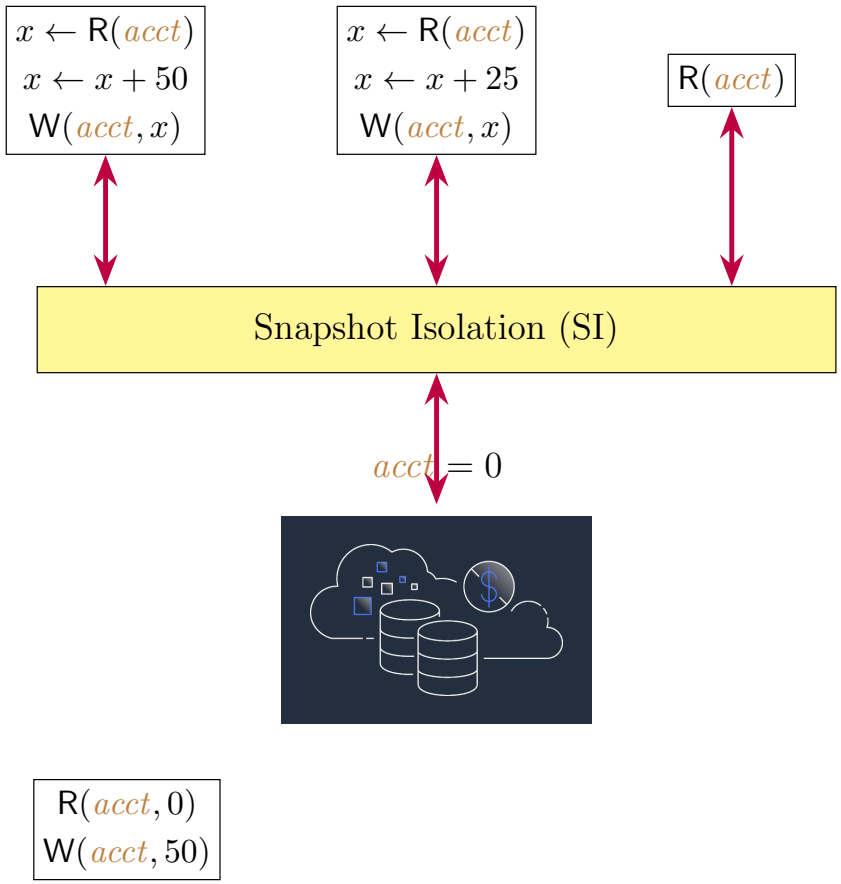

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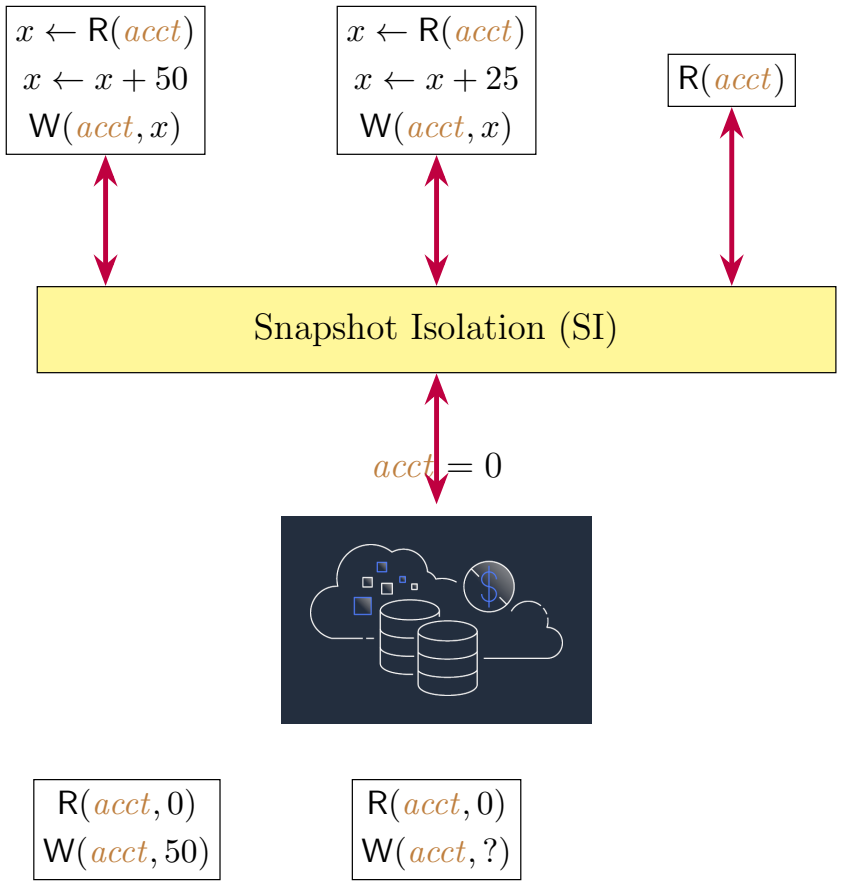

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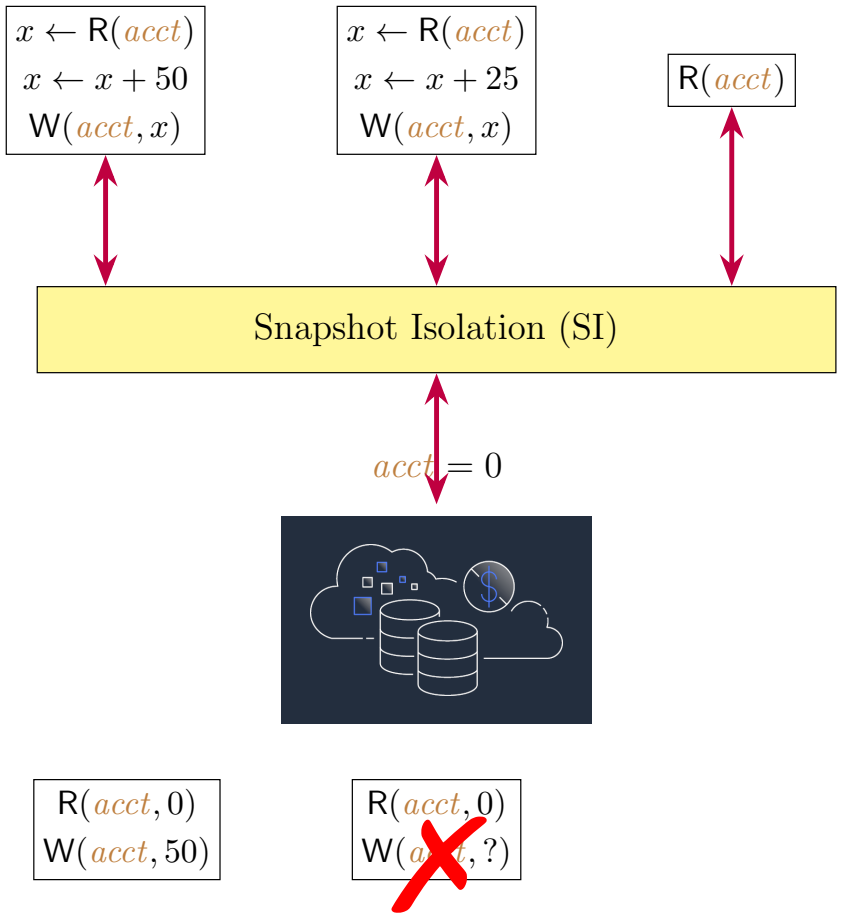

Snapshot Write: Concurrent transactions cannot write to the same key. One of them must be aborted.

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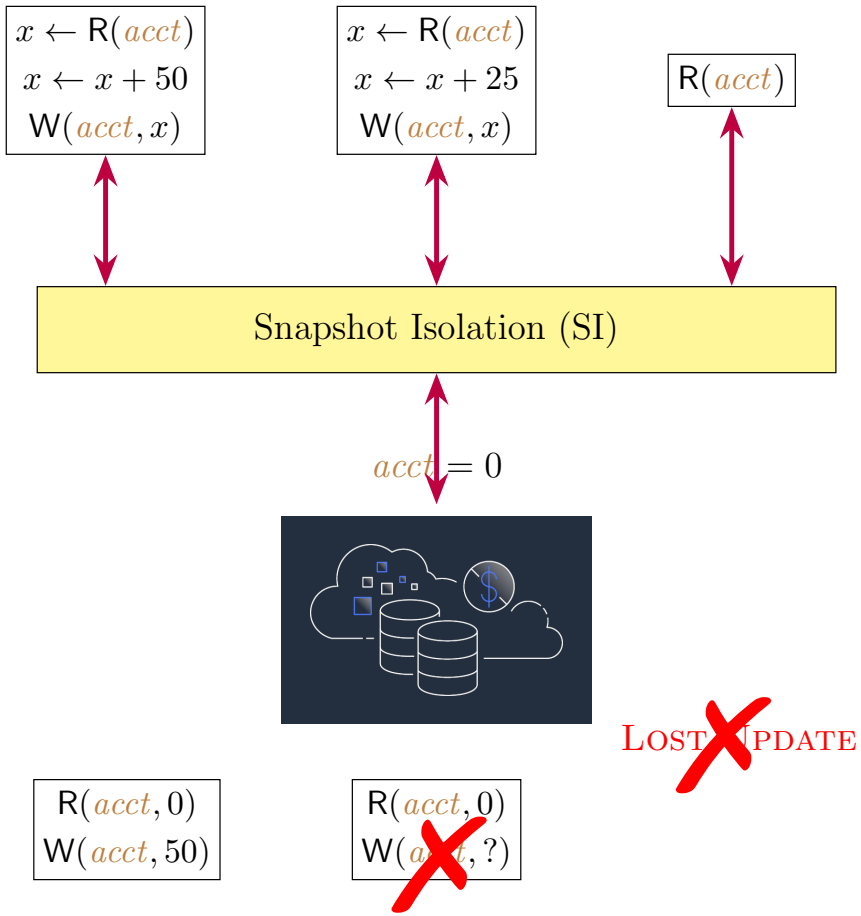

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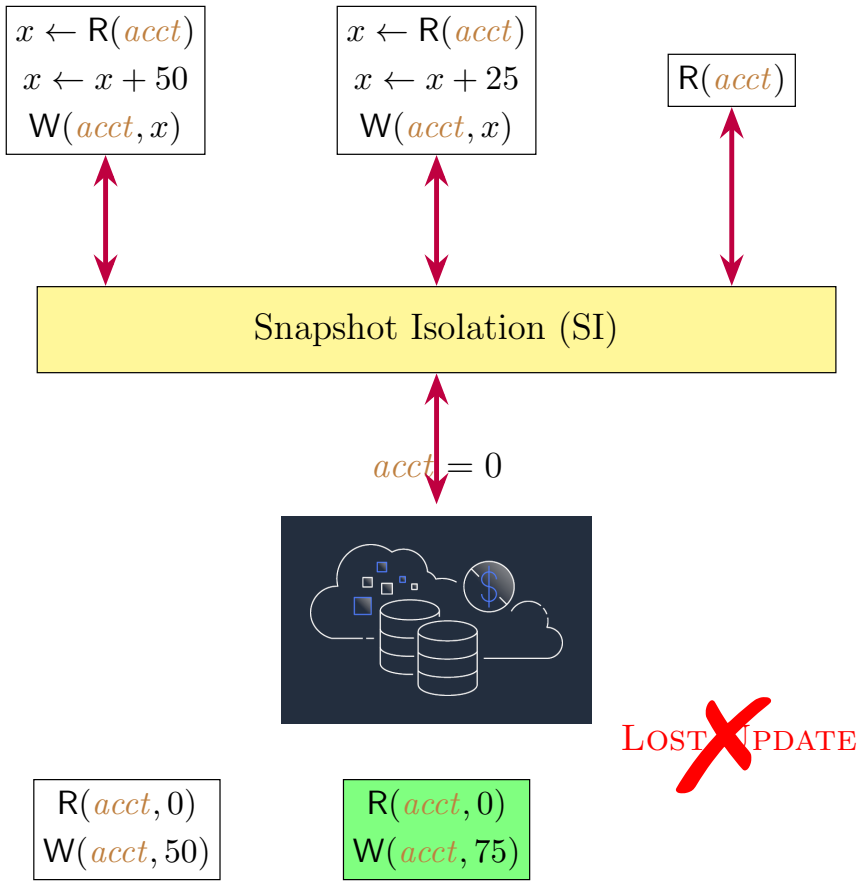

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$\mathsf{W}(x, post)$

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

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

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Causality Violation

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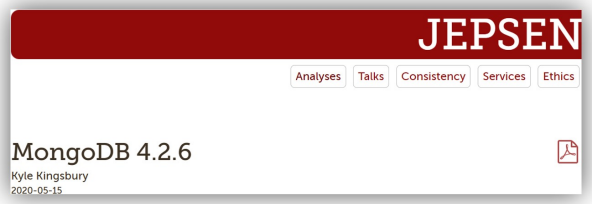
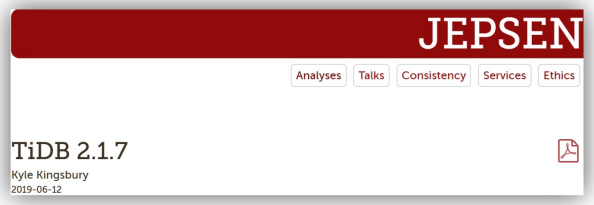
Database systems and Snapshot Isolation

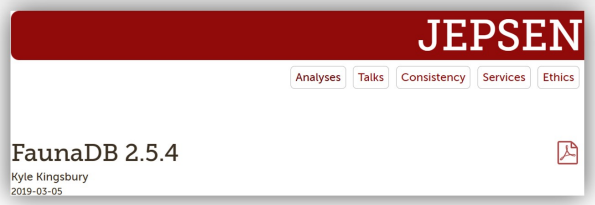
Many database systems choose to support SI.

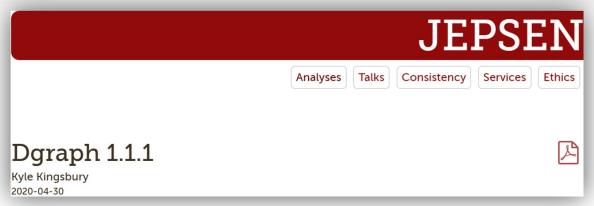
Database Systems and Snapshot Isolation

Database systems may fail to provide SI correctly as they claim.





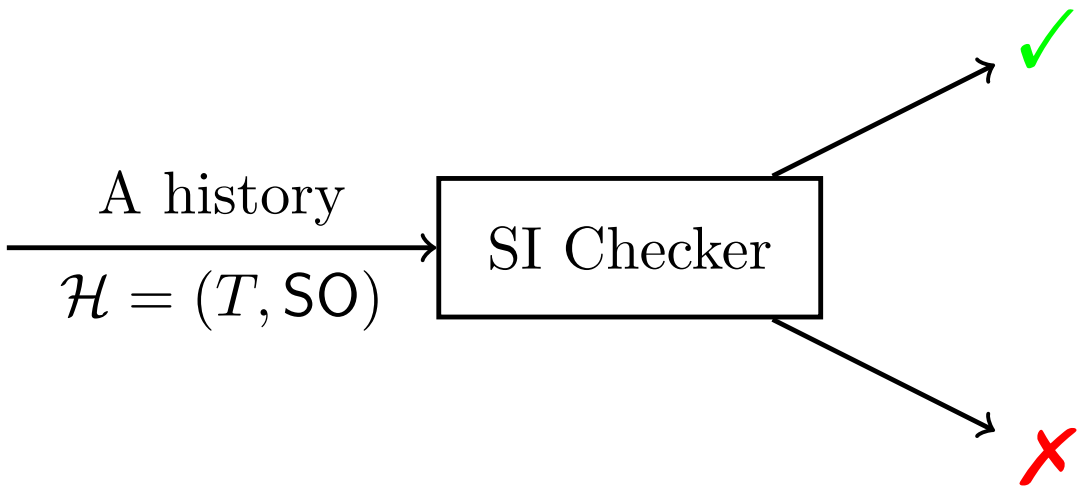




The SI Checking Problem

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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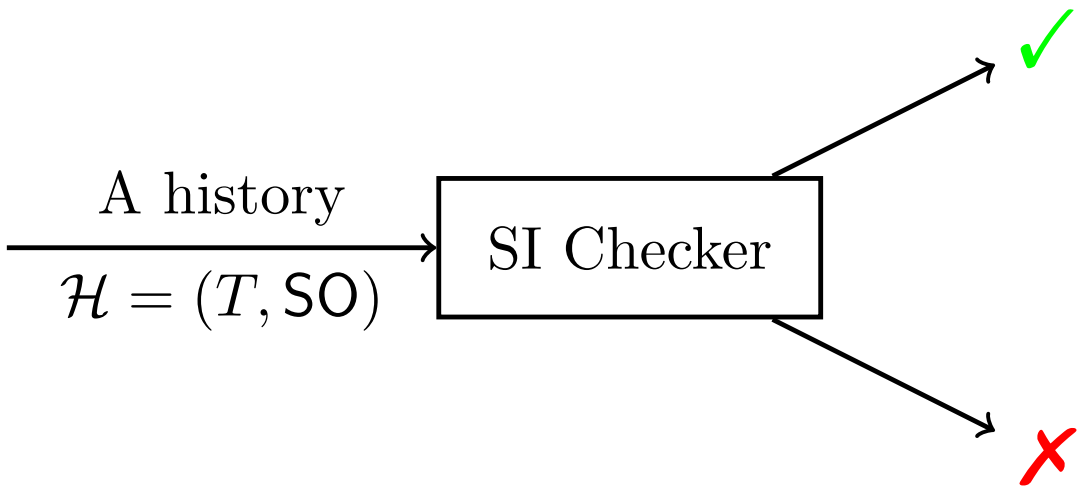
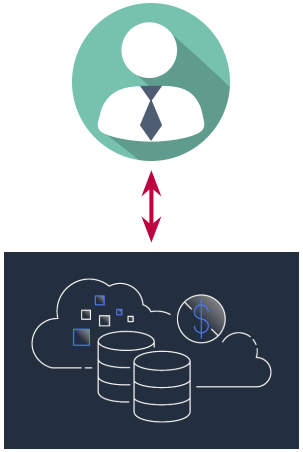


SO : *session order* among the set T of transactions

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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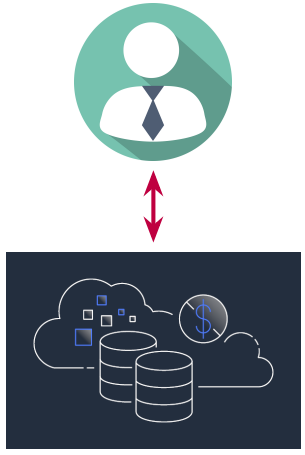

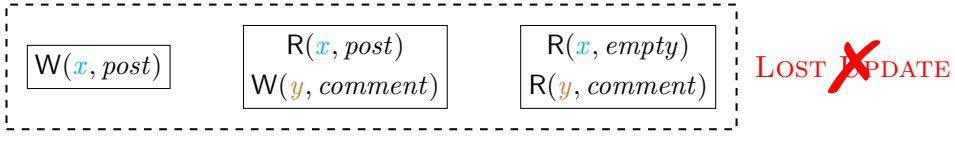

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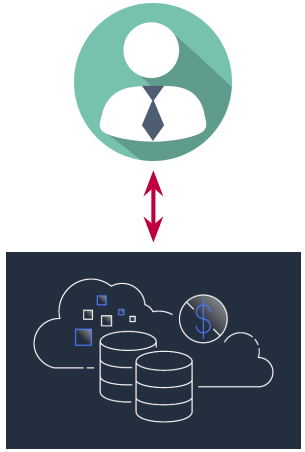

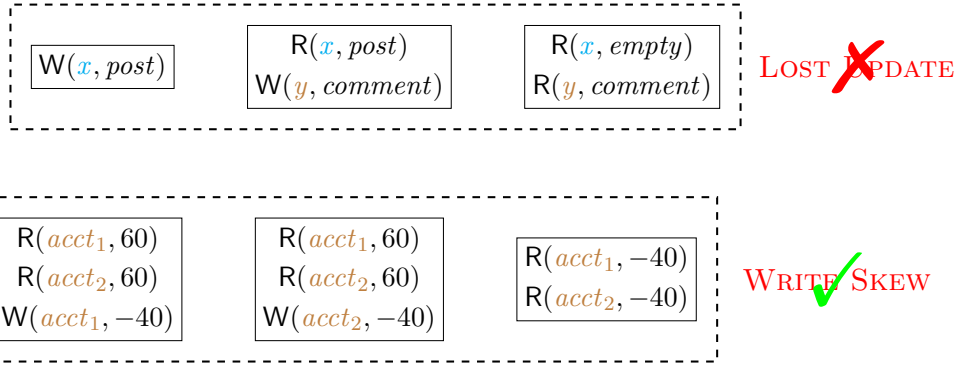

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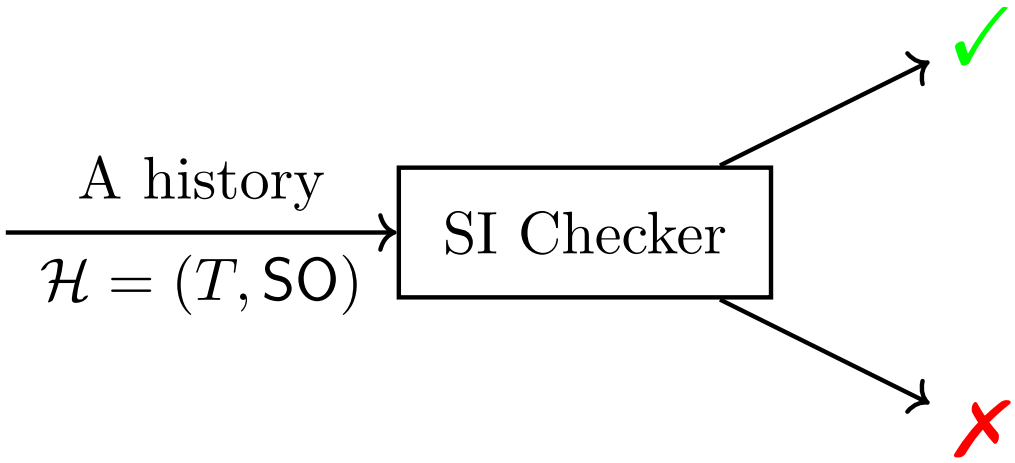

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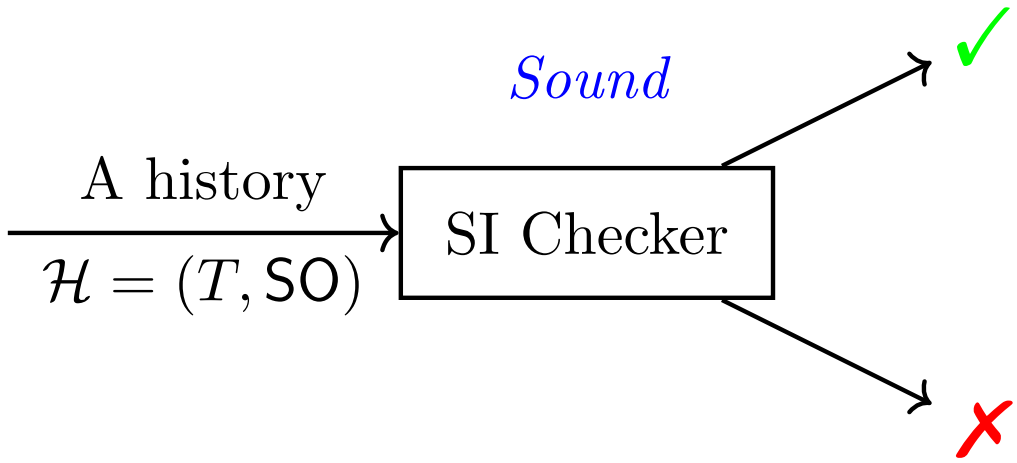

Sound: If the checker says ✗, then the history does *not* satisfy SI.

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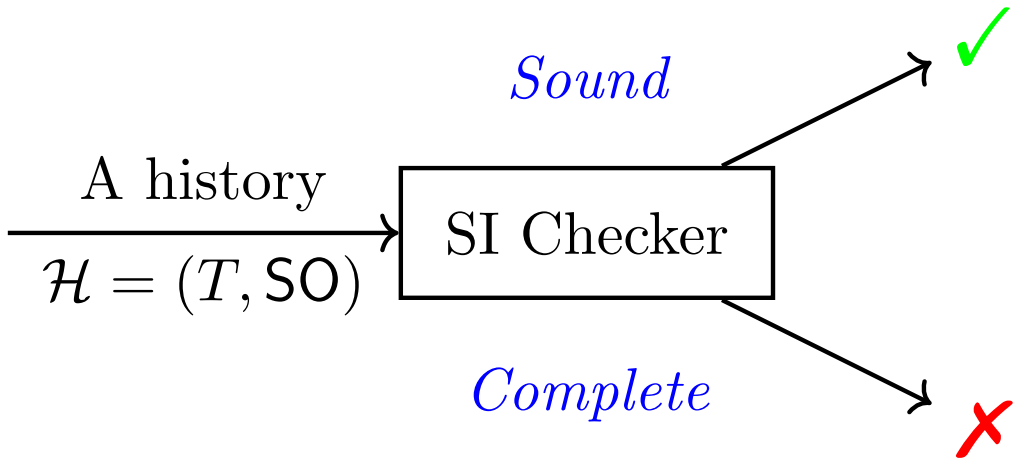

Complete: If the checker says ✓, then the history *satisfies* SI.

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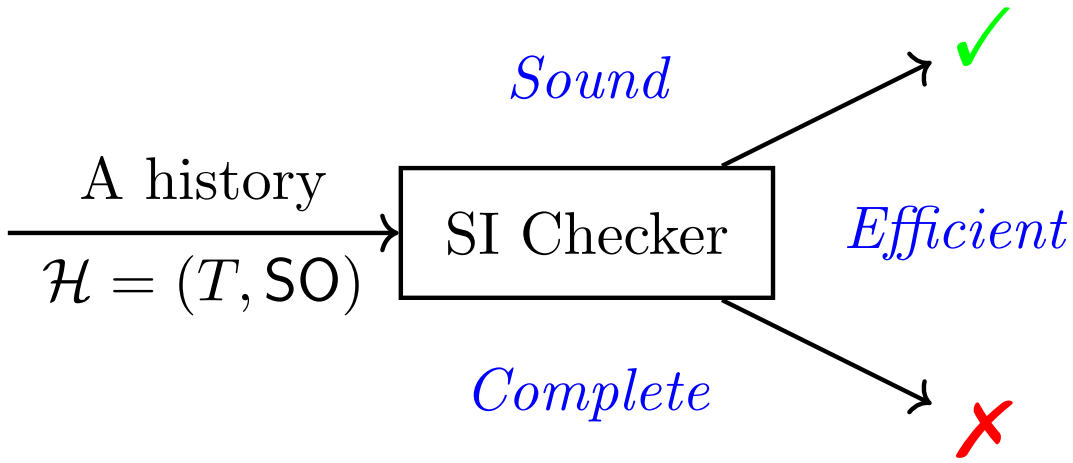
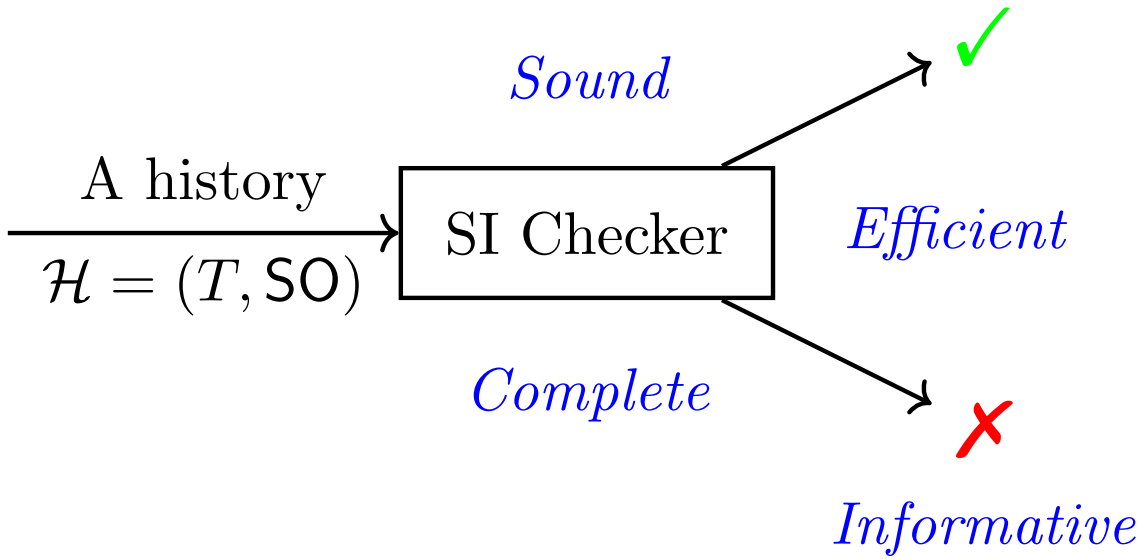


Efficient: The checker should *scale* up to large workloads.

The SI Checking Problem



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

Related Work

dbcop [Biswas and Enea, 2019] checker for SI

not practically efficient;

not informative, only "False" upon violations

[a] https://github.com/jepsen-io/elle/issues/17; Fixed now.

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Cobra [Tan et al., 2020] checker for SER

SI checking is *harder* than SER checking

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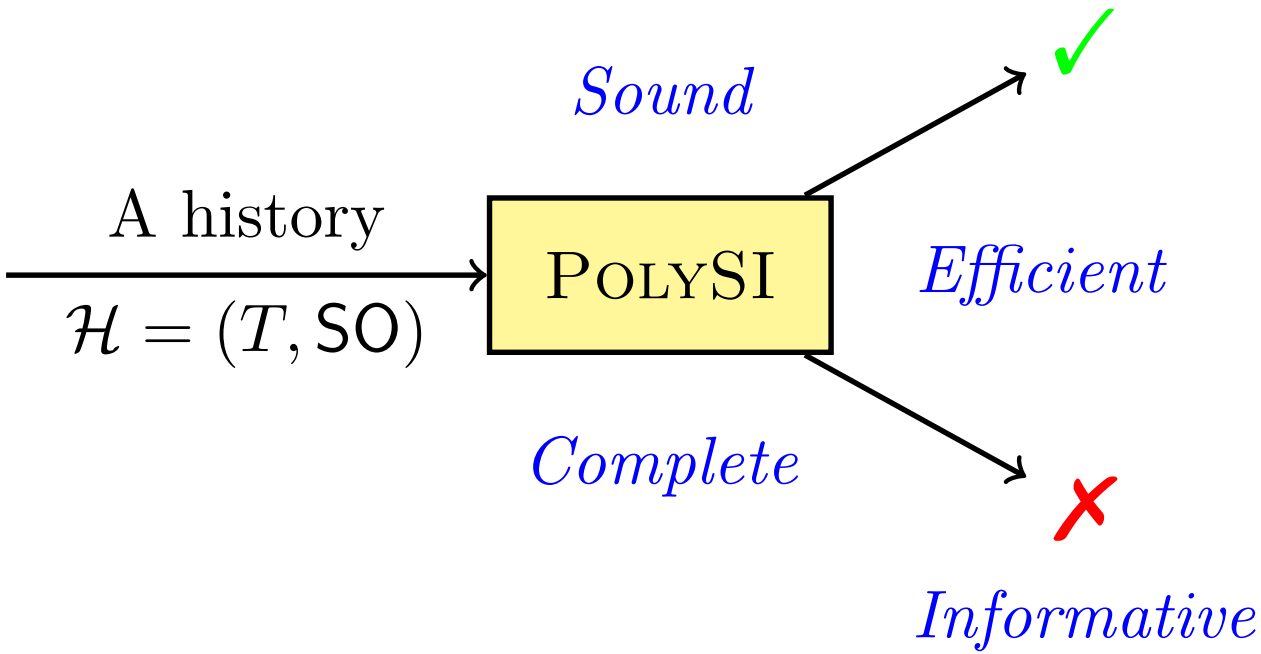
Contribution: the PolySI Checker



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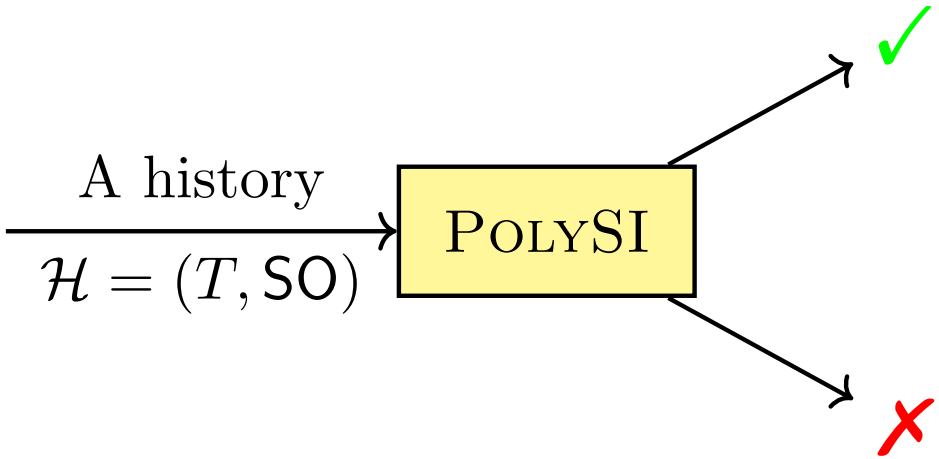

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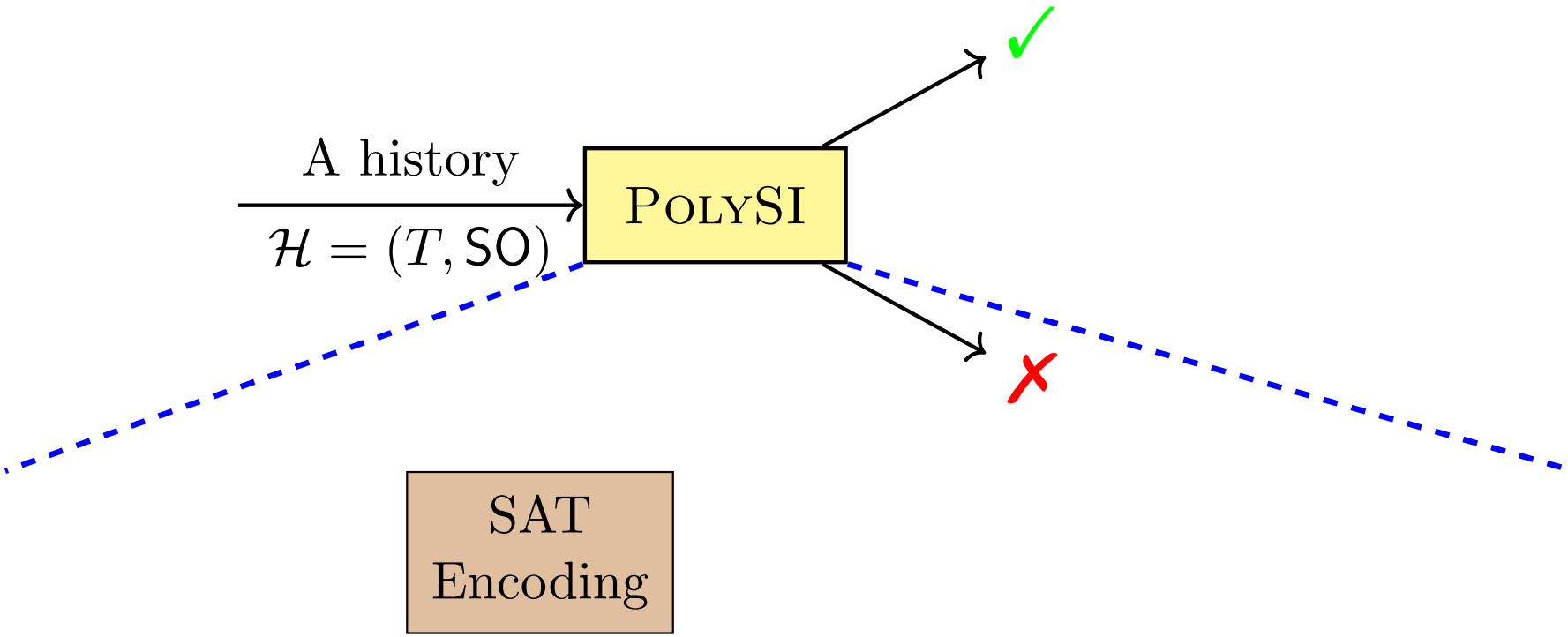
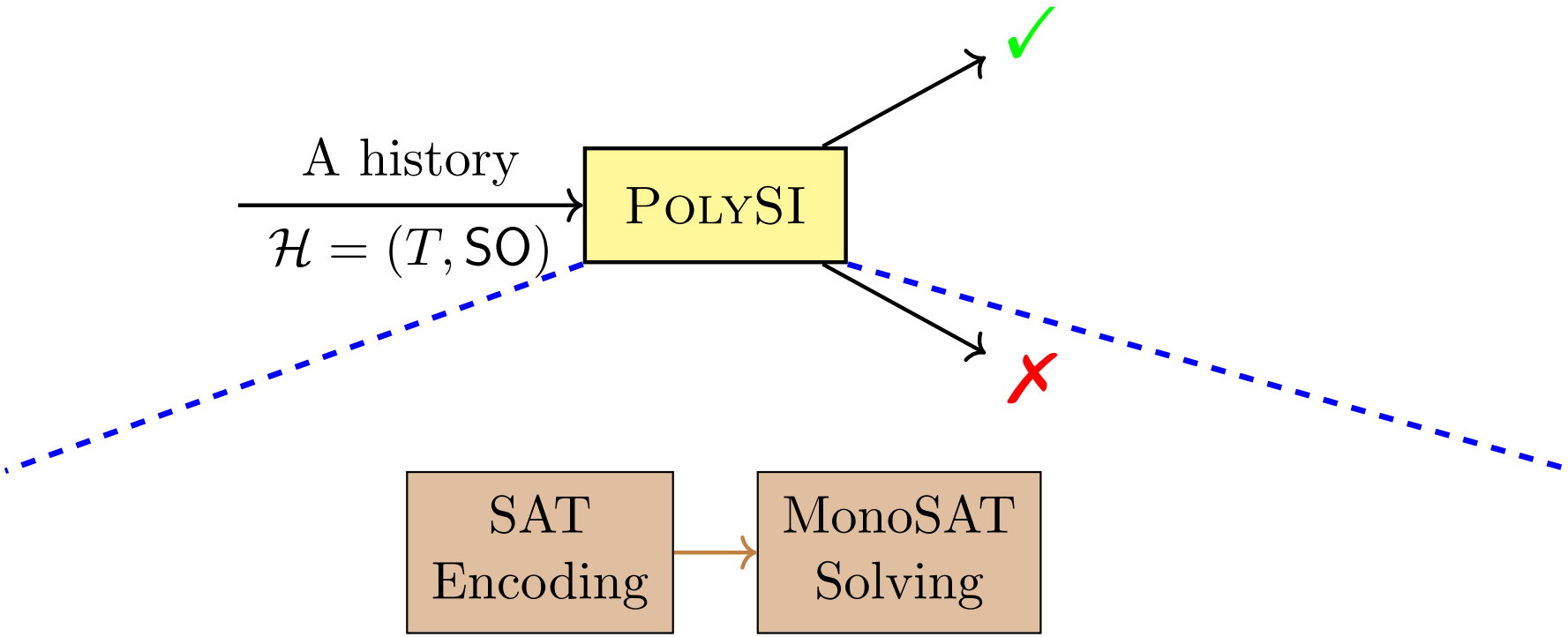


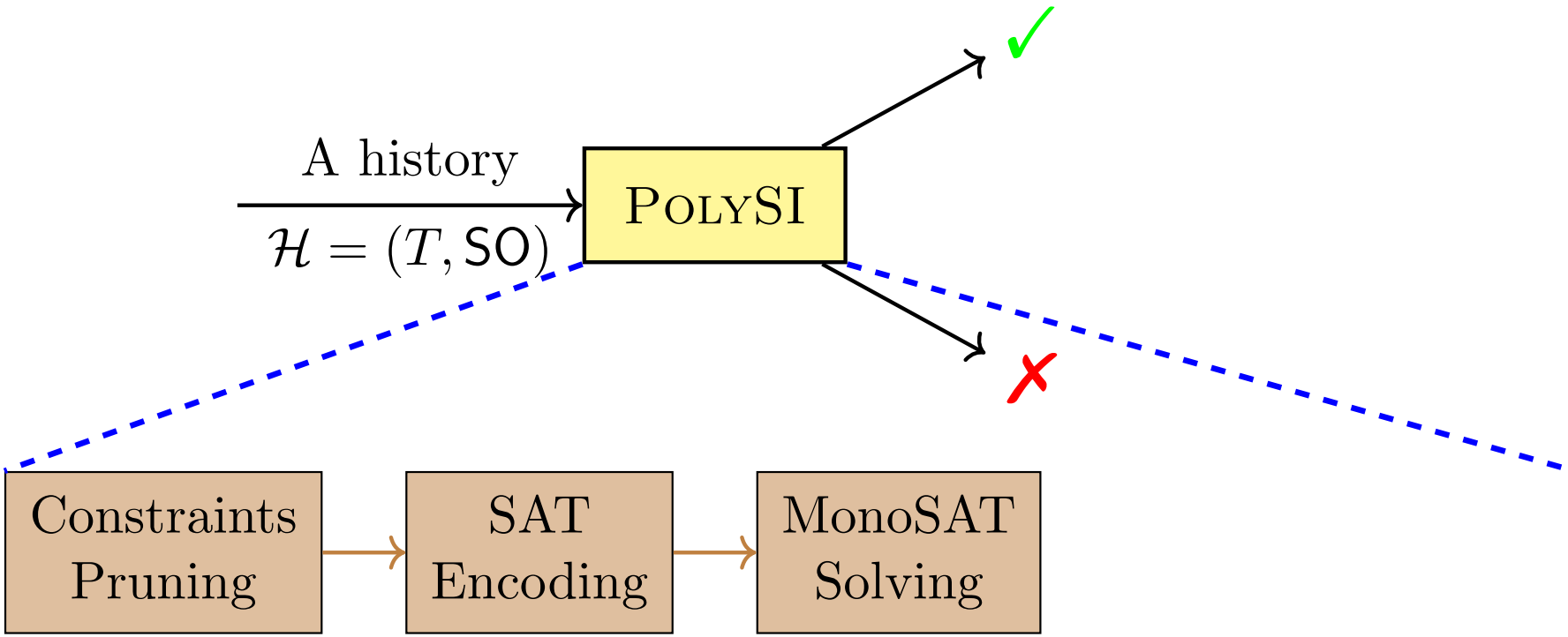
Sound & Complete: polygraph-based characterization of SI

Contribution: the PolySI Checker



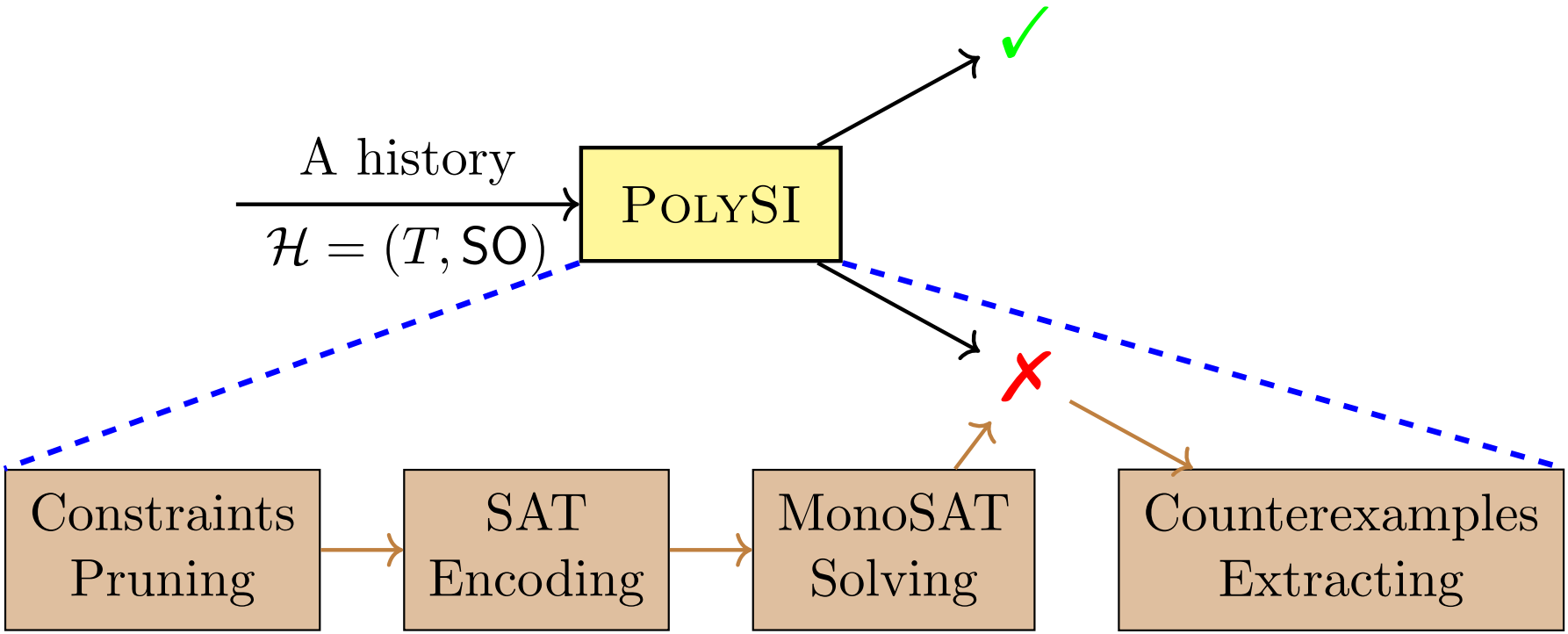
Efficient: utilizing MonoSAT solver optimized for graph problems

Contribution: the PolySI Checker



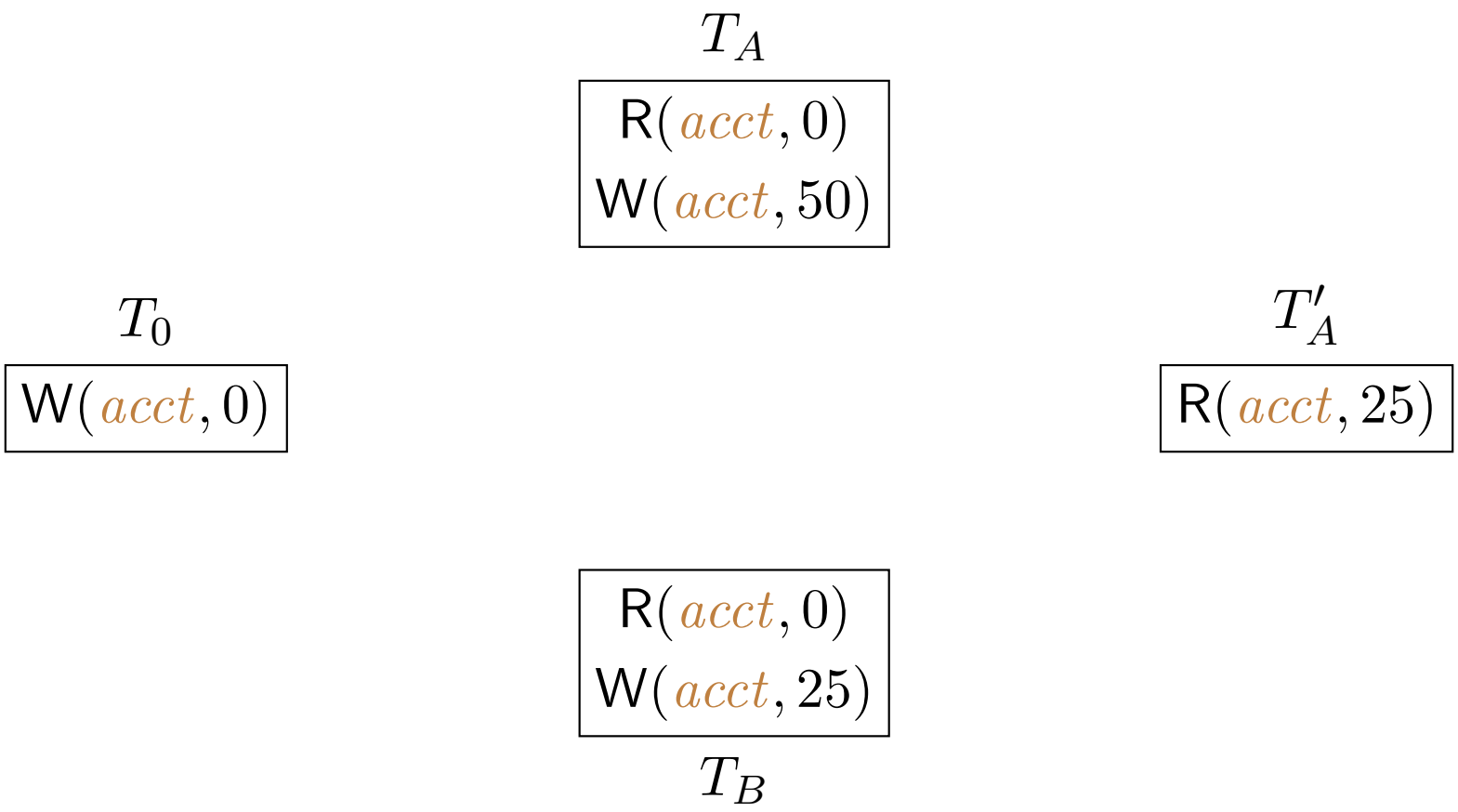
Efficient: domain-specific pruning before encoding

Contribution: the PolySI Checker



Informative: extract counterexamples from the unsatisifiable core

Dependency Graph-based Characterization of SI



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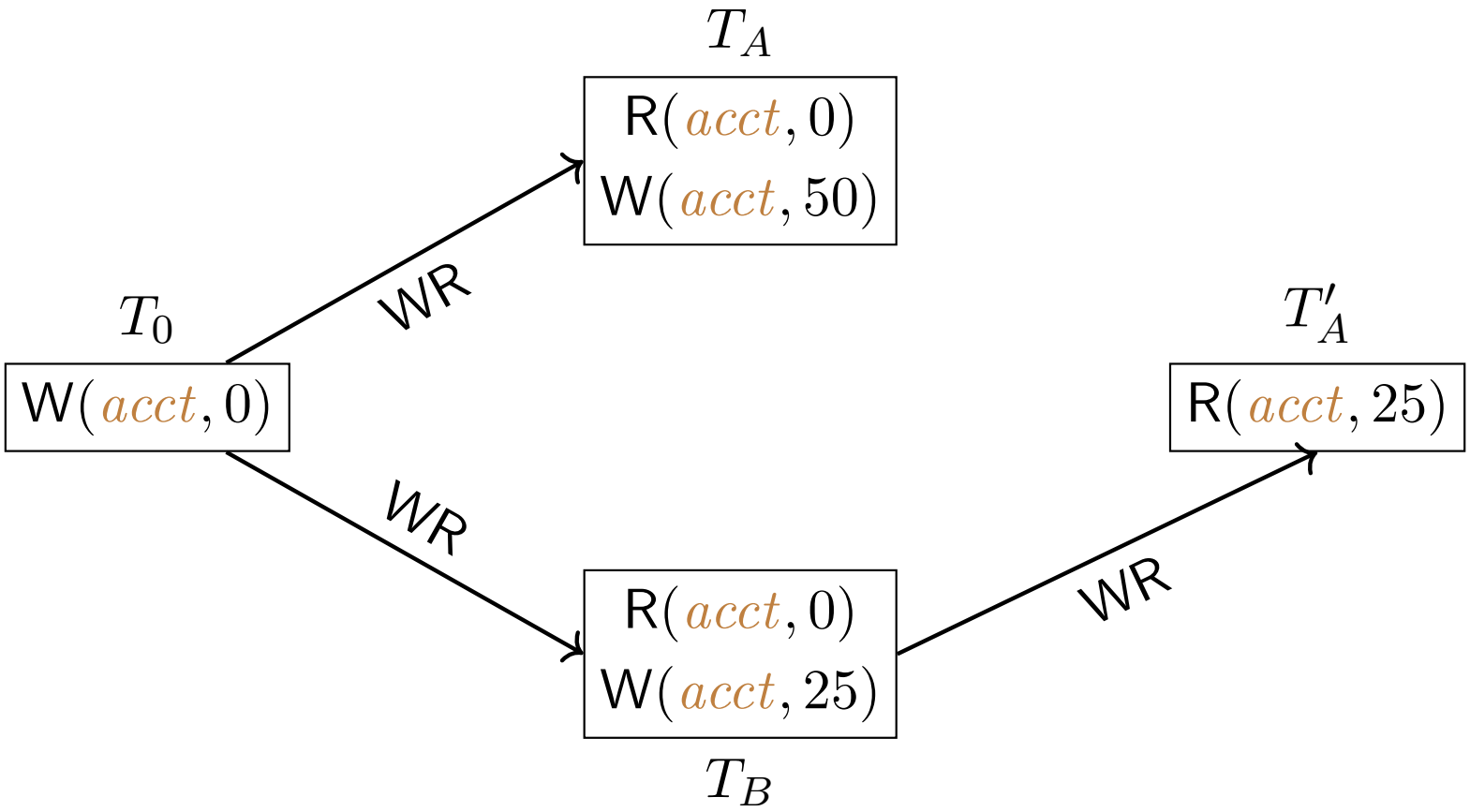
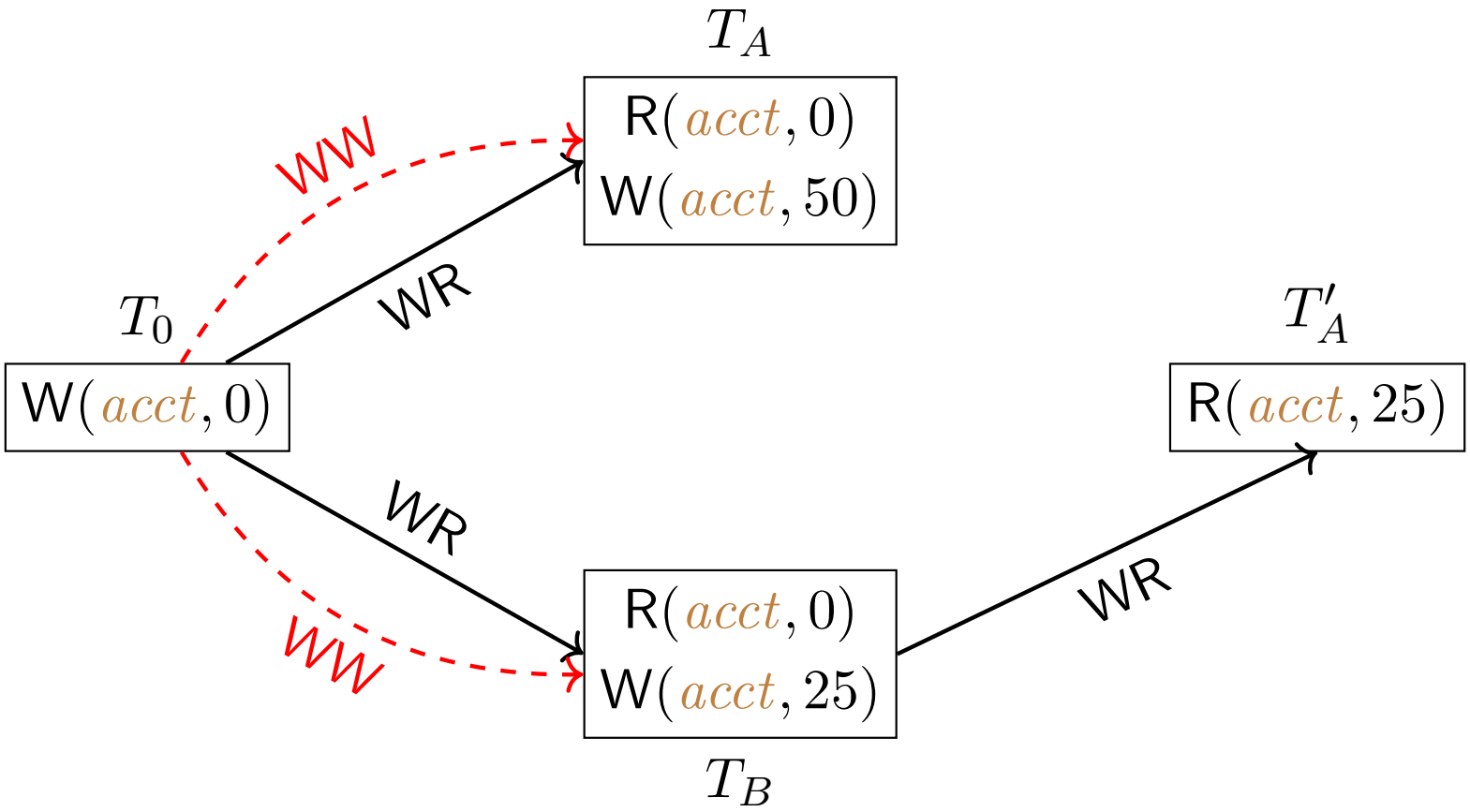


WR: "write-read" dependency capturing the "read-from" relation

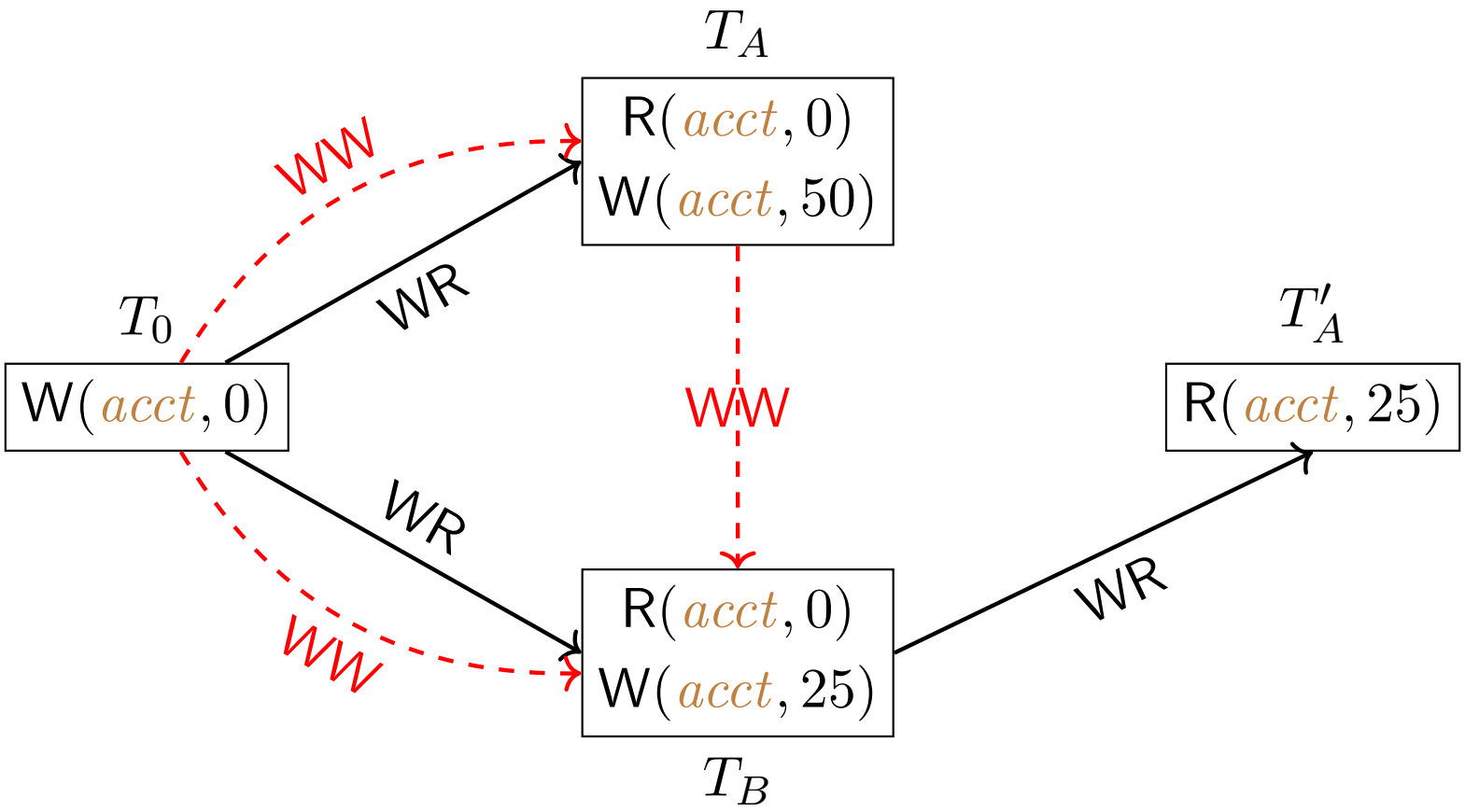
Dependency Graph-based Characterization of SI



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

Dependency Graph-based Characterization of SI

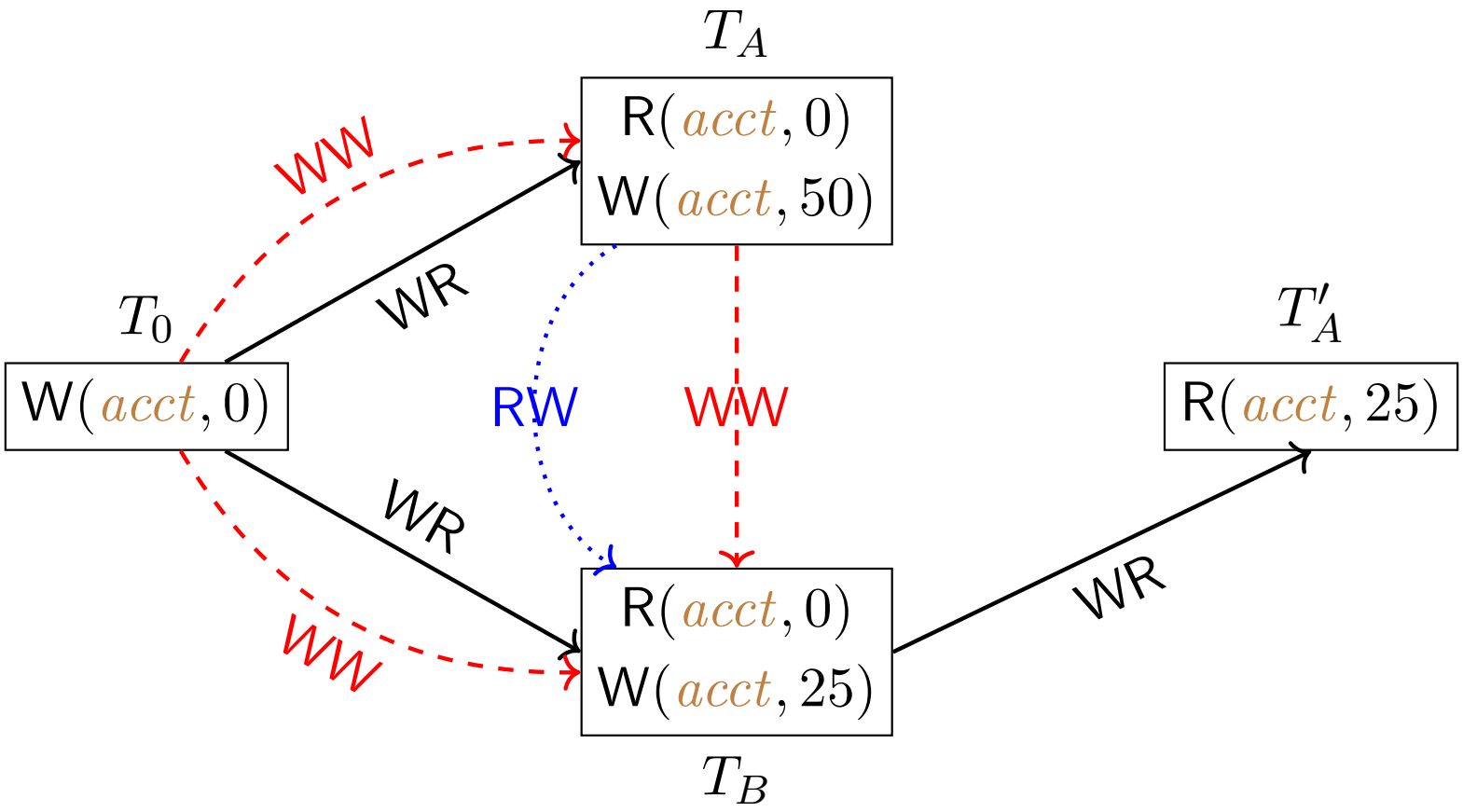
Suppose that $T_A \xrightarrow{\mathsf{WW}} T_B$



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

Dependency Graph-based Characterization of SI

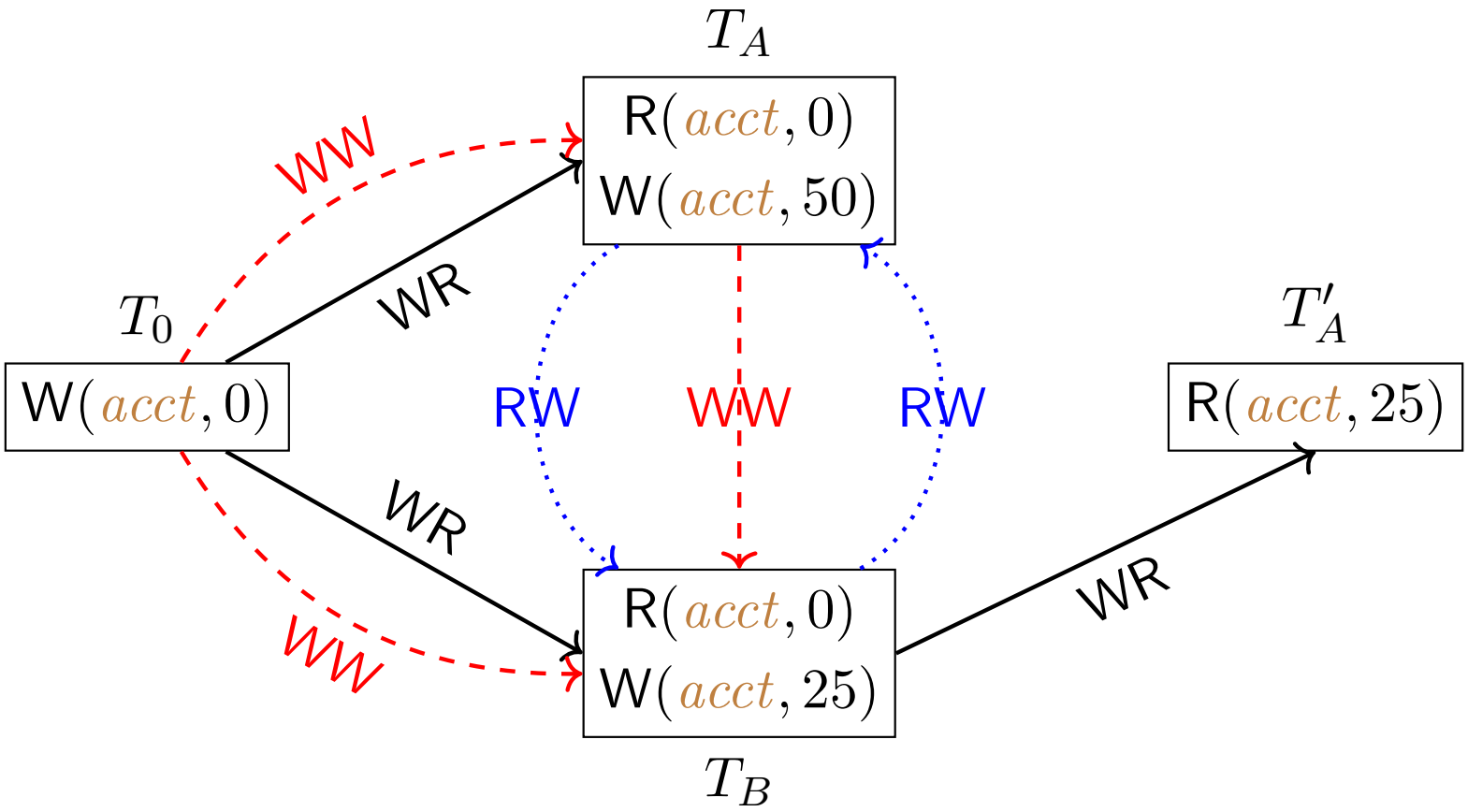
$$T_0 \xrightarrow{\mathsf{WR}} T_A \wedge T_0 \xrightarrow{\mathsf{WW}} T_B \implies T_A \xrightarrow{\mathsf{RW}} T_B$$



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

Dependency Graph-based Characterization of SI

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



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

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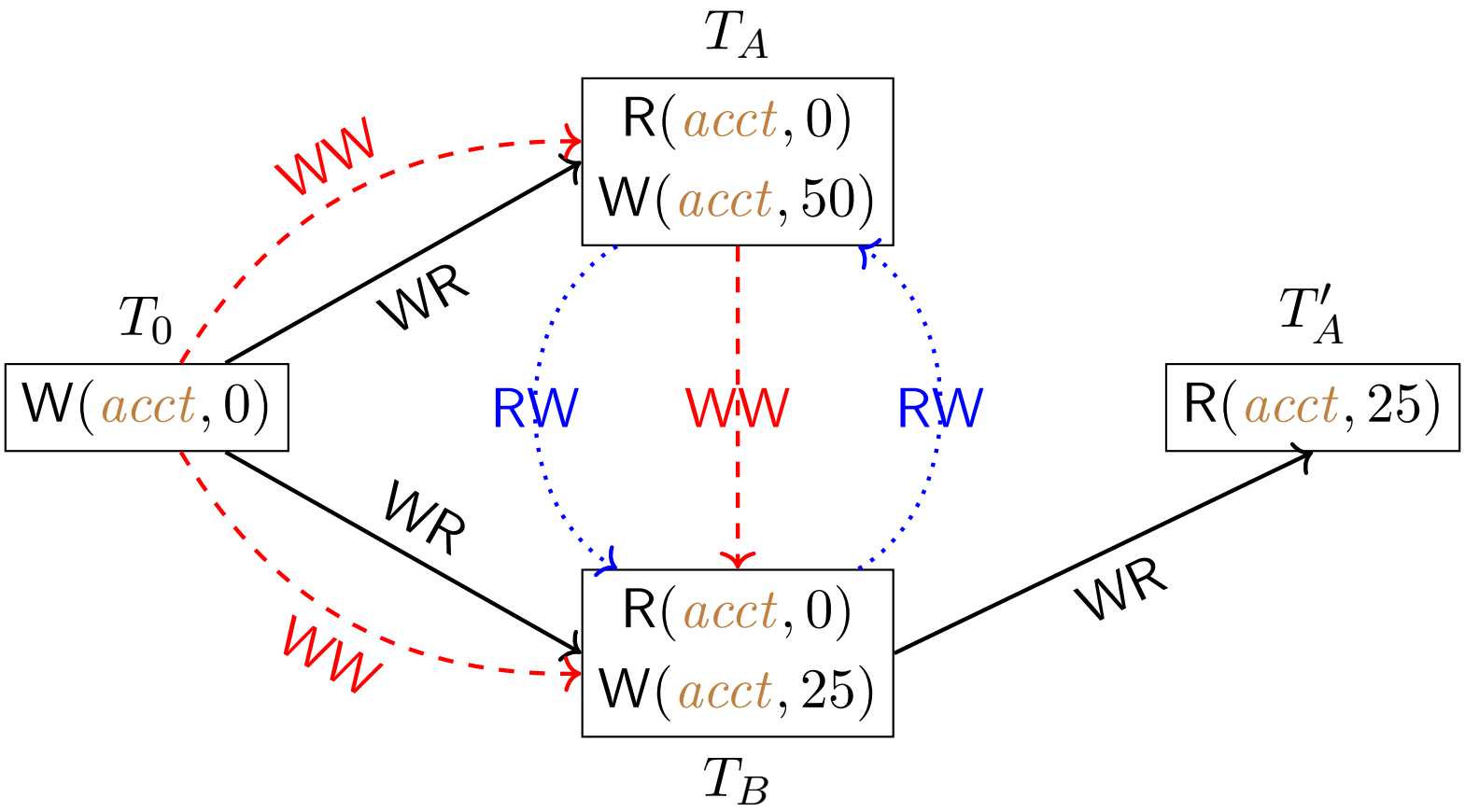
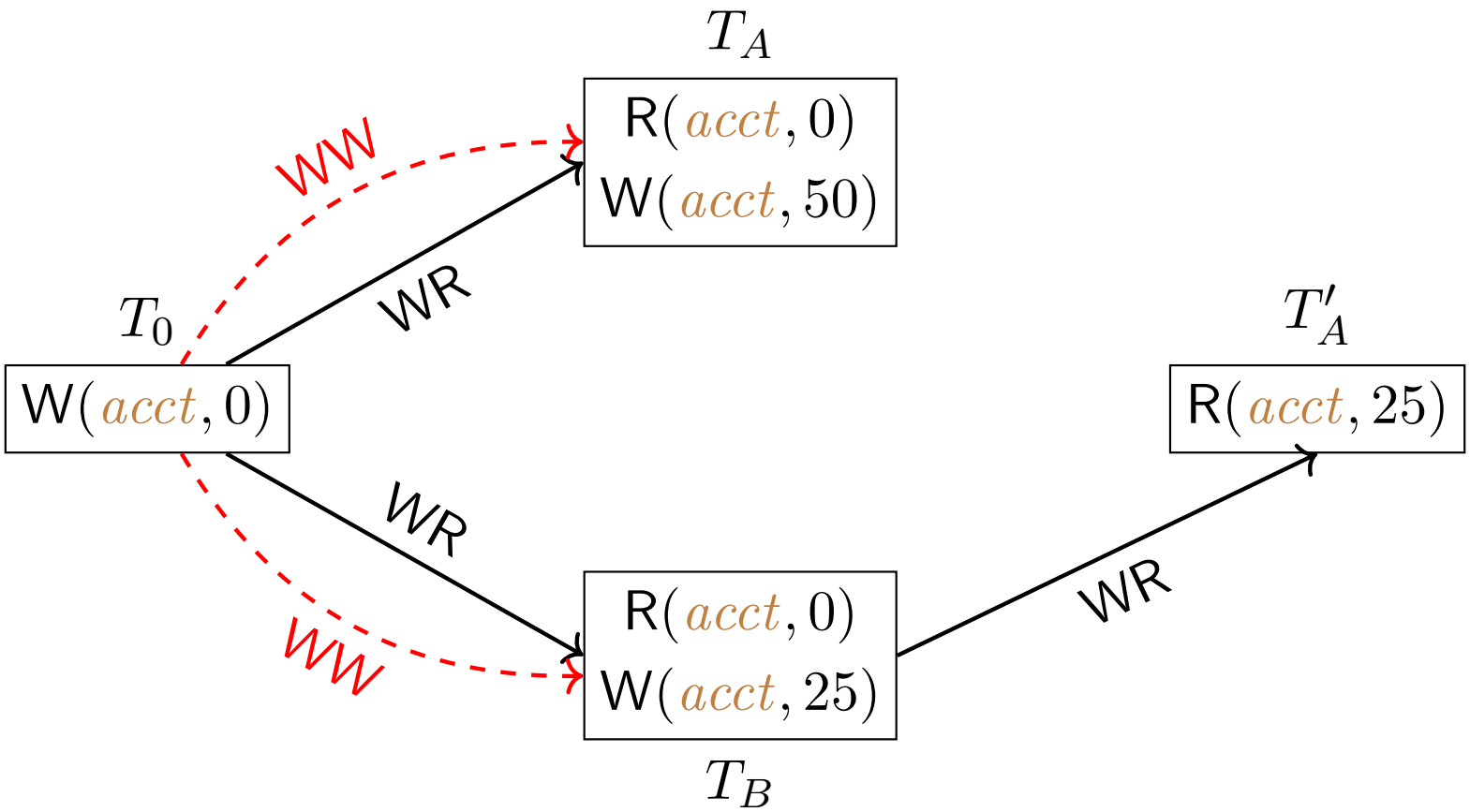


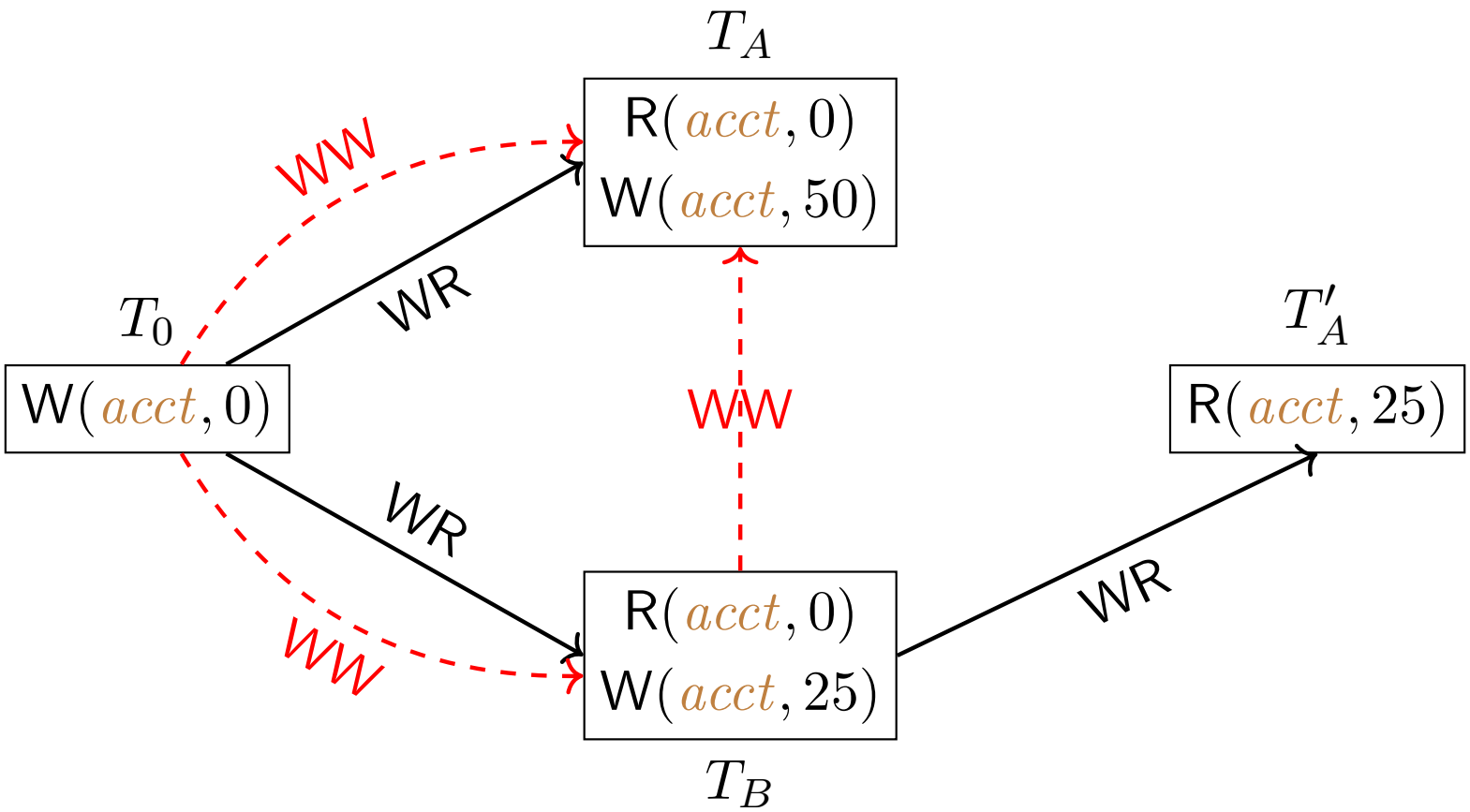
undesired cycle: $T_A \xrightarrow{\mathsf{WW}} T_B \xrightarrow{\mathsf{RW}} T_A$

Dependency Graph-based Characterization of SI



Dependency Graph-based Characterization of SI

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



Dependency Graph-based Characterization of SI

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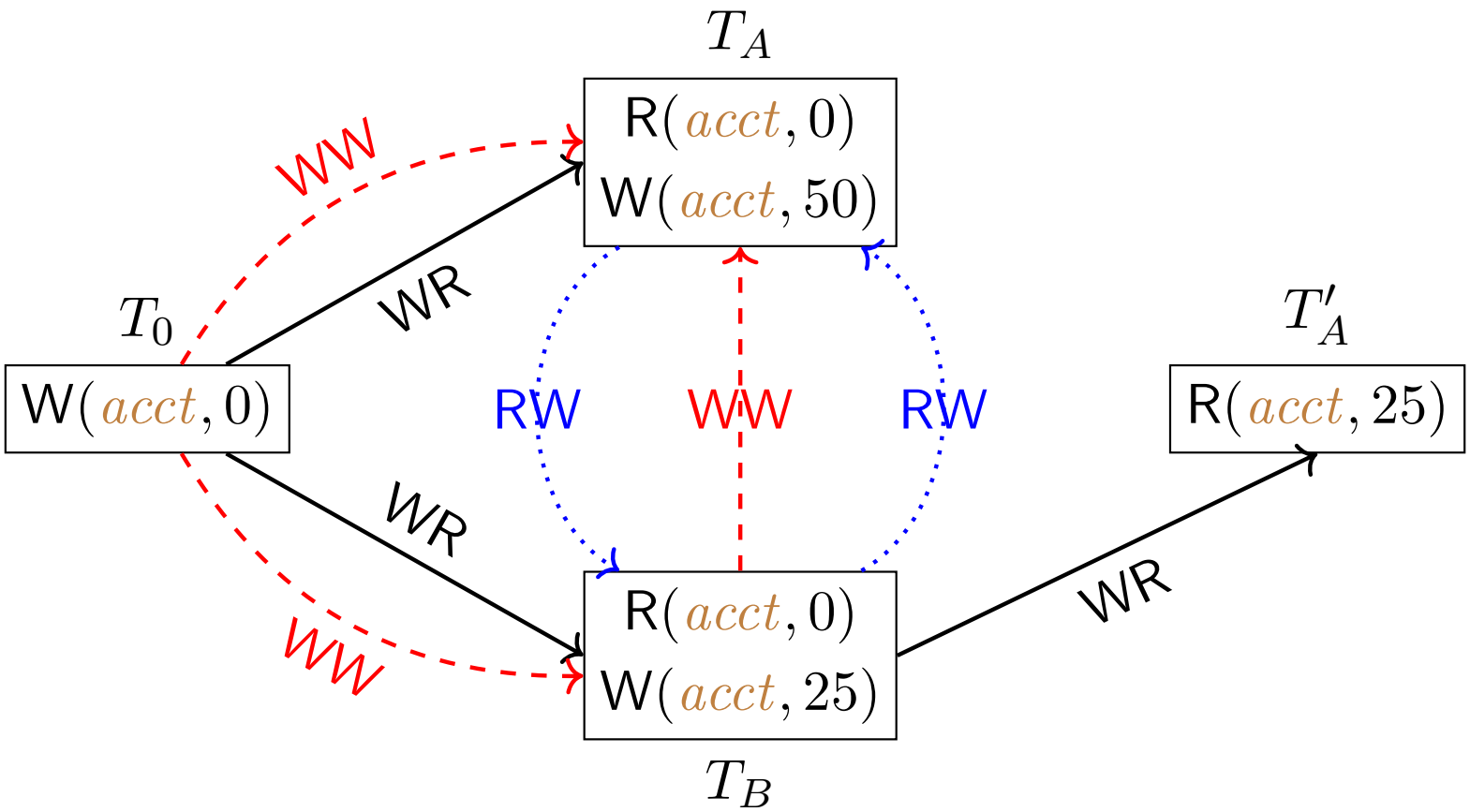

Dependency Graph-based Characterization of SI

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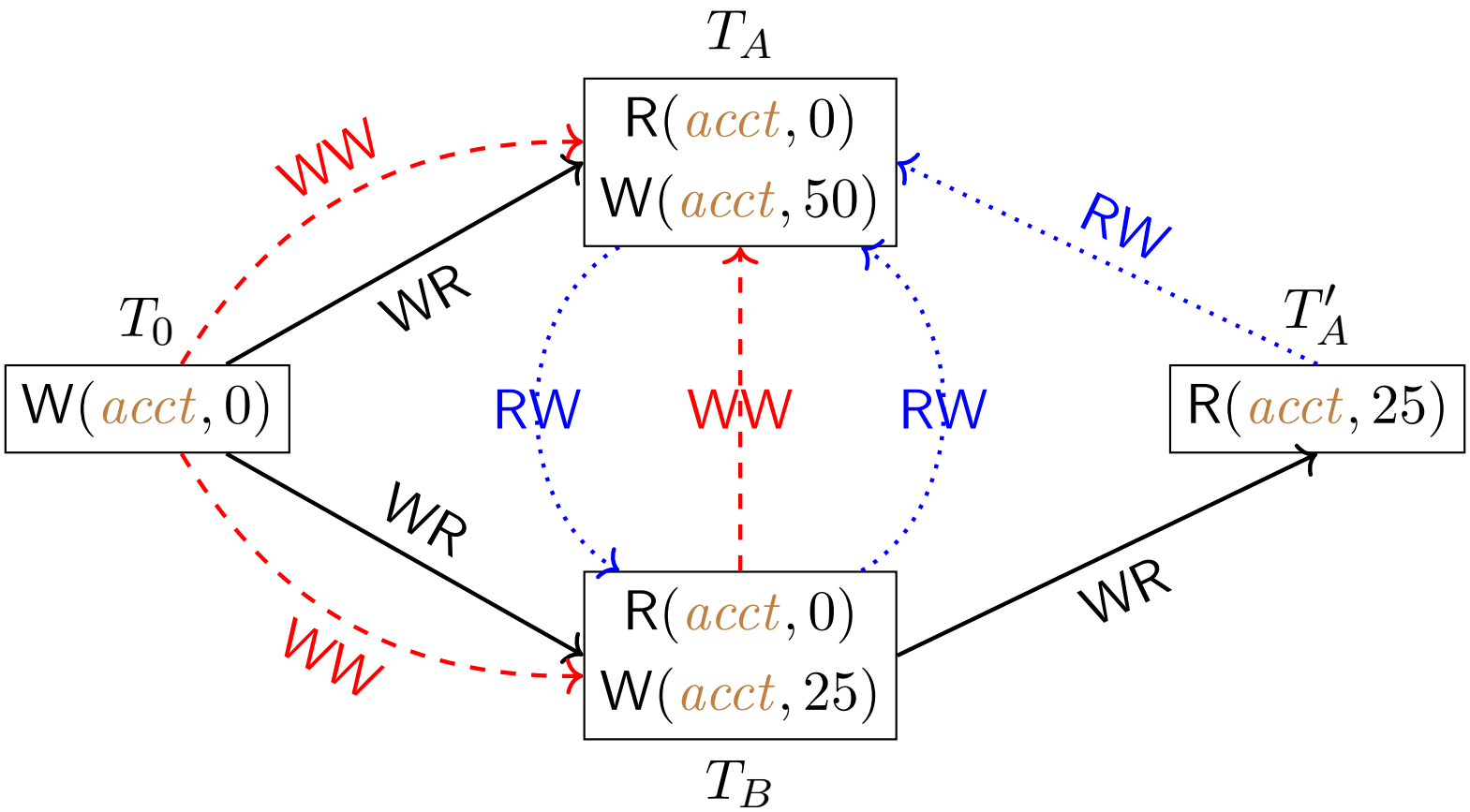
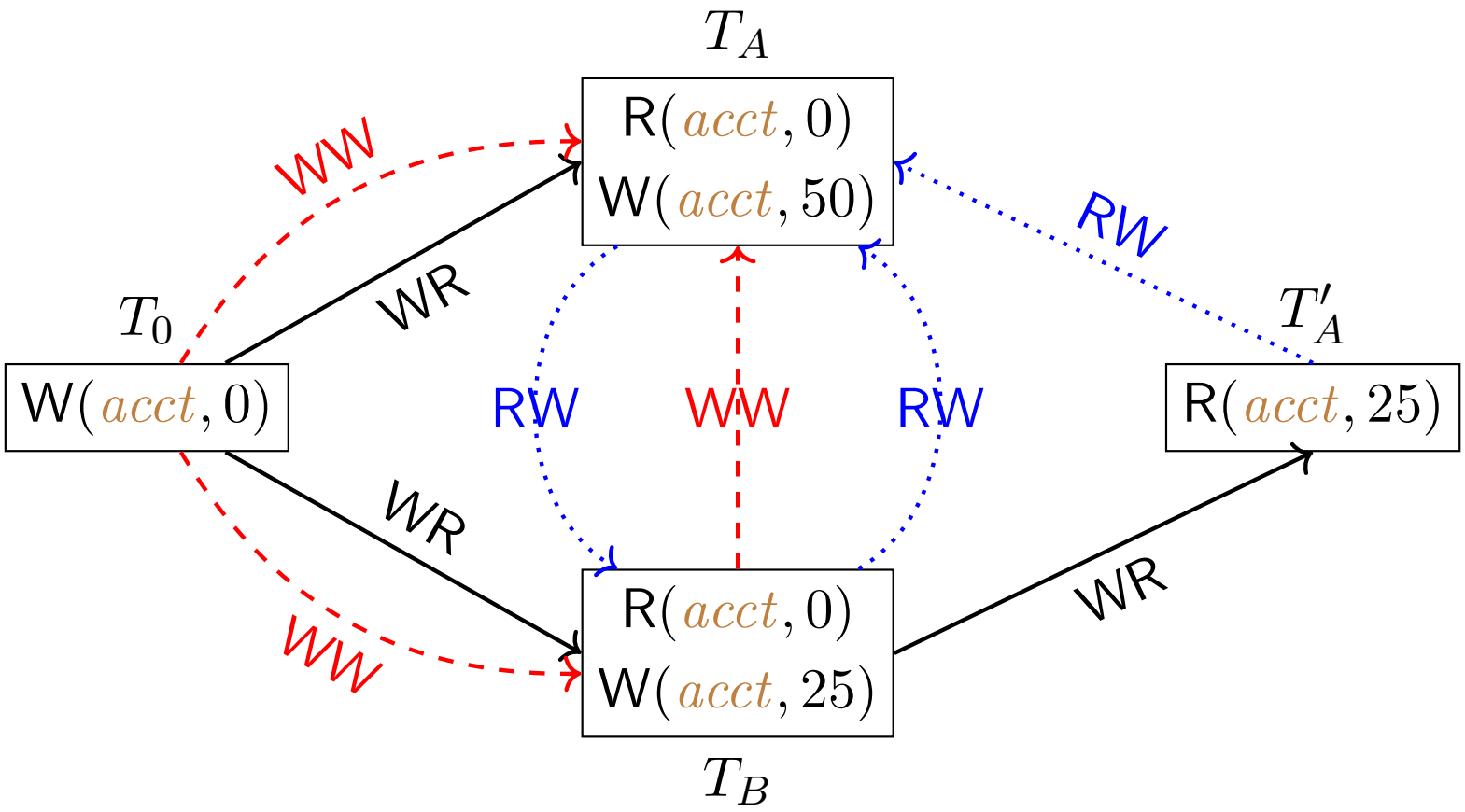


Dependency Graph-based Characterization of SI

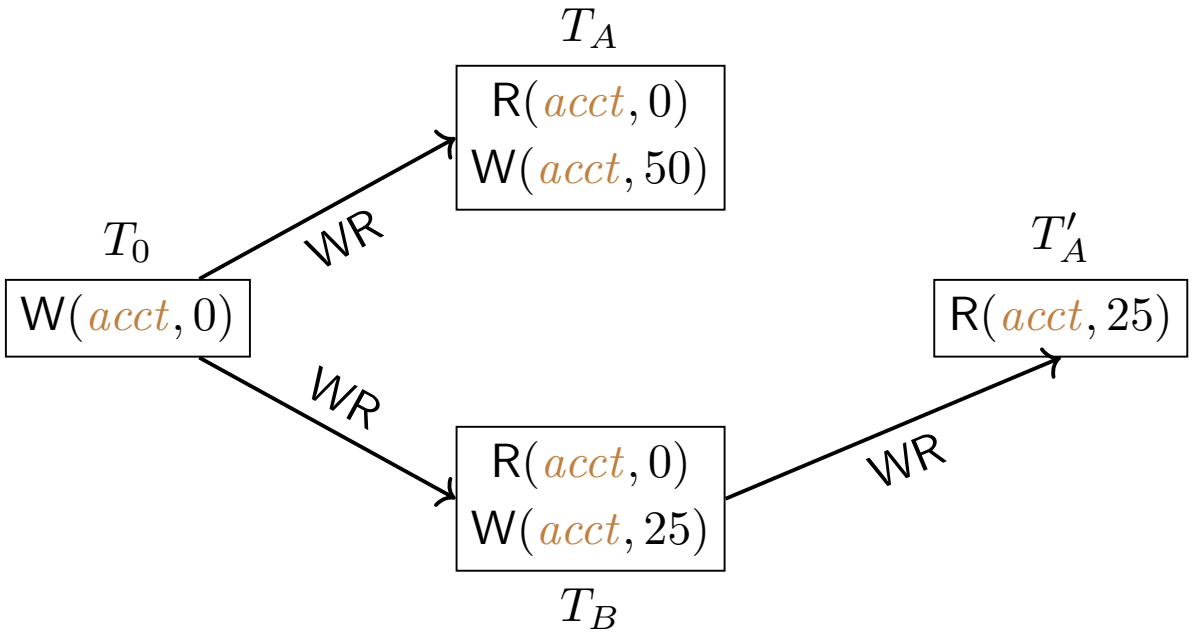
Suppose that $T_B \xrightarrow{\text{WW}} T_A$



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.

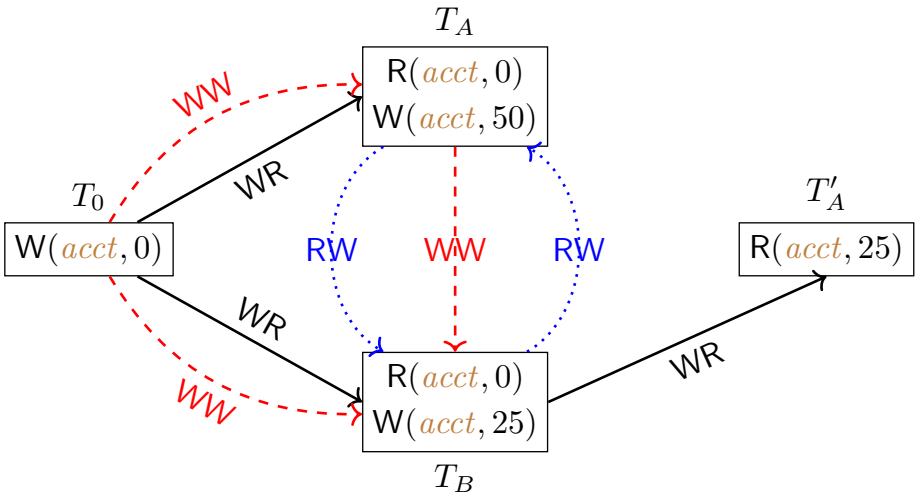
Therefore, it does not satisfy SI.

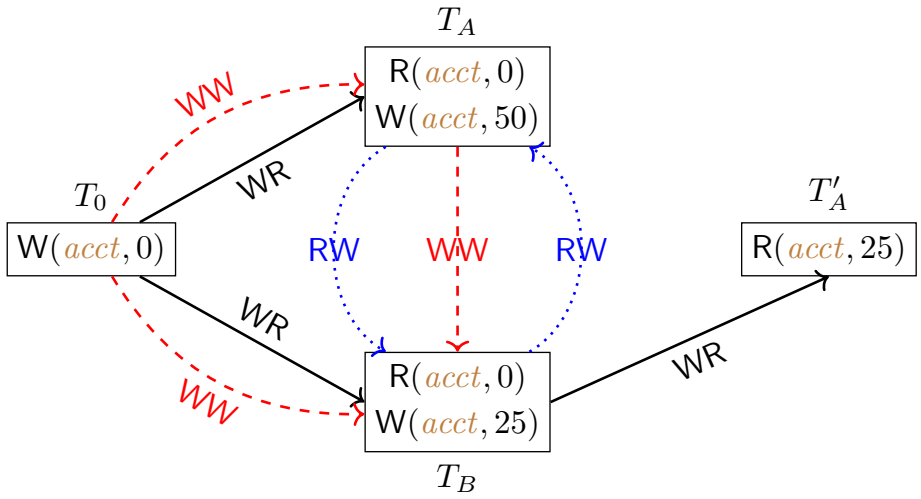
Dependency Graph-based Characterization of SI

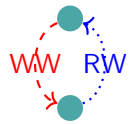
Theorem (Theorem 4.1 of [Cerone and Gotsman, 2018])

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 

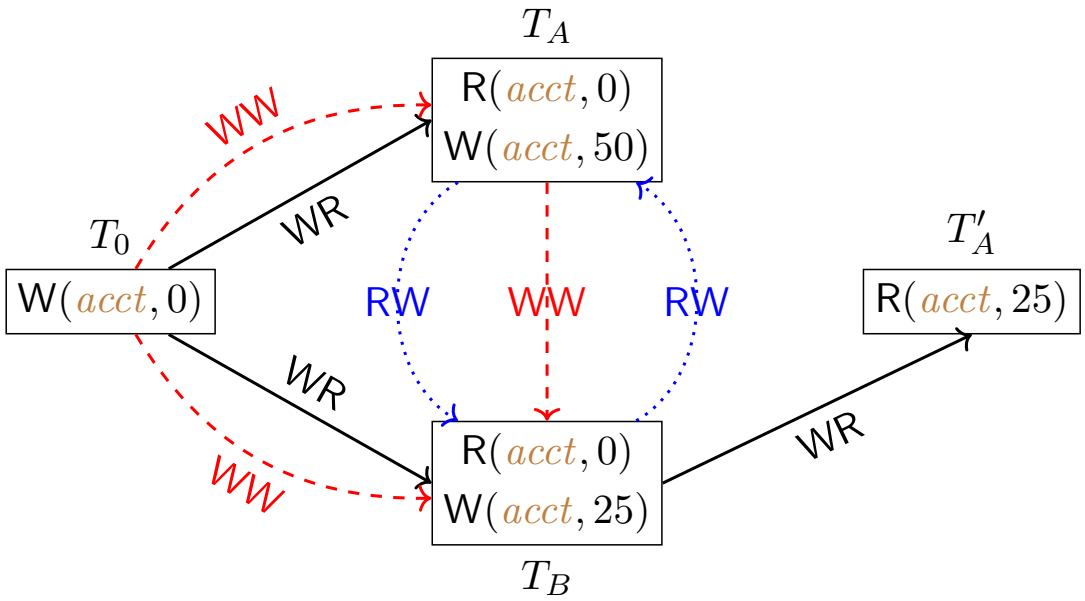
cycle.

Dependency Graph-based Characterization of SI

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

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

$$\mathcal{H} \models \text{SI} \iff \mathcal{H} \models \textsc{Int} \wedge$$
$$\exists\, \mathsf{WR}, \mathsf{WW}, \mathsf{RW}.\ \mathcal{G} = (\mathcal{H}, \mathsf{WR}, \mathsf{WW}, \mathsf{RW}) \wedge$$
$$(((\mathsf{SO}_{\mathcal{G}} \cup \mathsf{WR}_{\mathcal{G}} \cup \mathsf{WW}_{\mathcal{G}})\ ;\ \mathsf{RW}_{\mathcal{G}}?) \ \ \textit{is acyclic}).$$



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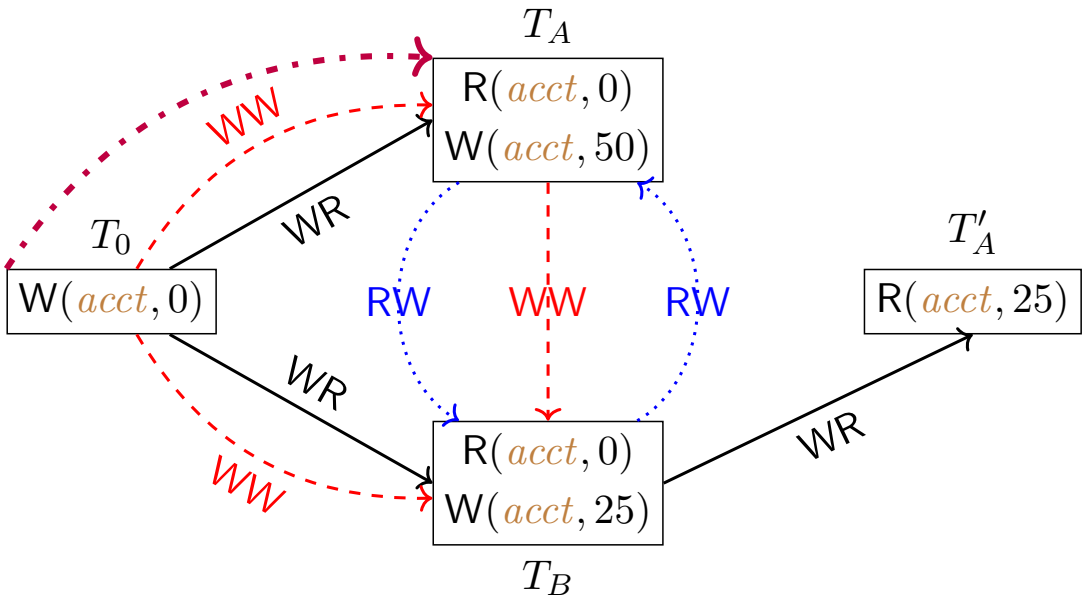

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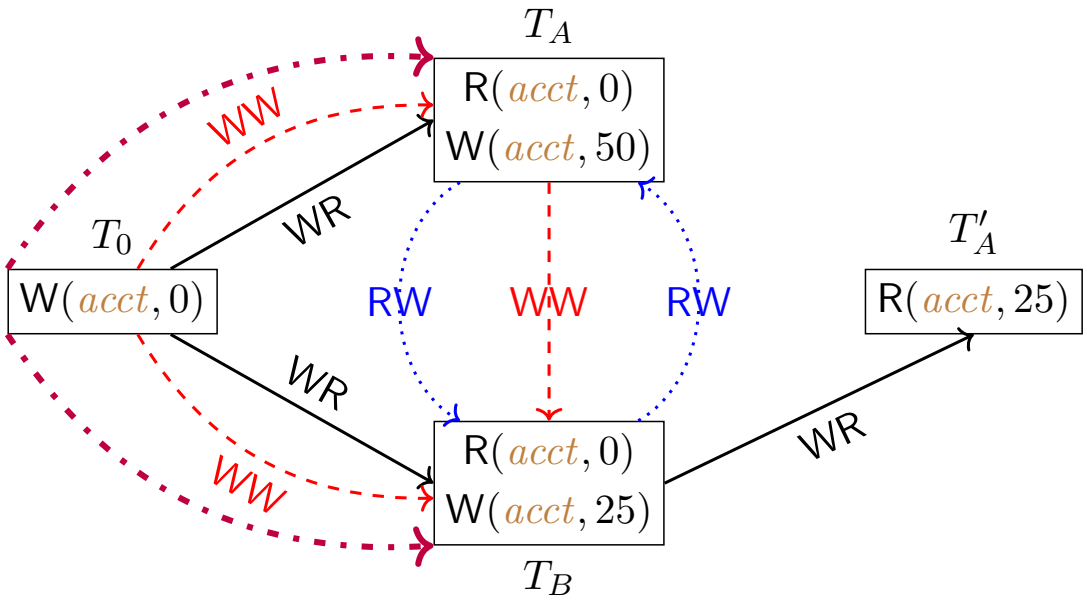

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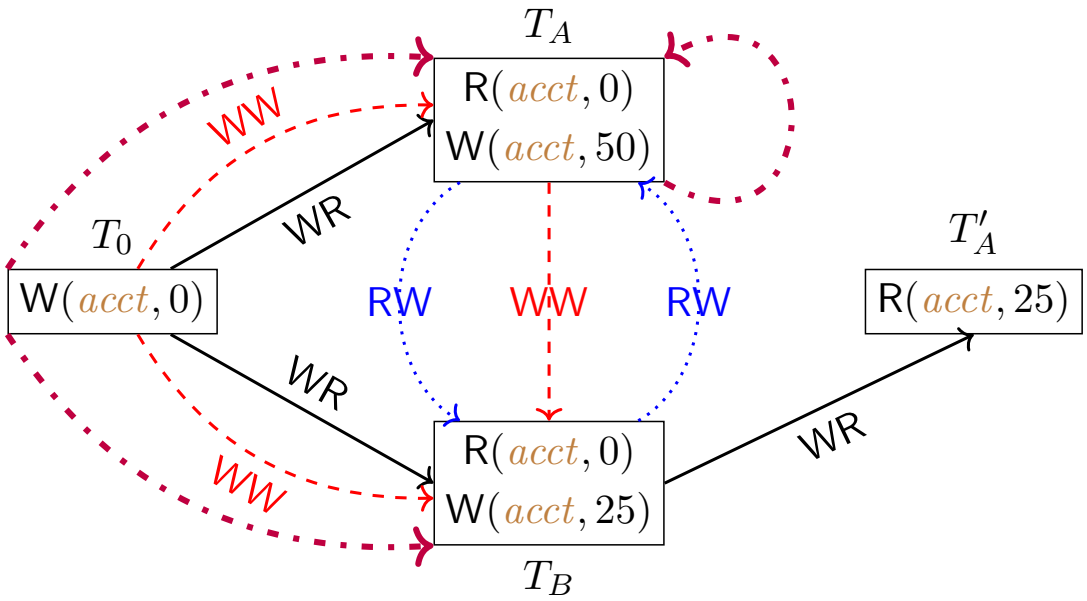

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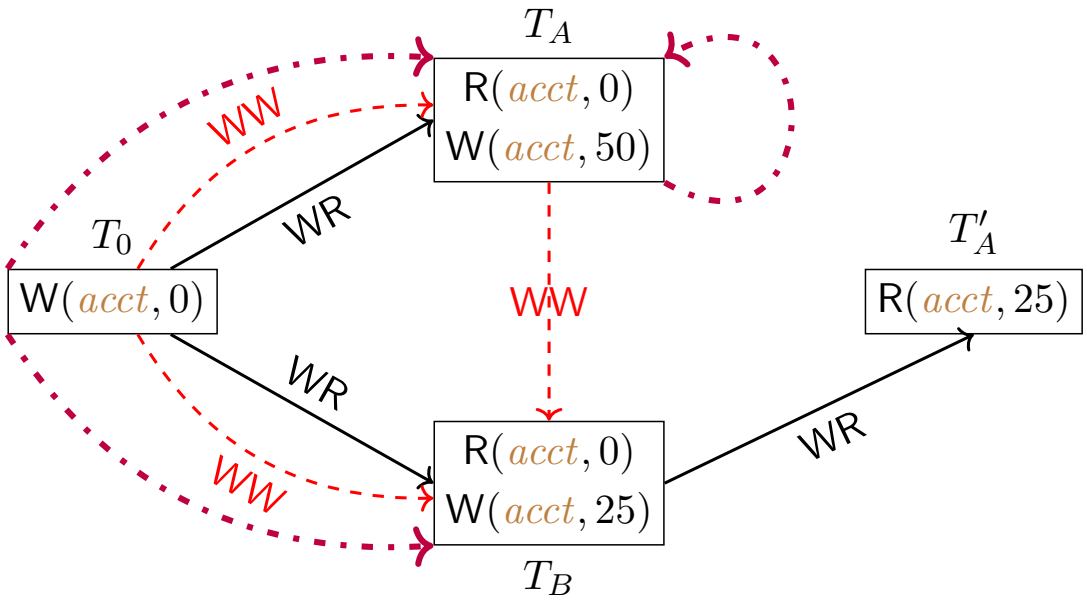
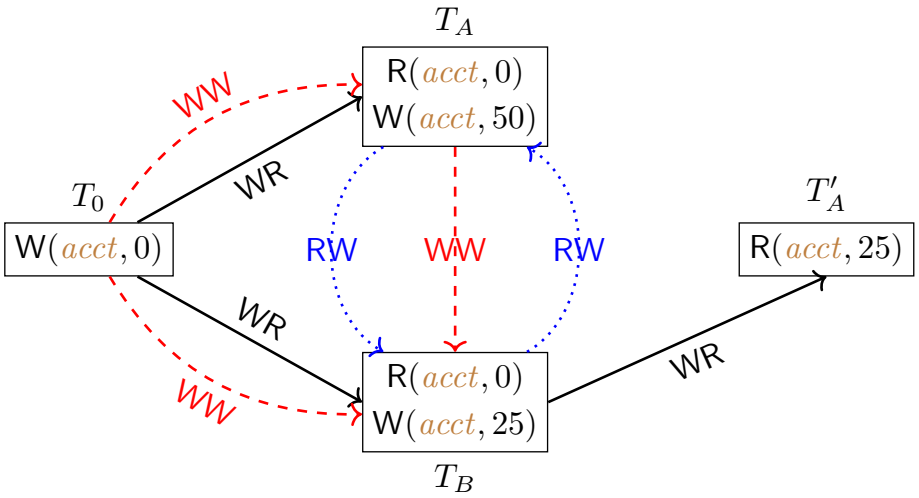
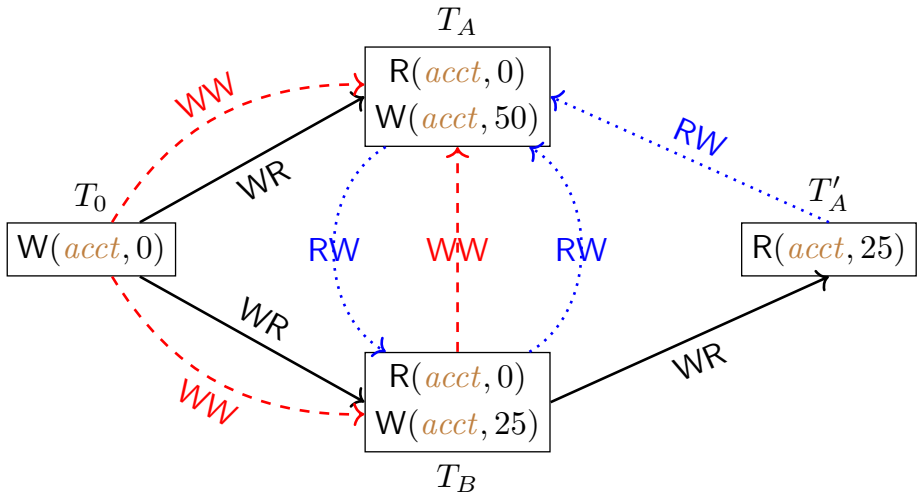


Dependency Graph-based Characterization of SI

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





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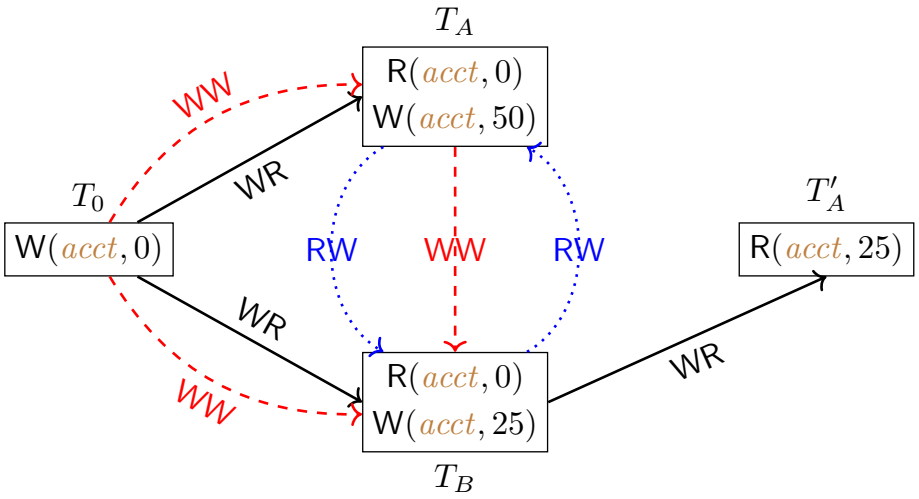
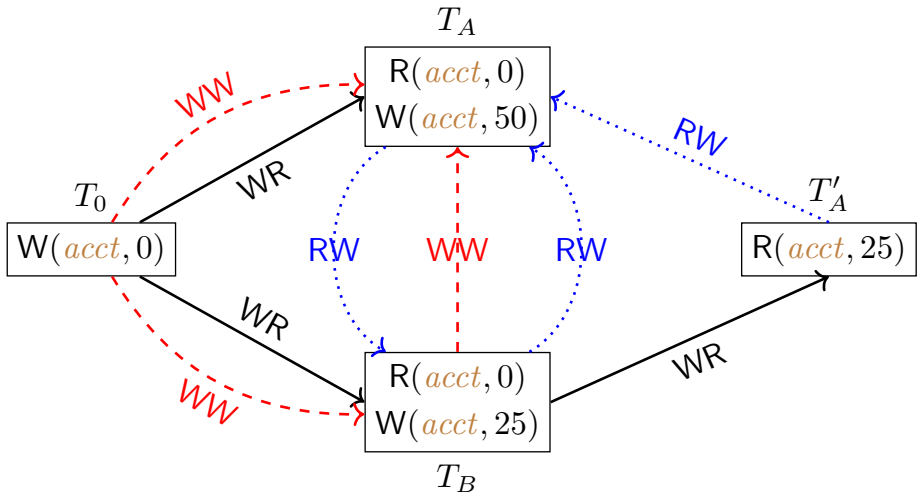
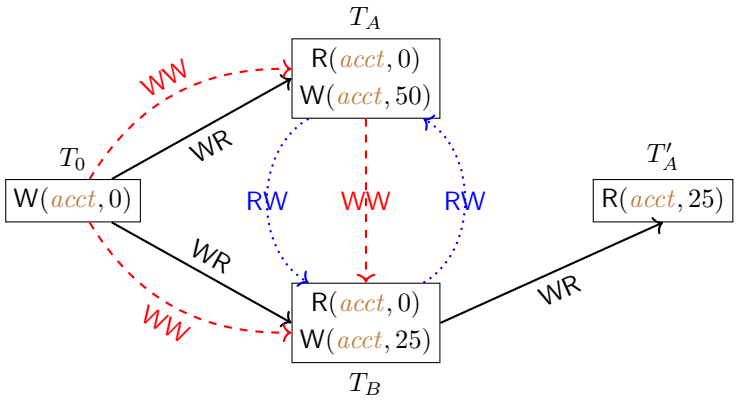


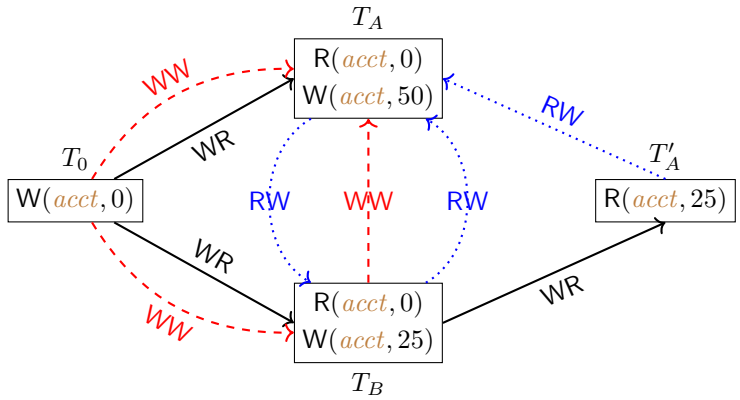


$\mathcal{A}$: encode them into SAT formulas based on (generalized) polygraphs and solve them using SAT solvers.

Polygraphs: A Family of Dependency Graphs

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





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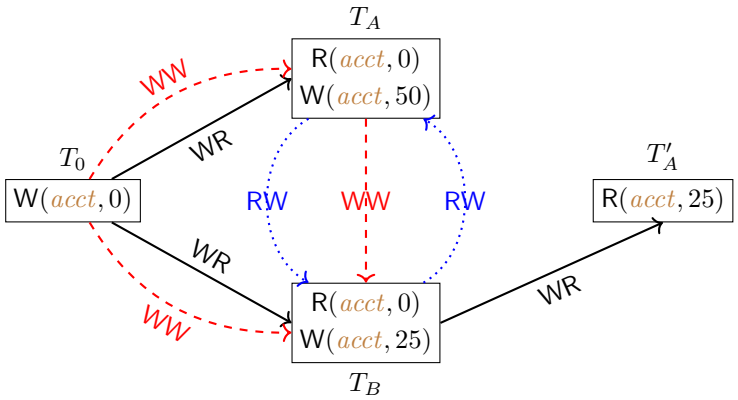

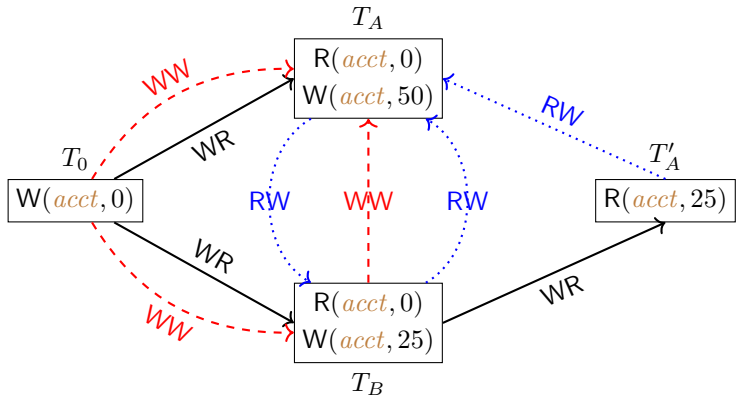

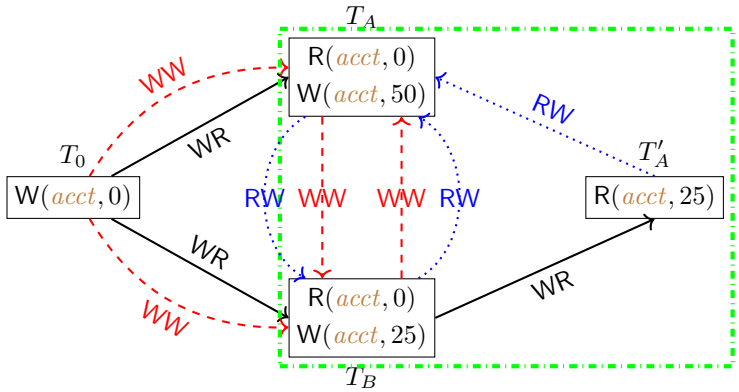

generalized polygraph:

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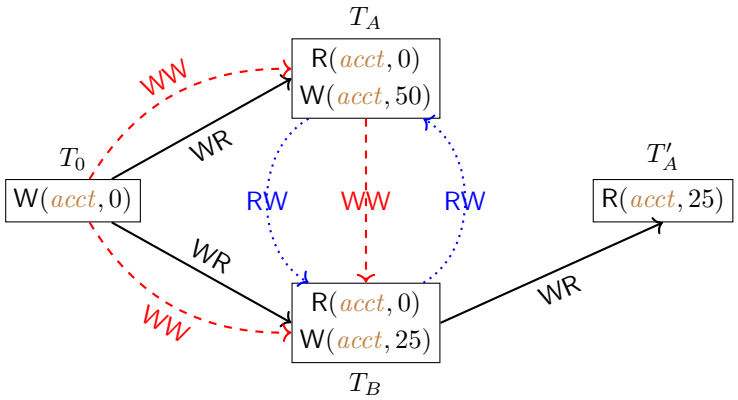
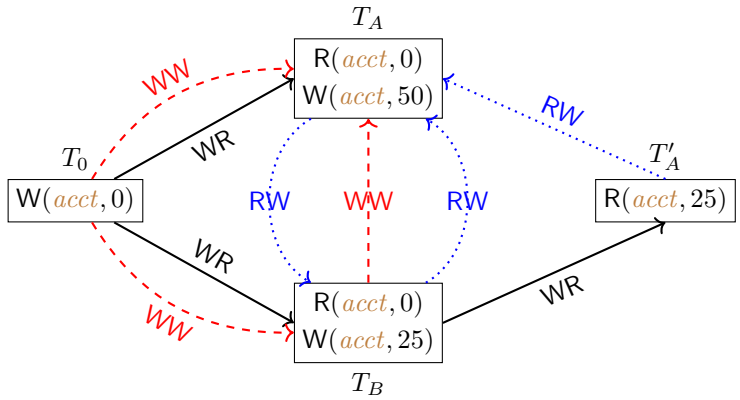
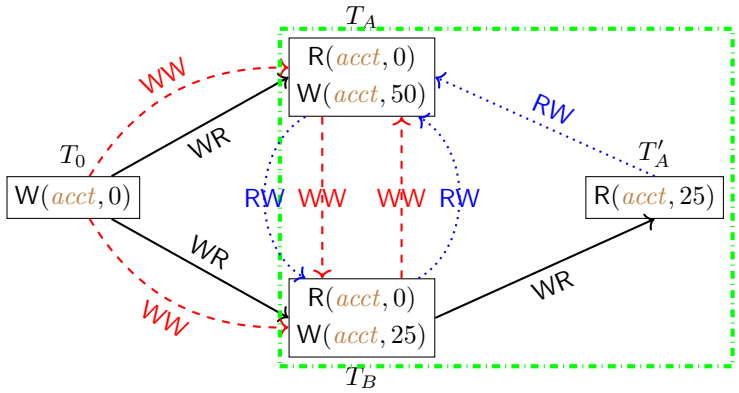


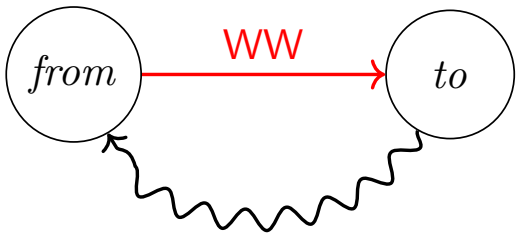


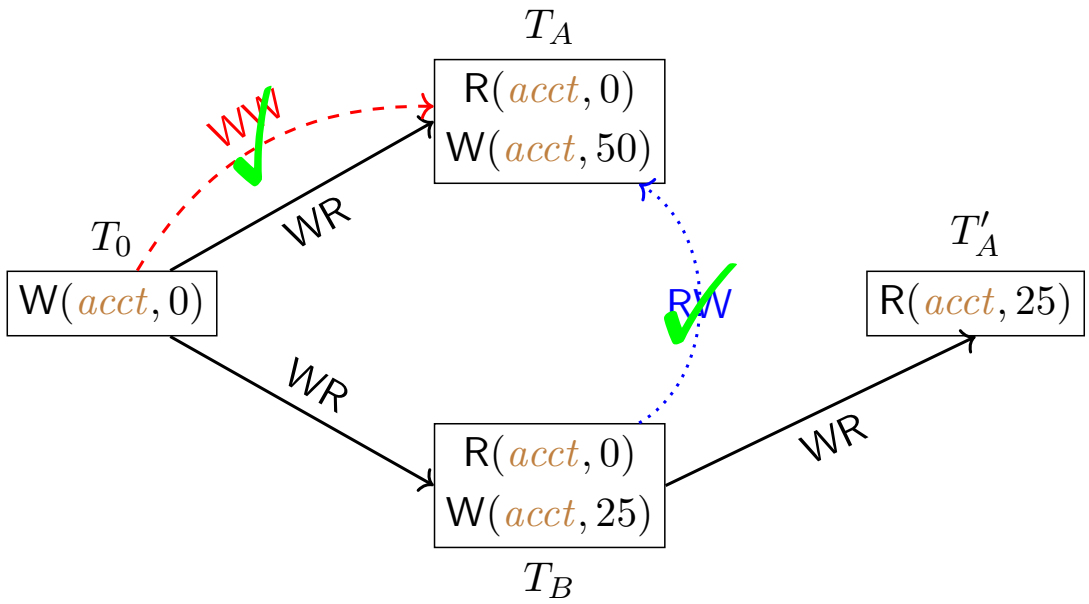


generalized polygraph:

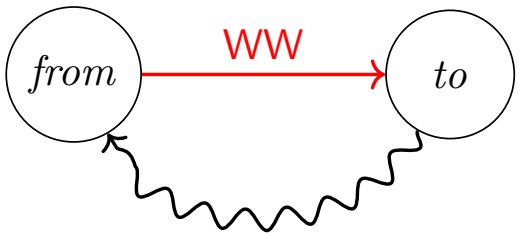
$$\langle either \triangleq \{T_A \xrightarrow{\text{WW}} T_B\}, or \triangleq \{T_B \xrightarrow{\text{WW}} T_A, T'_A \xrightarrow{\text{RW}} T_A\}\rangle$$

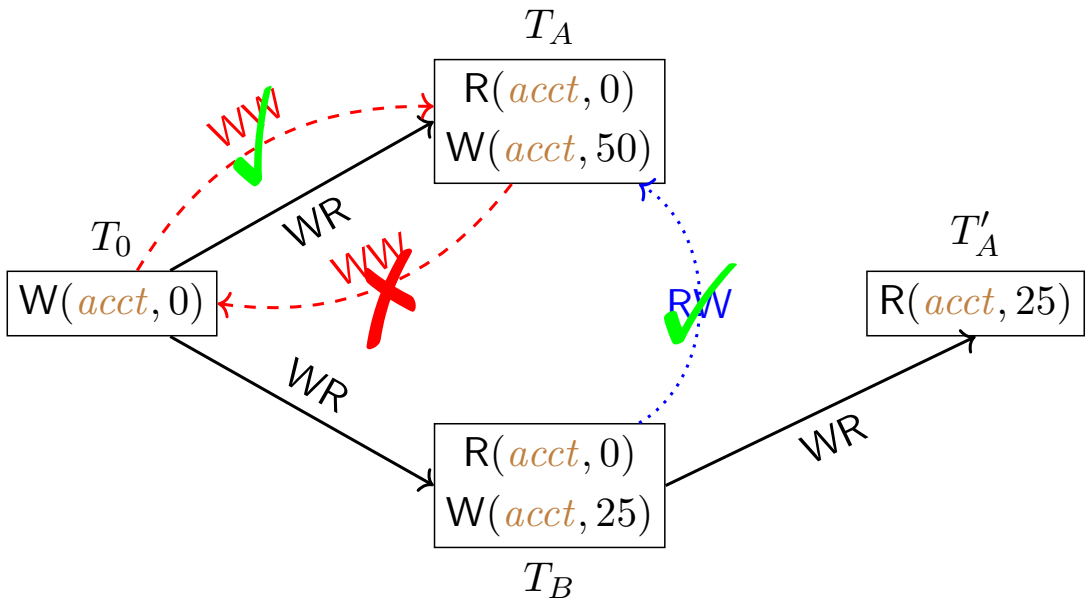
PolySI: Pruning before Encoding (the WW case)





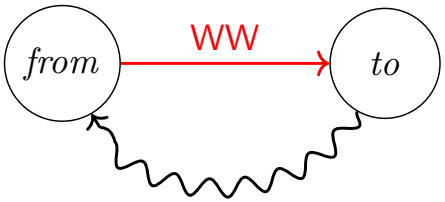
PolySI: Pruning before Encoding (the WW case)

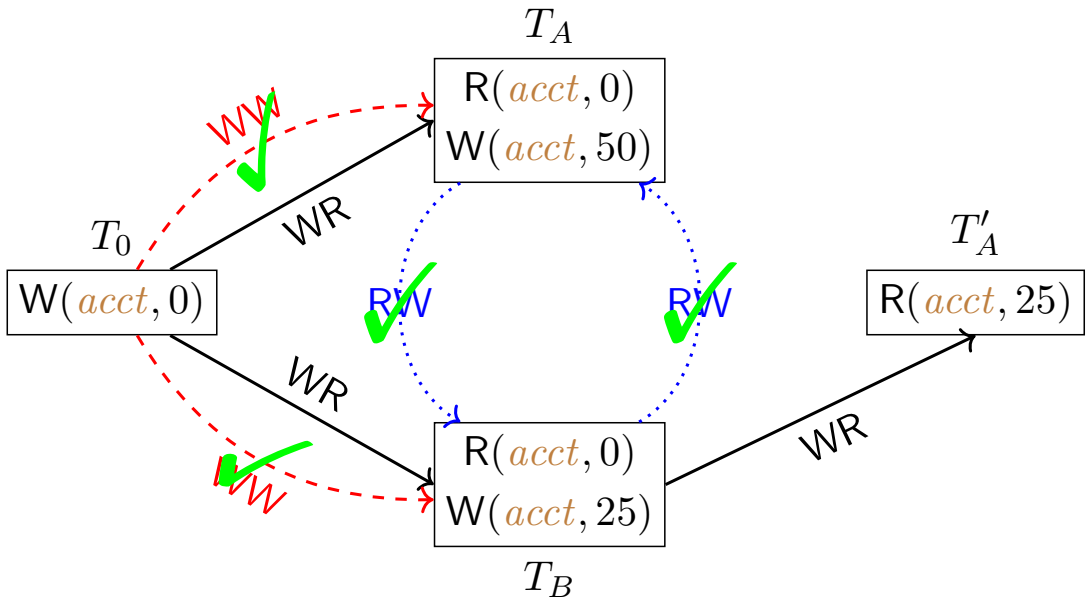




$T_A \xrightarrow{\text{WW}} T_0$ can be pruned due to the $T_A \xrightarrow{\text{WW}} T_0 \xrightarrow{\text{WR}} T_A$ cycle.

PolySI: Pruning before Encoding (the WW case)





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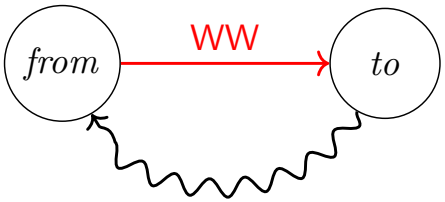
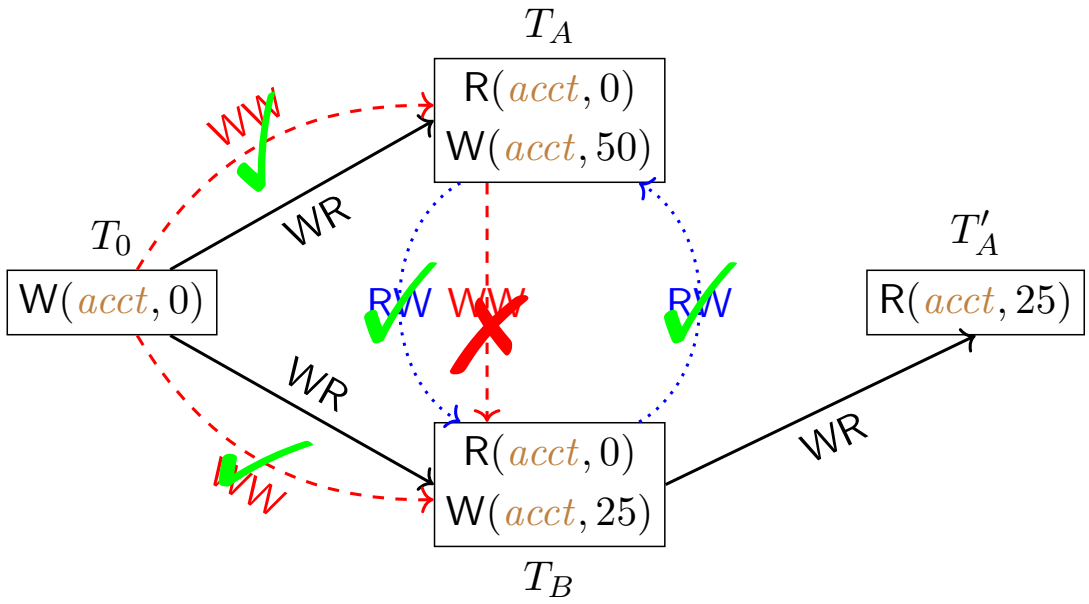
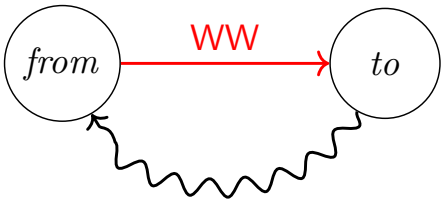
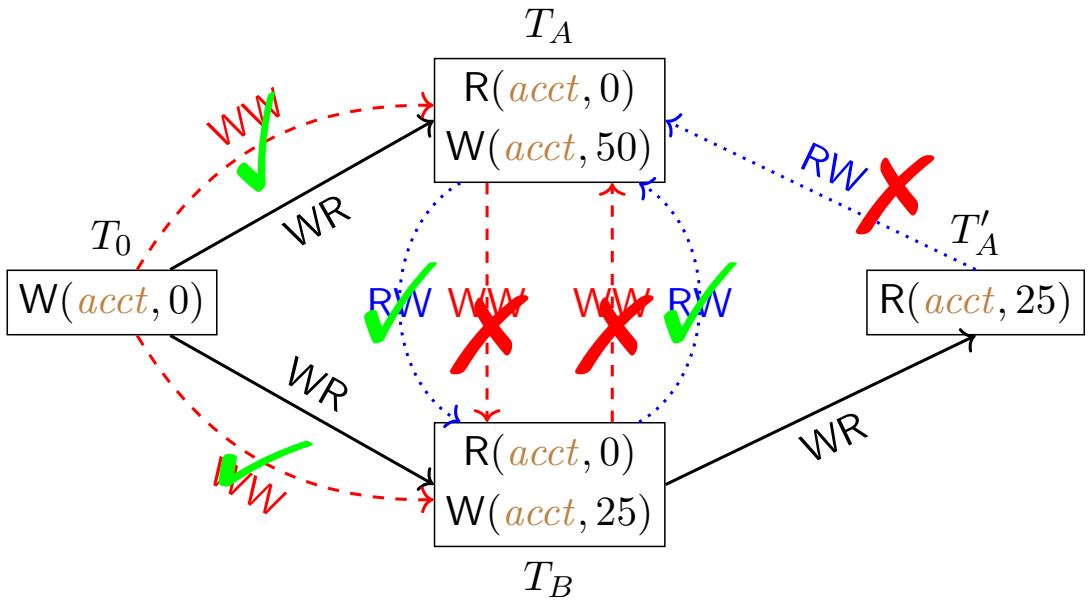




$T_A \xrightarrow{\mathsf{WW}} T_B$ is pruned due to the $T_A \xrightarrow{\mathsf{WW}} T_B \xrightarrow{\mathsf{RW}} T_A$ cycle.

PolySI: Pruning before Encoding (the WW case)

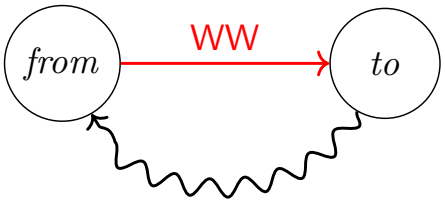


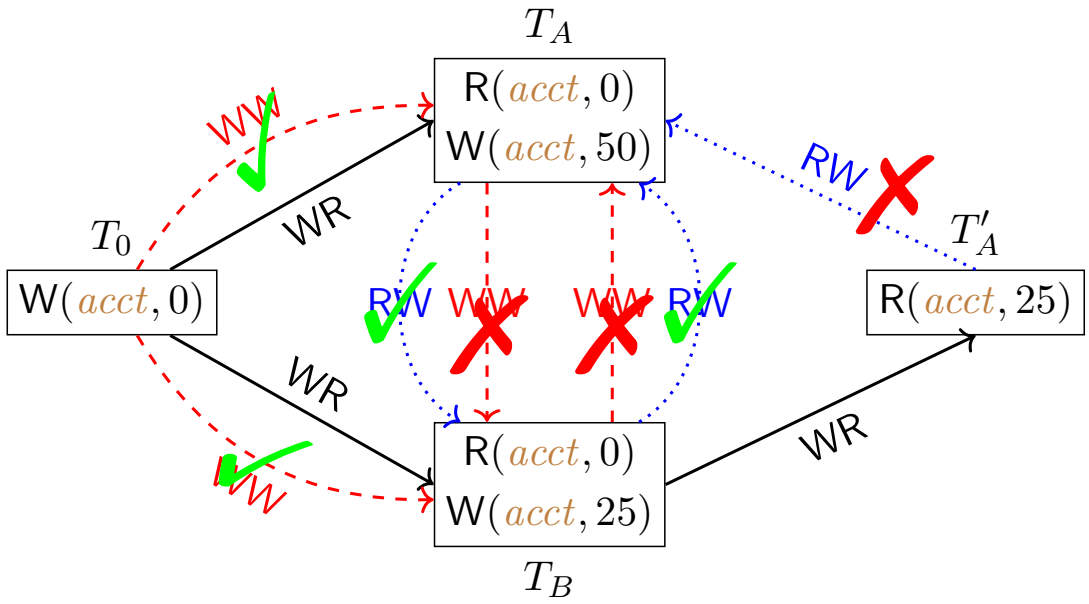


$T_A \xrightarrow{\text{WW}} T_B$ is pruned due to the $T_A \xrightarrow{\text{WW}} T_B \xrightarrow{\text{RW}} T_A$ cycle.

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

PolySI: Pruning before Encoding (the WW case)





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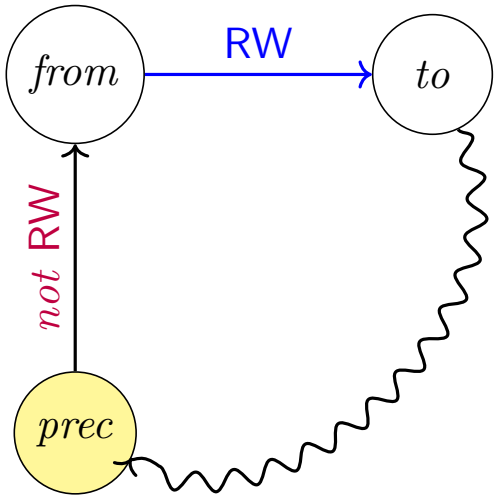
$T_B \xrightarrow{\text{WW}} T_A$ is pruned due to the $T_B \xrightarrow{\text{WW}} T_A \xrightarrow{\text{RW}} T_B$ cycle.

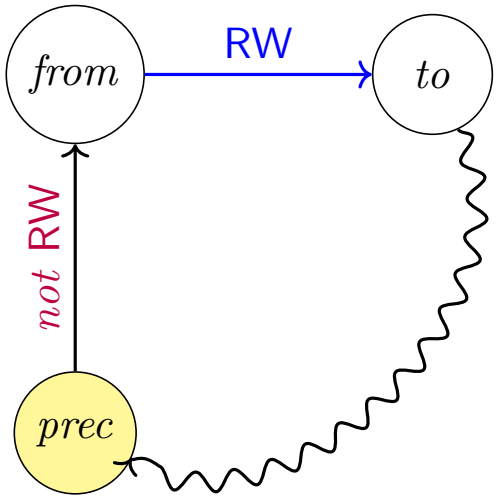
Therefore, we are sure that the history does *not* satisfy SI.

PolySI: Pruning before Encoding (the RW case)

PolySI: Pruning before Encoding (the RW case)



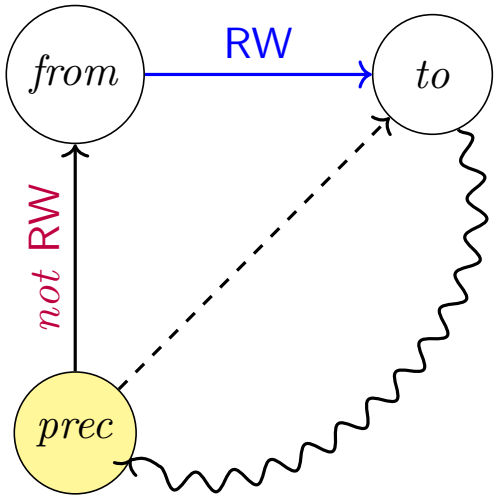
PolySI: Pruning before Encoding (the RW case)



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.*

PolySI: Pruning before Encoding (the RW case)



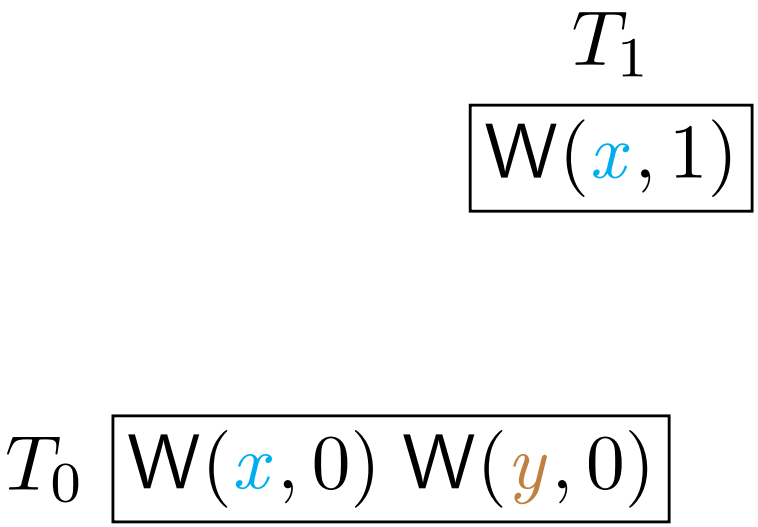
Theorem (Theorem 4.1 of [Cerone and Gotsman, 2018])

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.*

PolySI: An Illustrating Example of "Long Fork"

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

PolySI: An Illustrating Example of "Long Fork"



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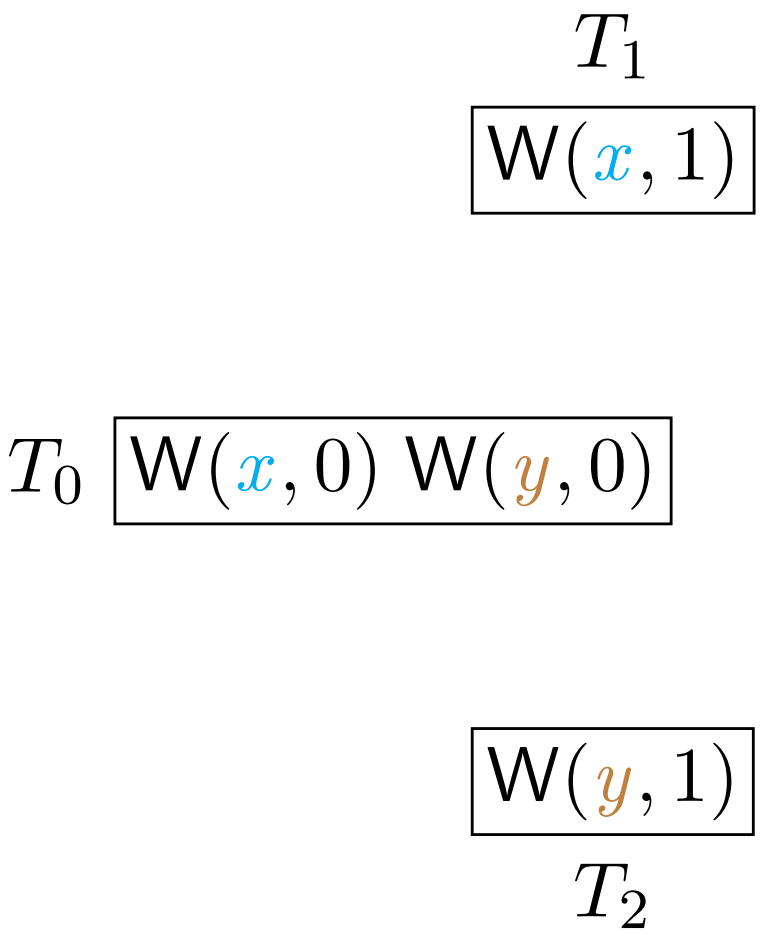

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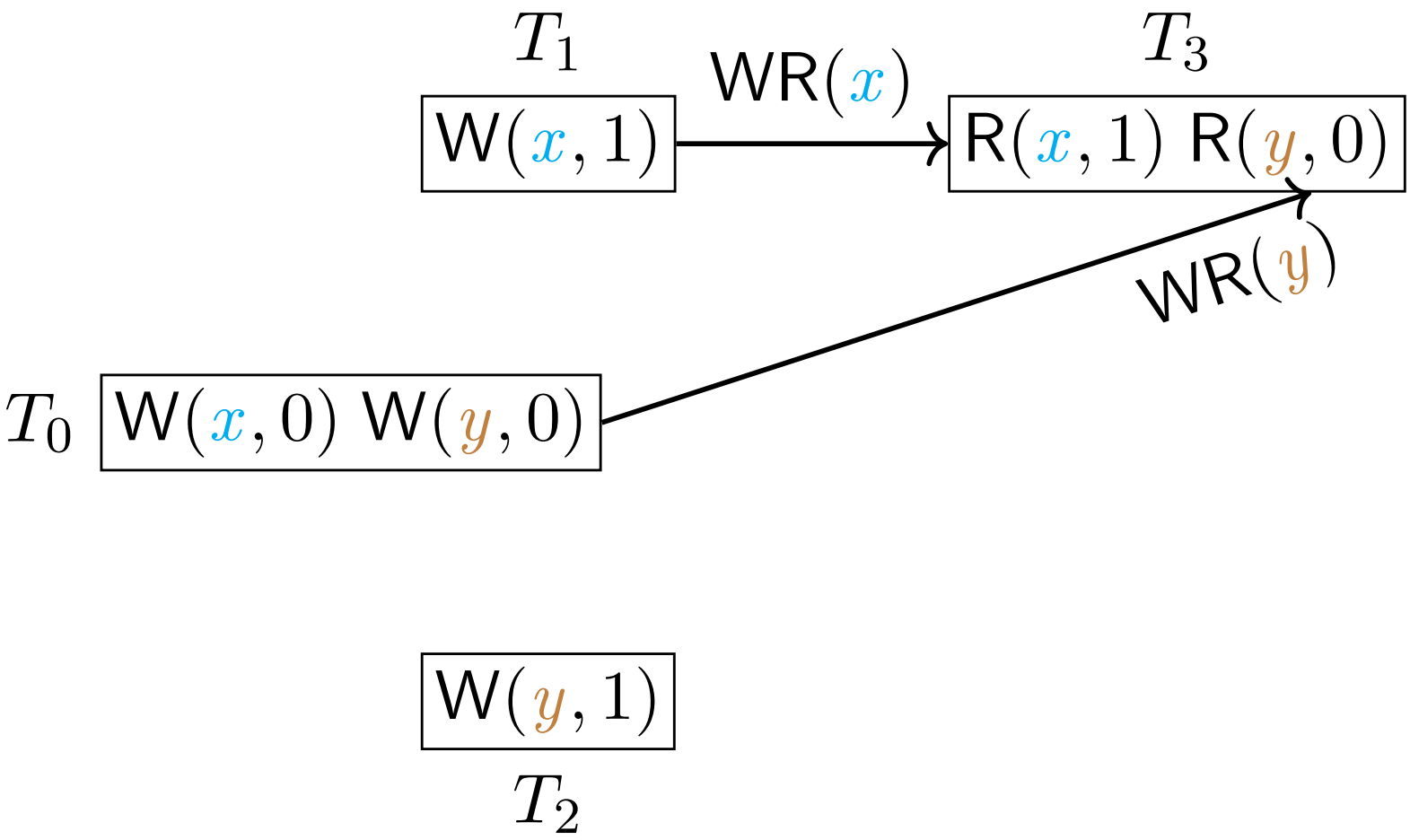

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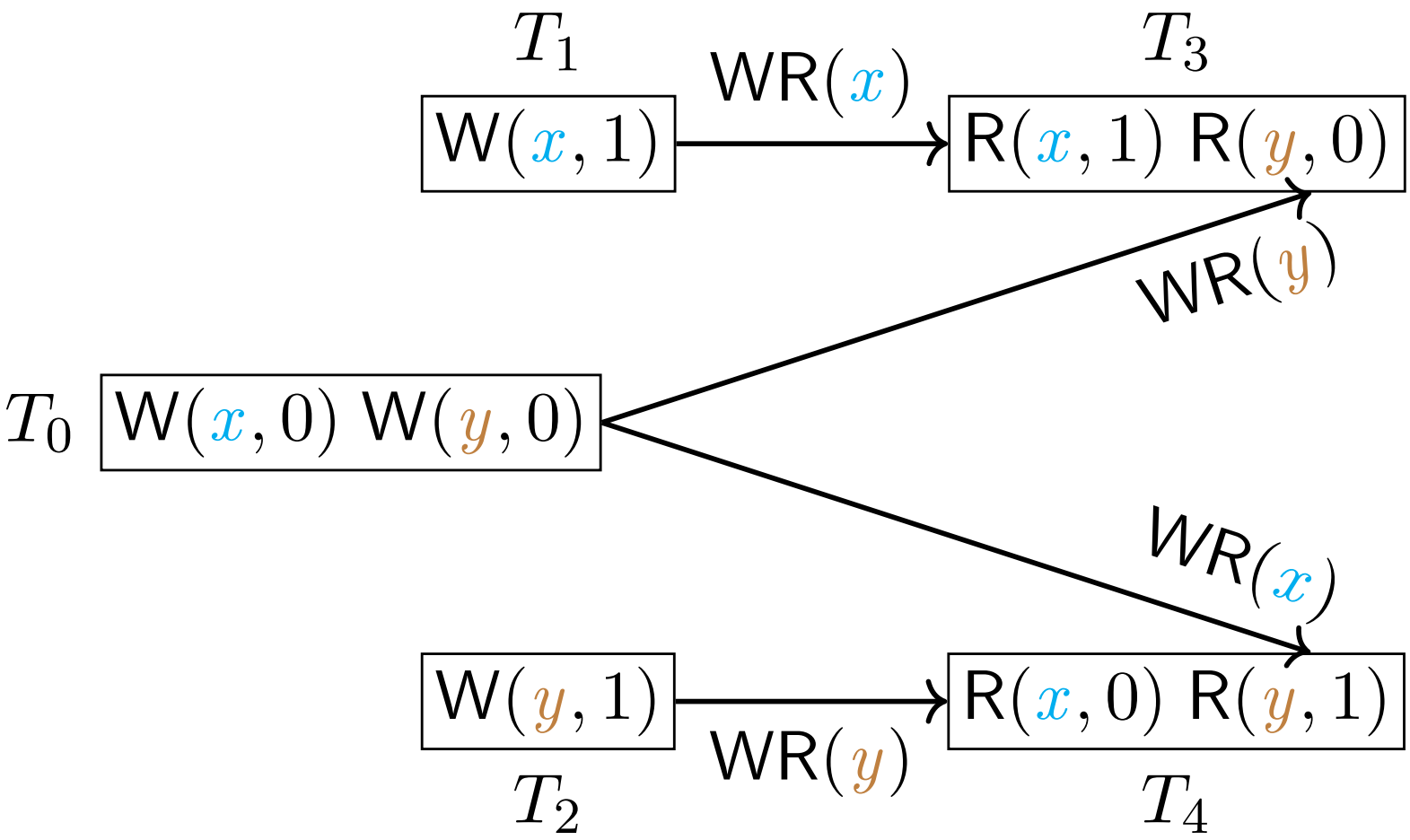
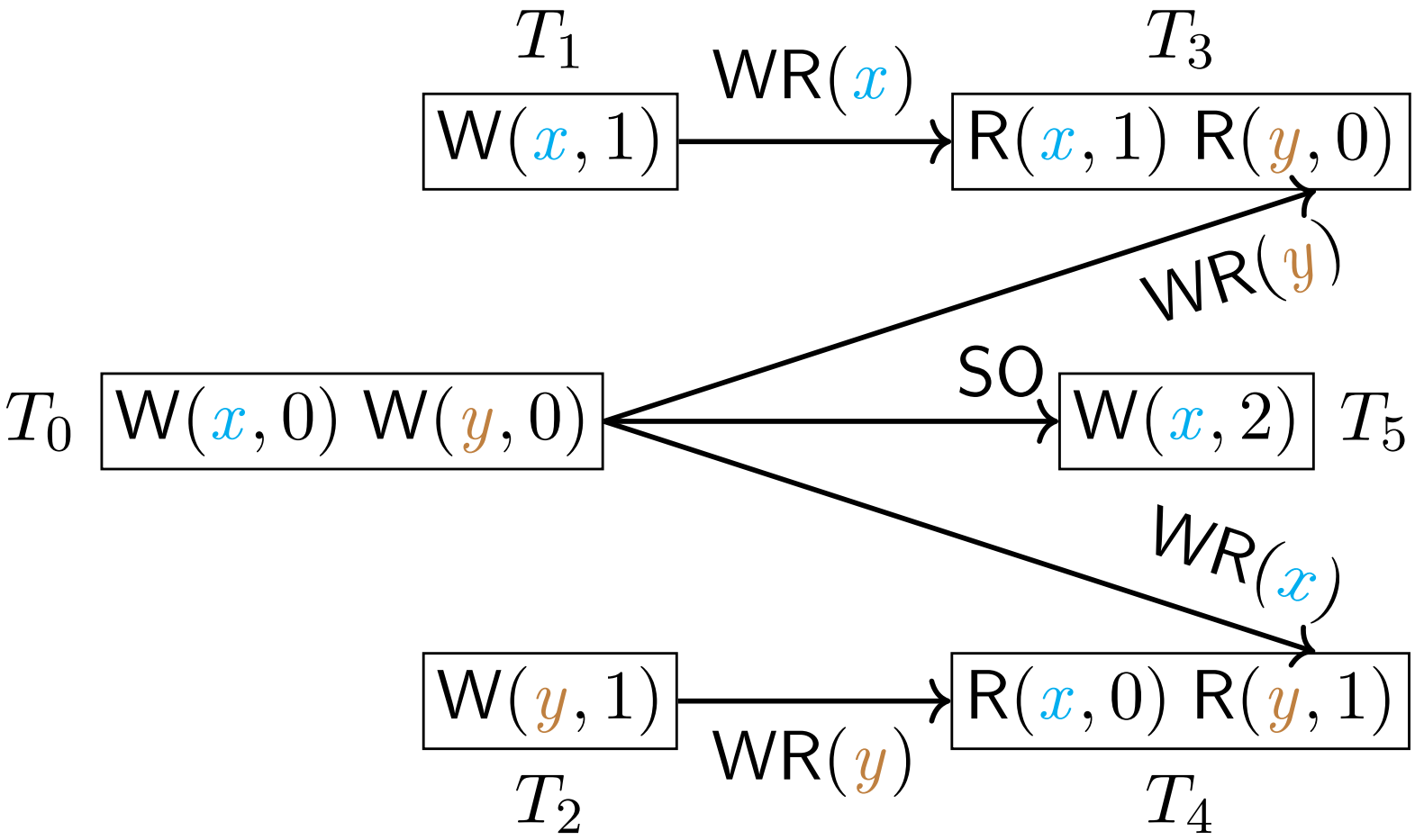
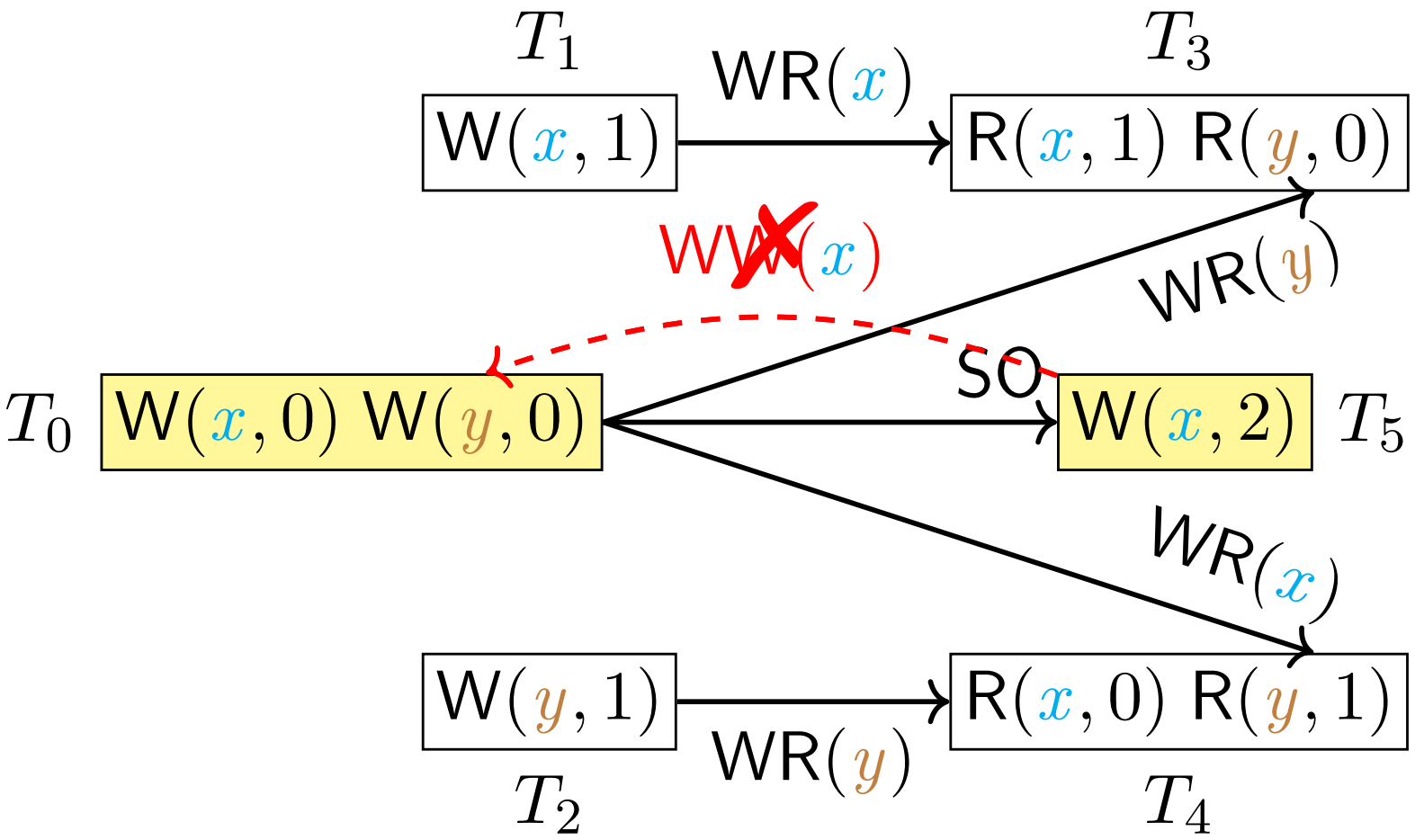


PolySI: An Illustrating Example of "Long Fork"



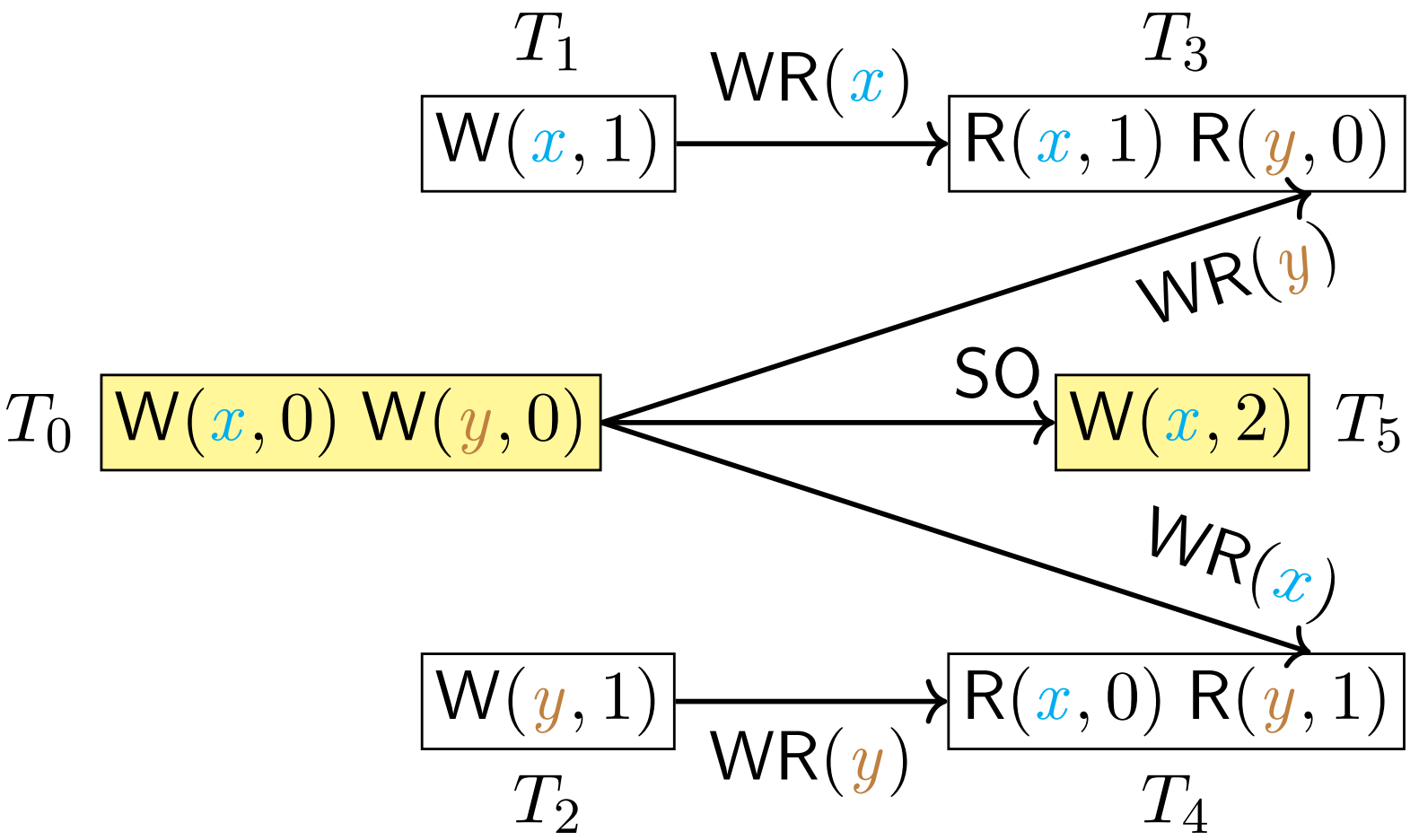
order between T_0, T_1, and T_5 (on x) and between T_0 and T_2 (on y)

PolySI: An Illustrating Example of "Long Fork"

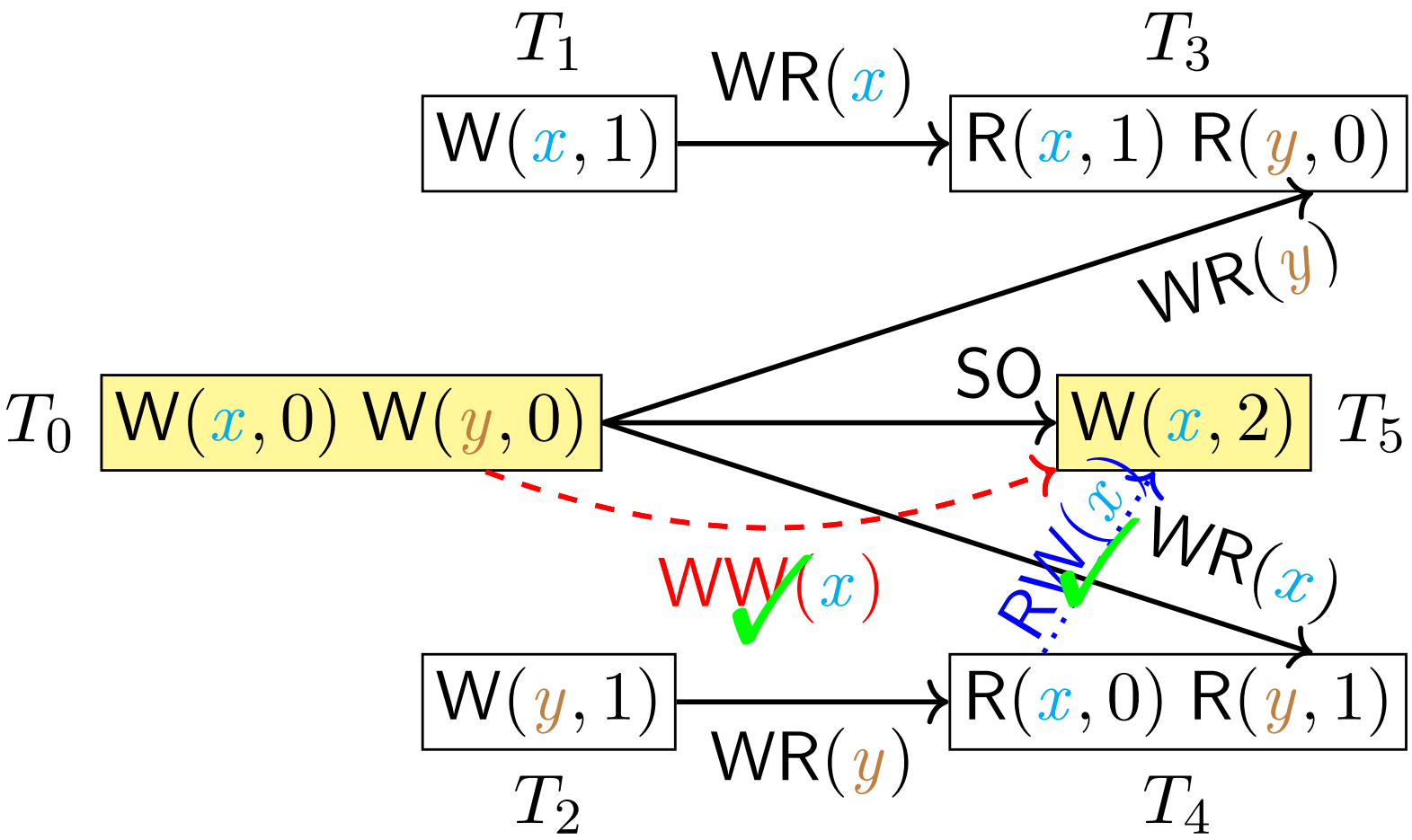


The $T_5 \xrightarrow{\mathsf{WW}(x)} T_0$ case is pruned due to $T_0 \xrightarrow{\mathsf{SO}} T_5 \xrightarrow{\mathsf{WW}(x)} T_0$.

PolySI: An Illustrating Example of "Long Fork"

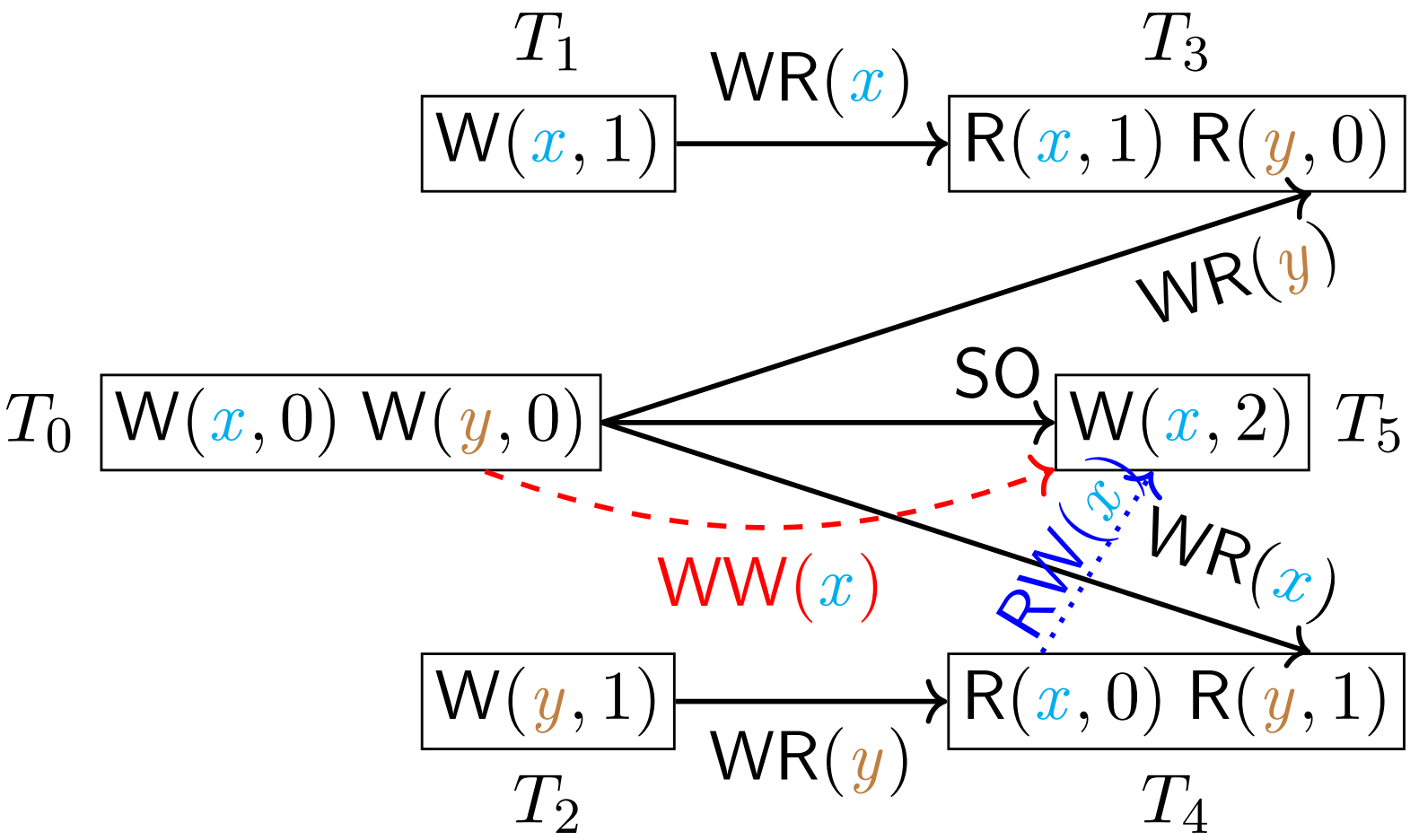


PolySI: An Illustrating Example of "Long Fork"

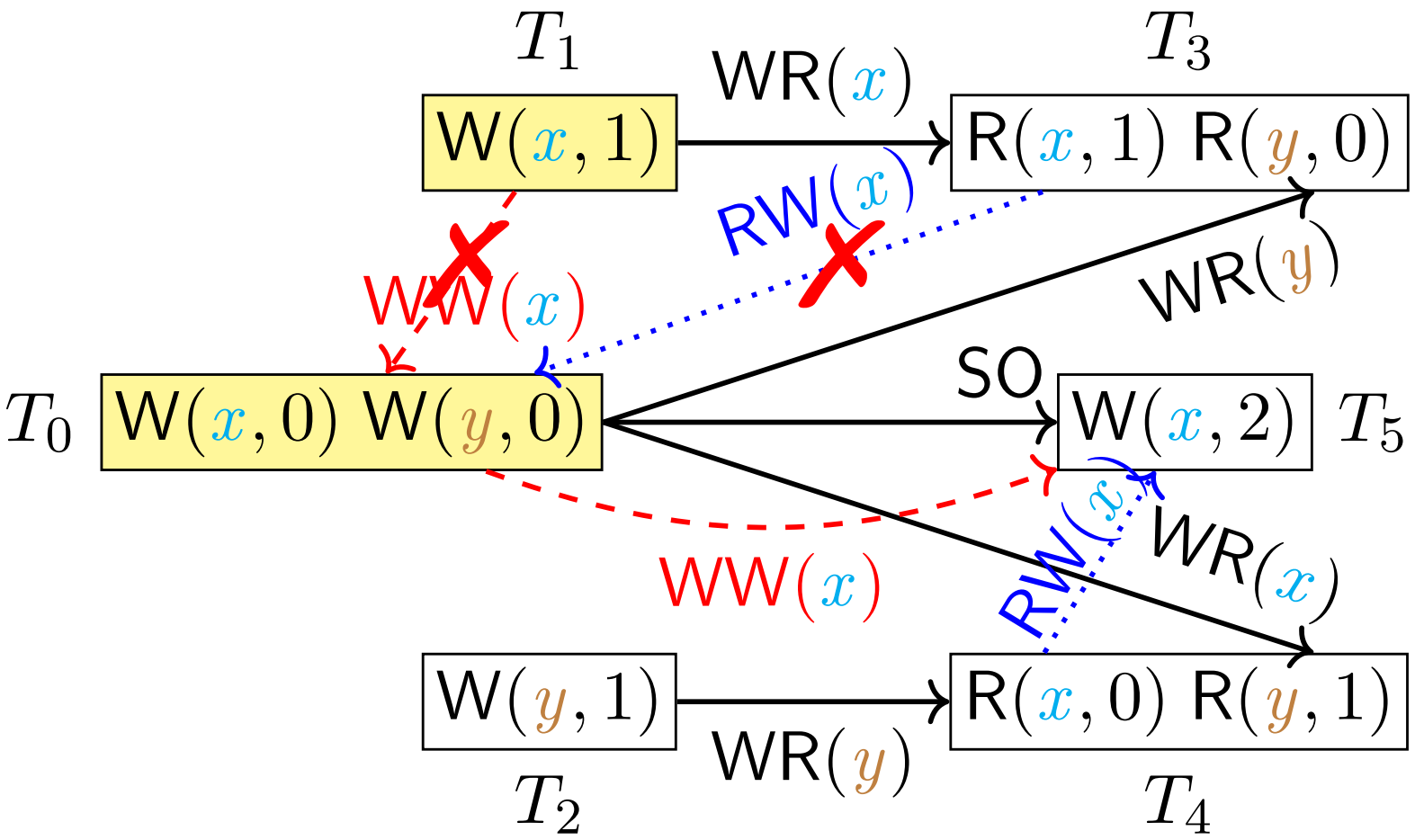


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_5$ case becomes known.

PolySI: An Illustrating Example of "Long Fork"

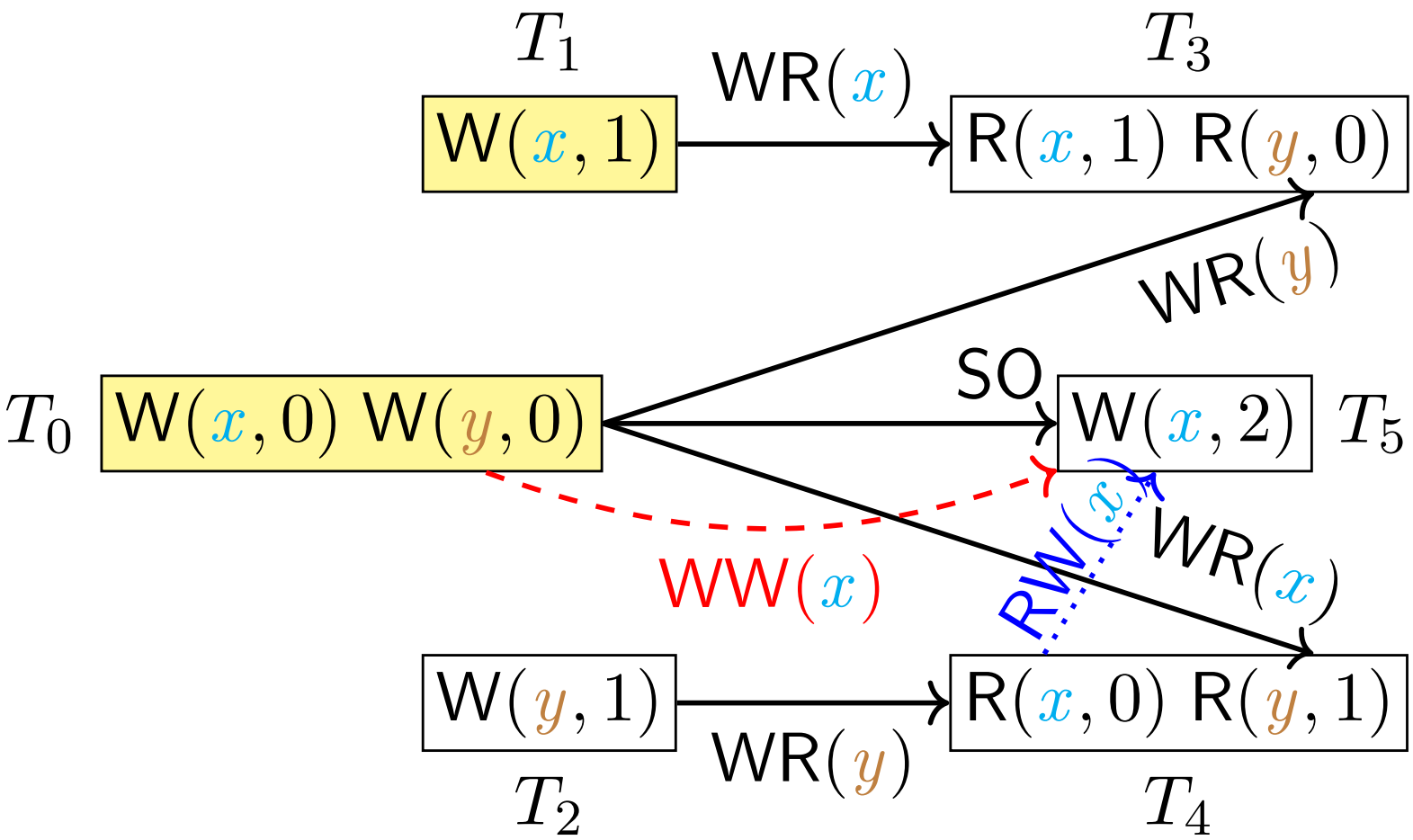


PolySI: An Illustrating Example of "Long Fork"

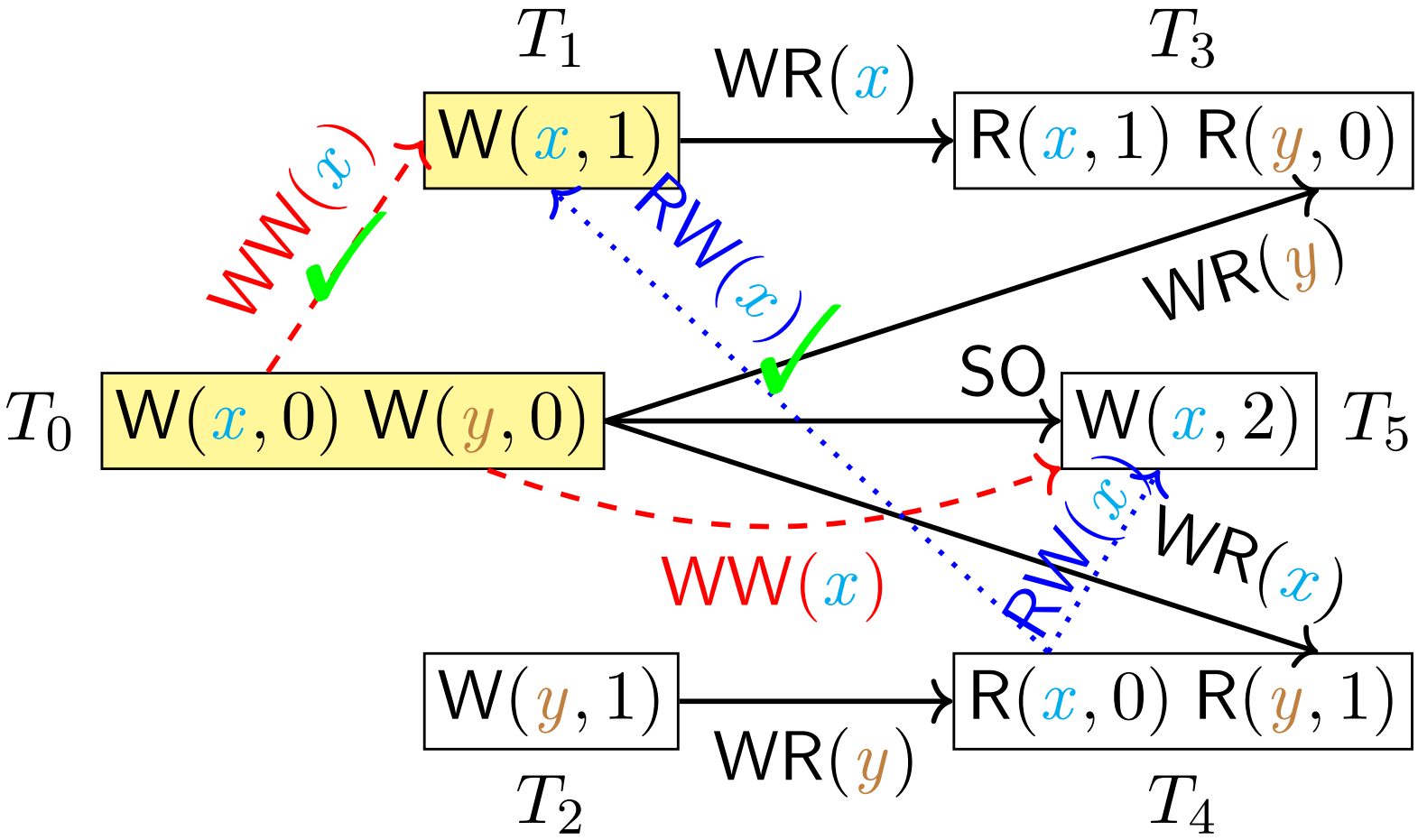


The $T_1 \xrightarrow{\mathsf{WW}(x)} T_0$ case is pruned due to $T_3 \xrightarrow{\mathsf{RW}(x)} T_0 \xrightarrow{\mathsf{WR}(y)} T_3$.

PolySI: An Illustrating Example of "Long Fork"

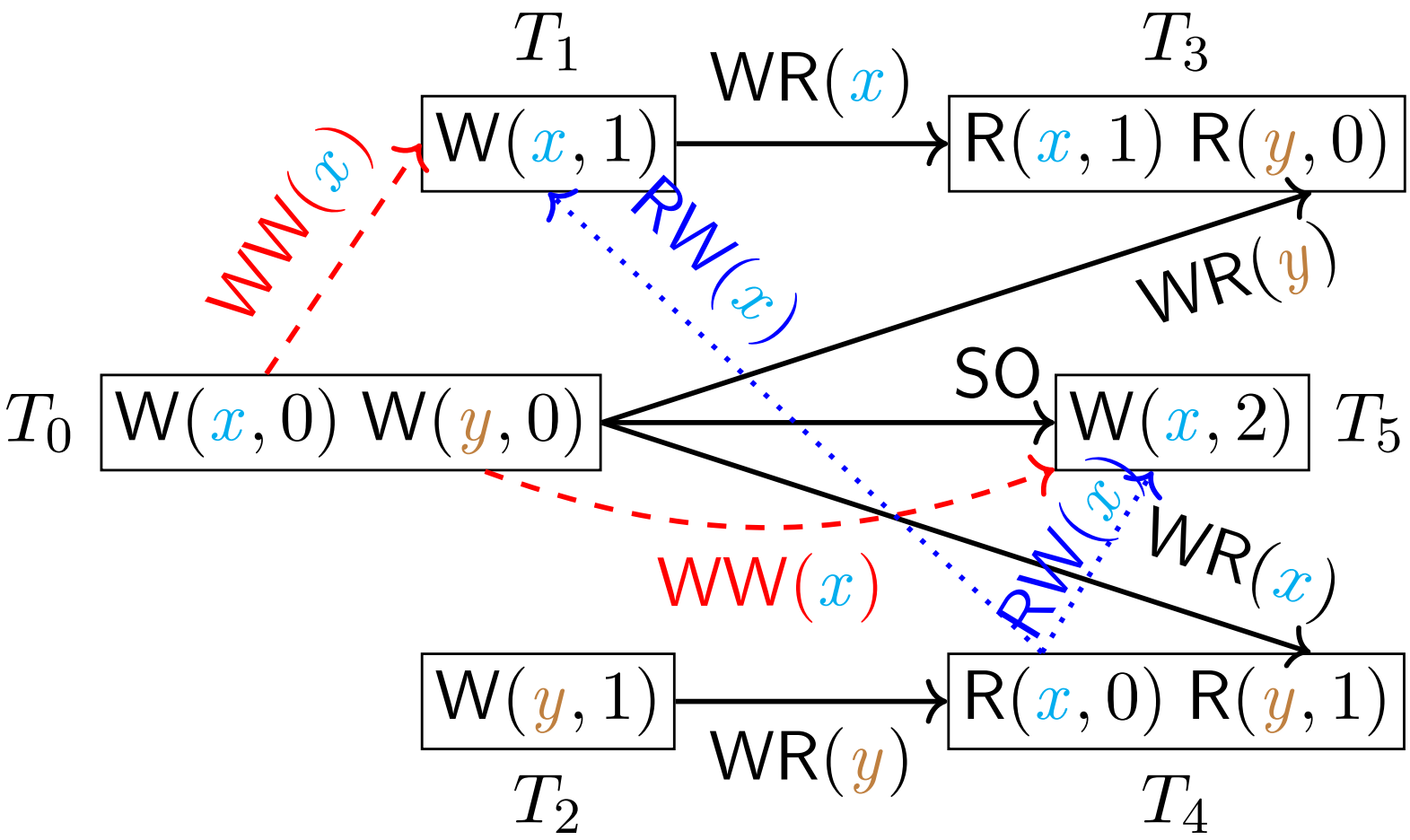


PolySI: An Illustrating Example of "Long Fork"

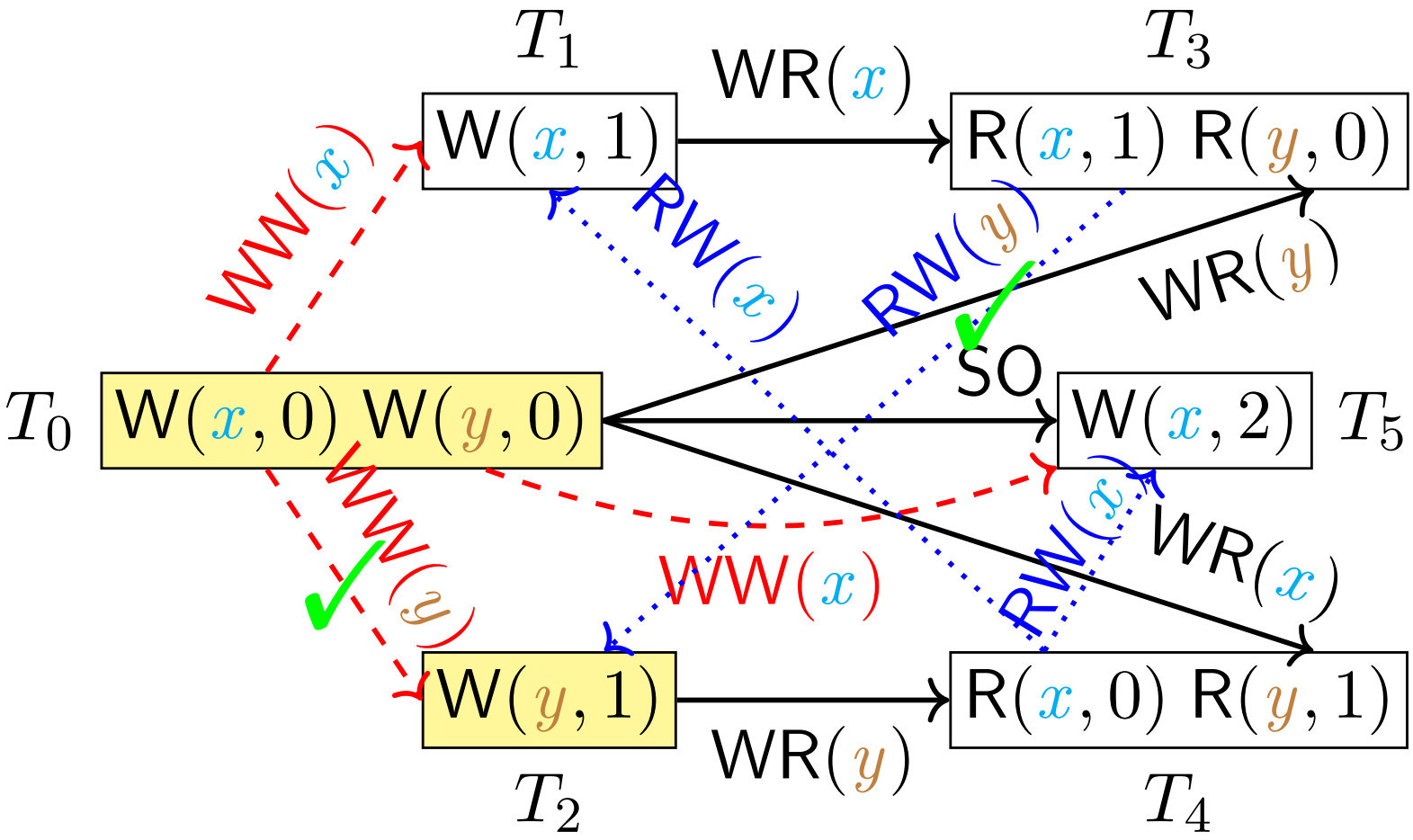


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_1$ case becomes known.

PolySI: An Illustrating Example of "Long Fork"



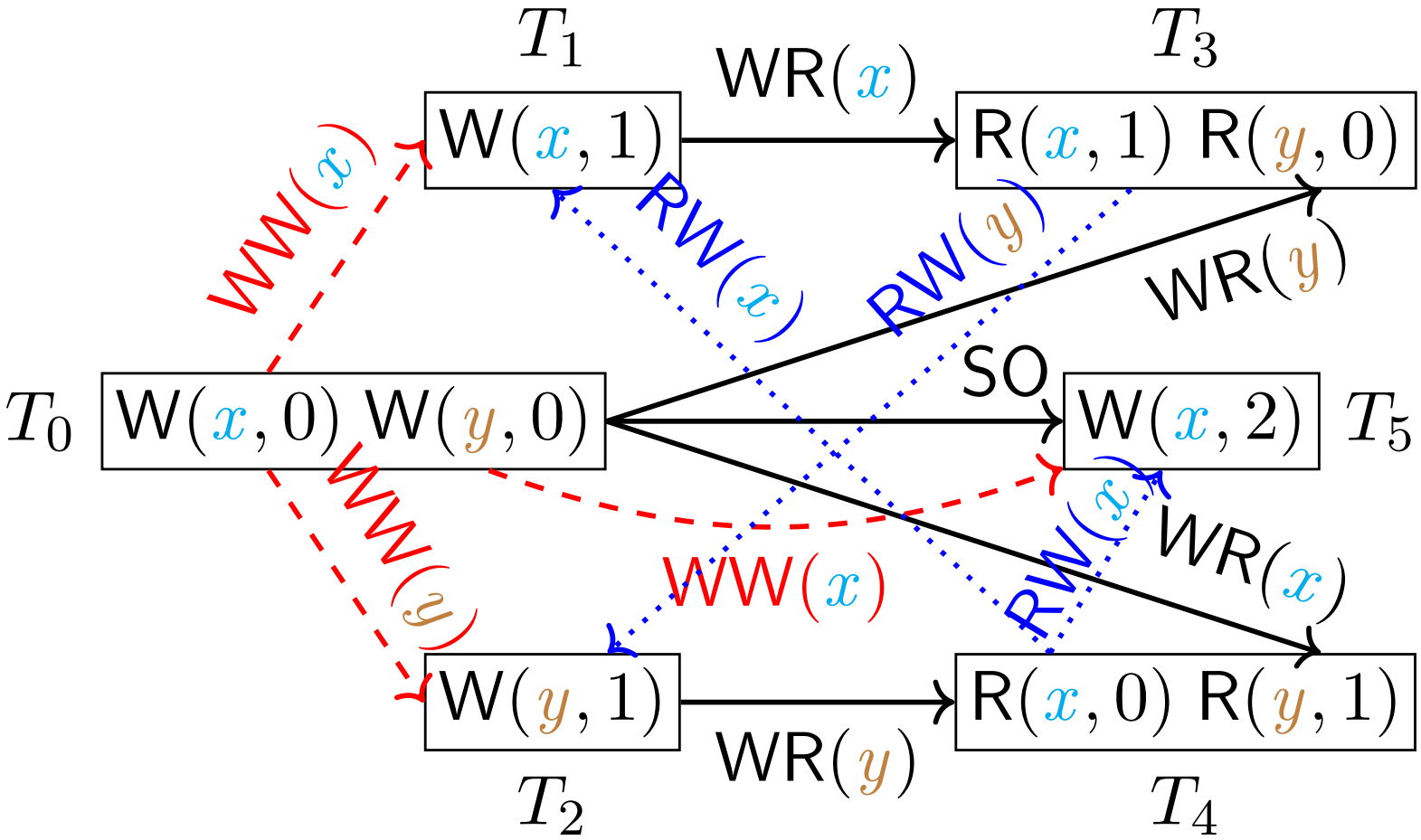
PolySI: An Illustrating Example of "Long Fork"



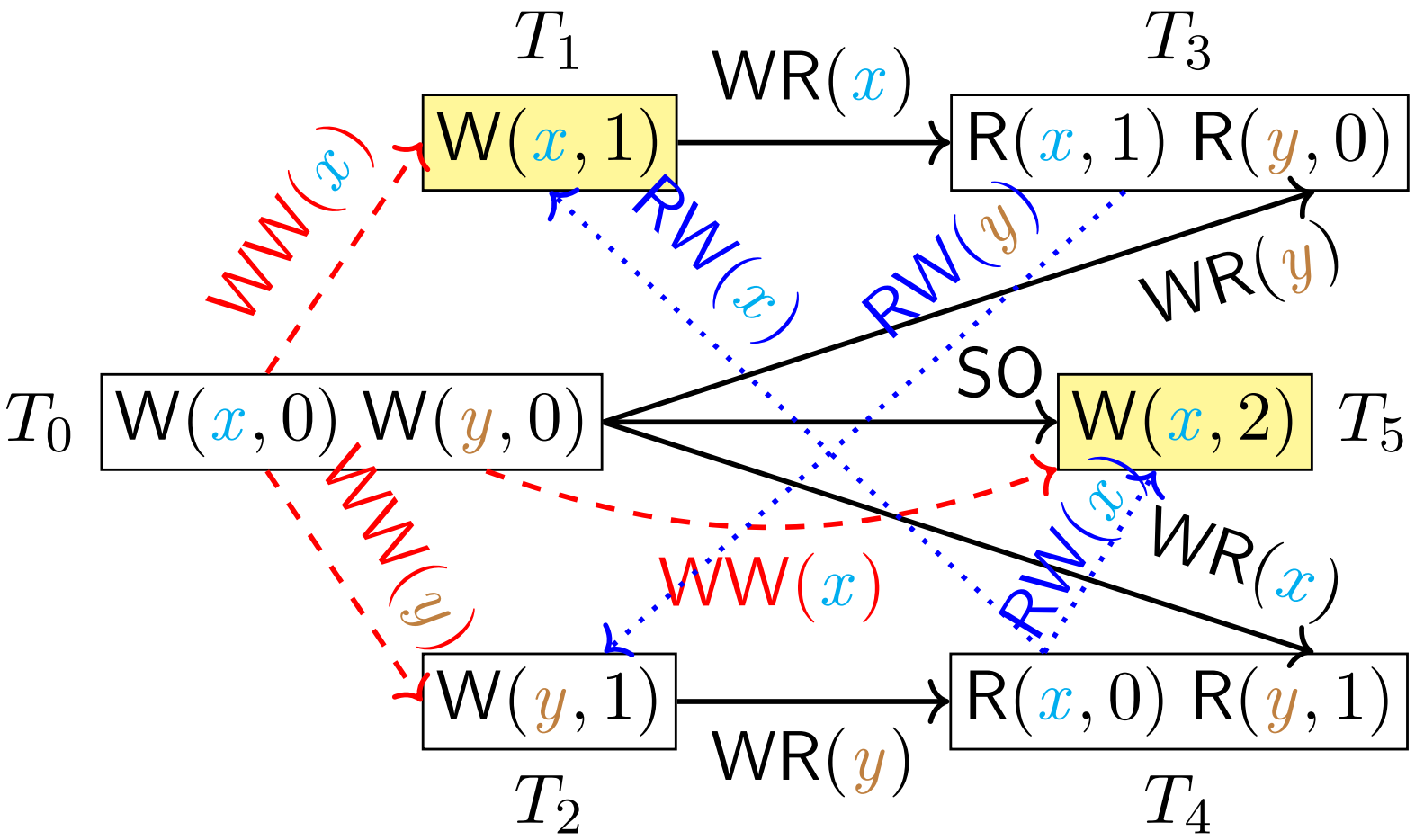
The $T_2 \xrightarrow{\mathsf{WW}(y)} T_0$ case is pruned,

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

PolySI: An Illustrating Example of "Long Fork"

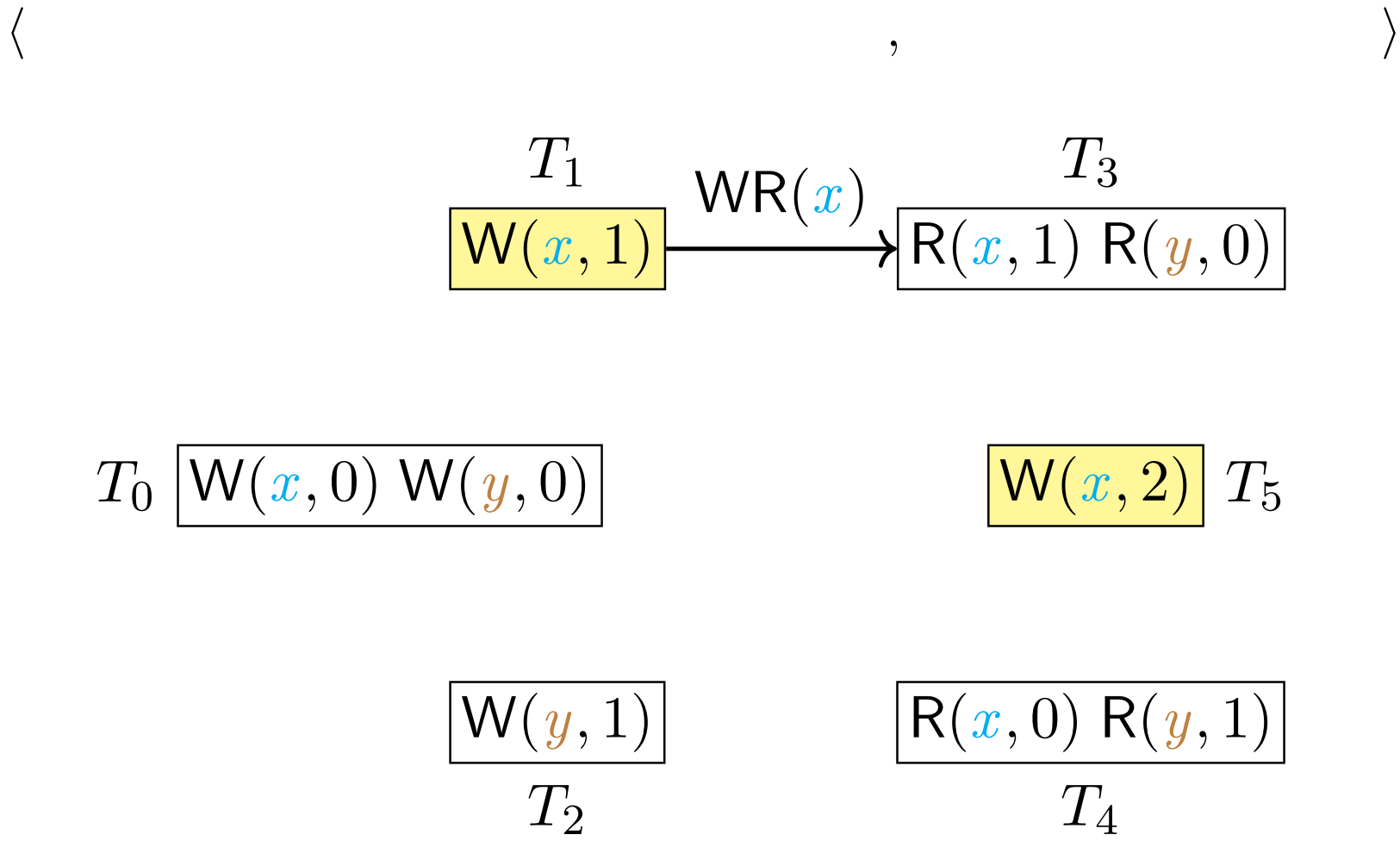


PolySI: An Illustrating Example of "Long Fork"



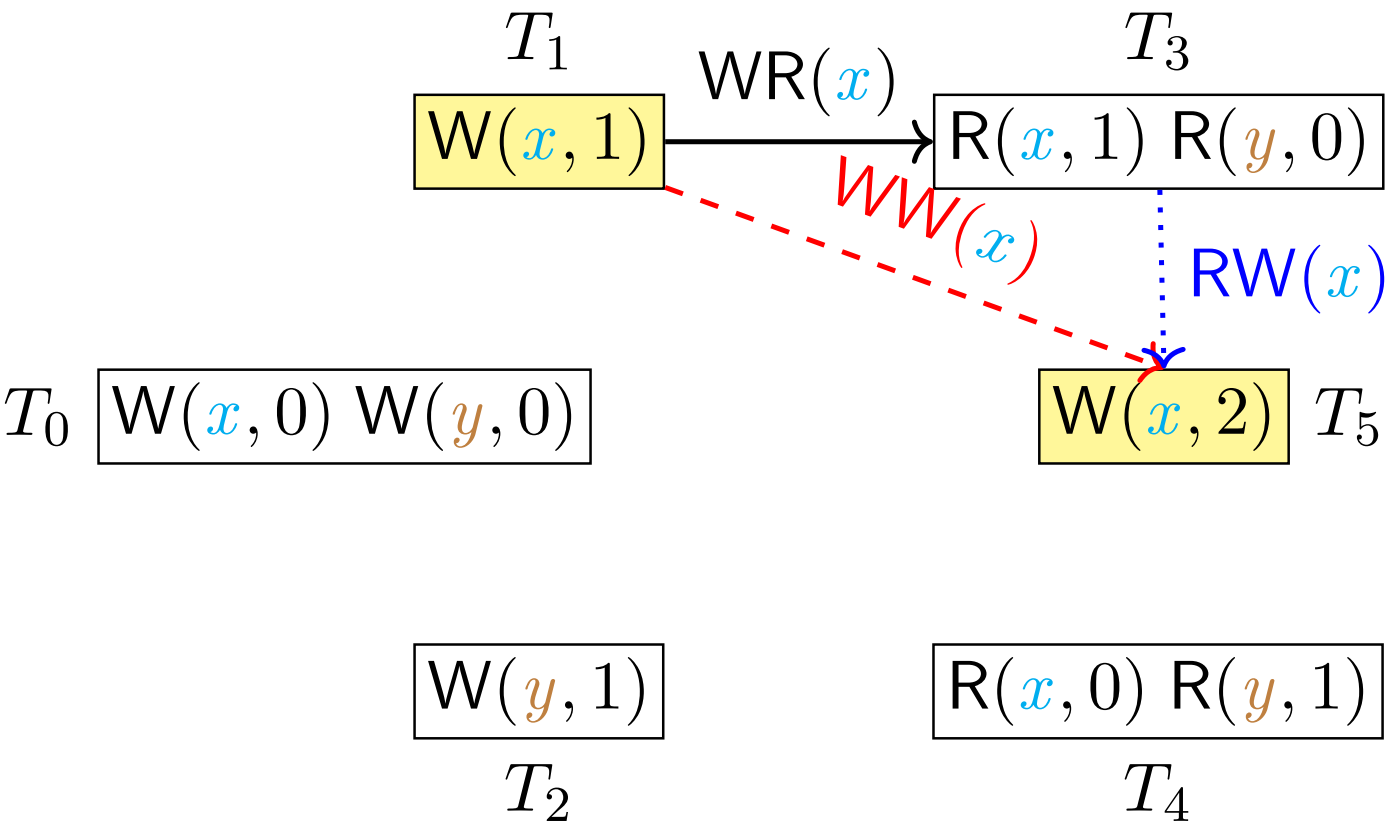
The order between T_1 and T_5 is still uncertain after pruning.

PolySI: An Illustrating Example of "Long Fork"



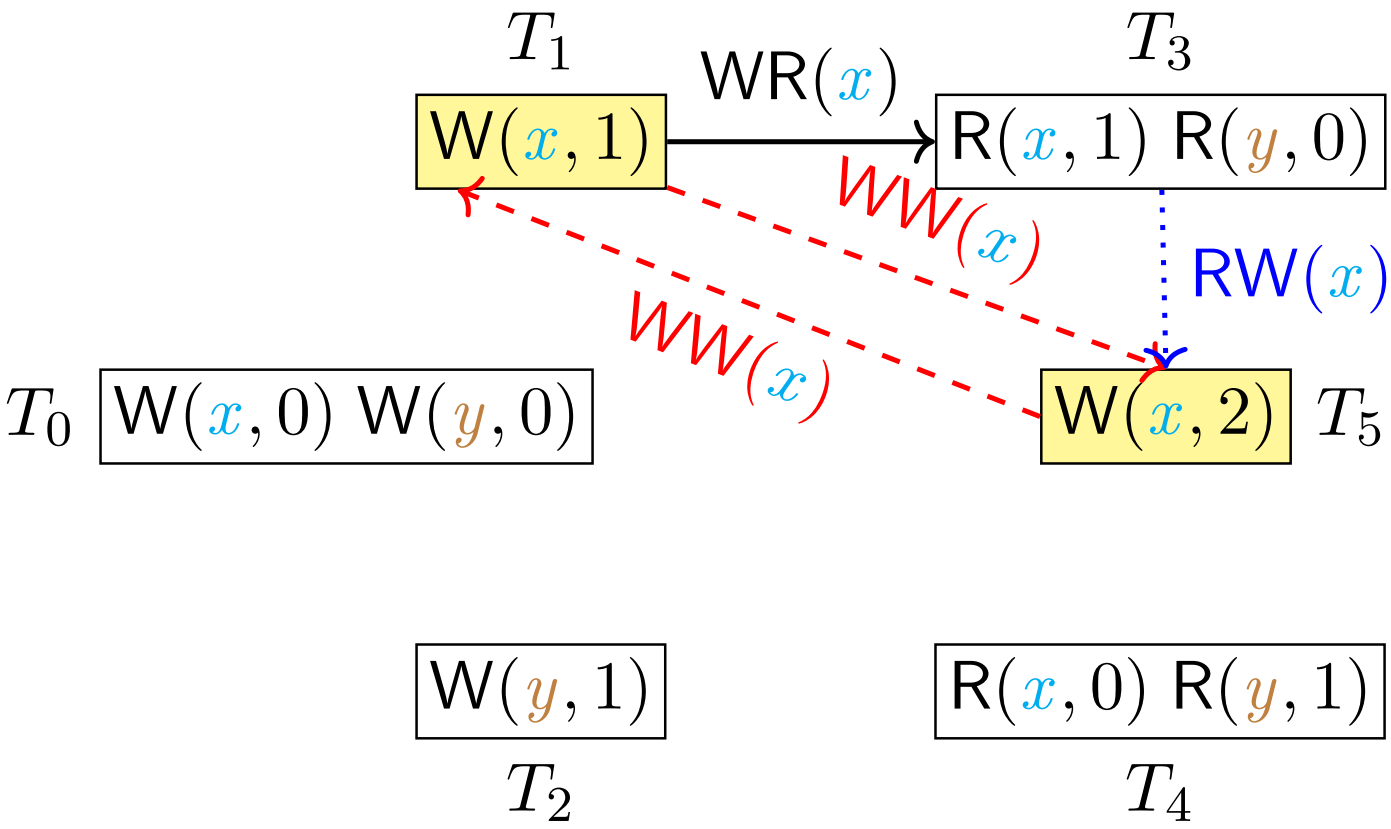
PolySI: An Illustrating Example of "Long Fork"

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



PolySI: An Illustrating Example of "Long Fork"

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



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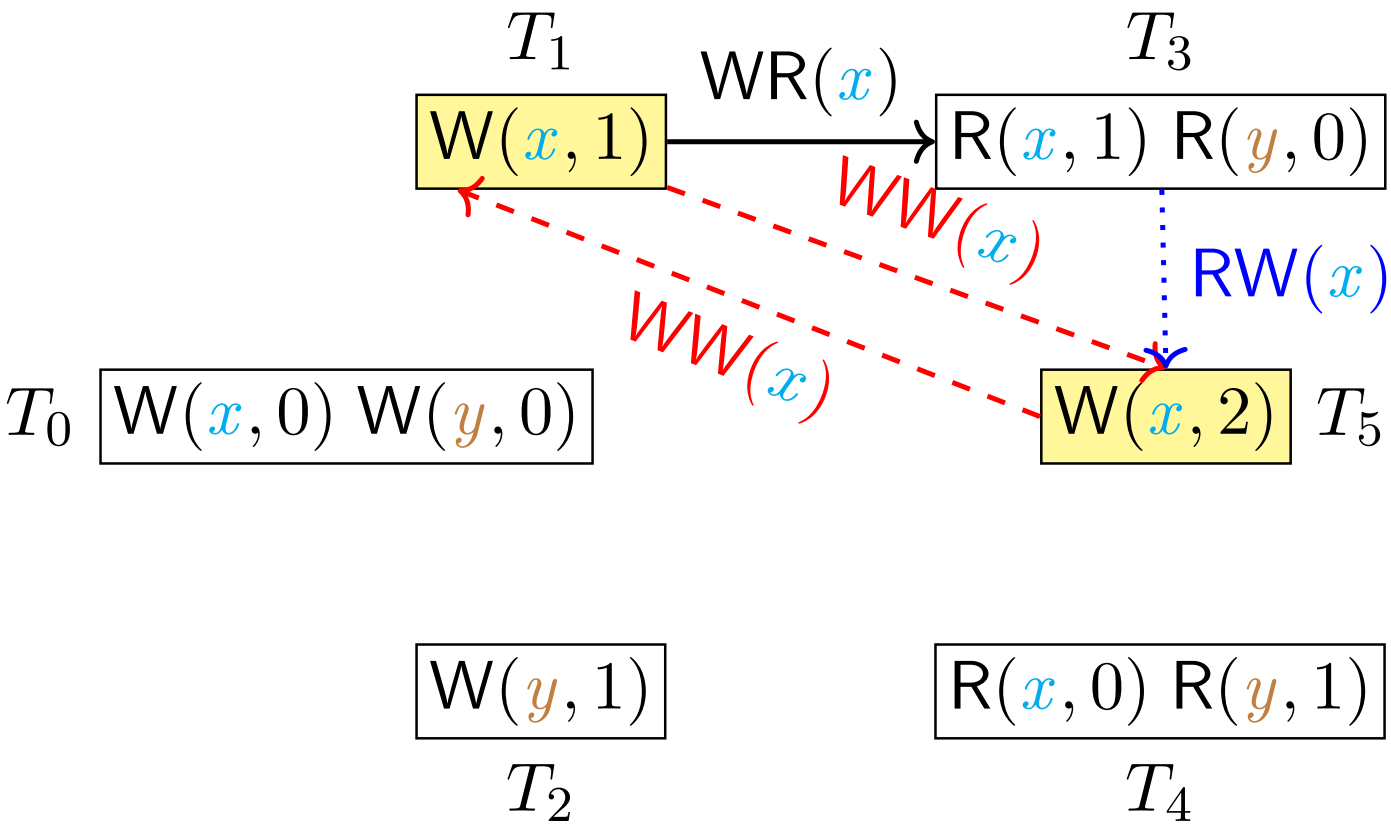
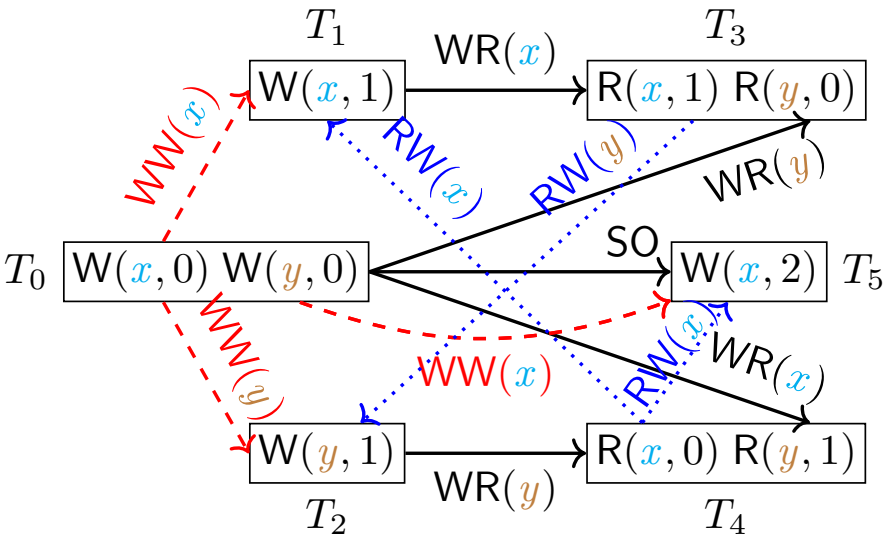
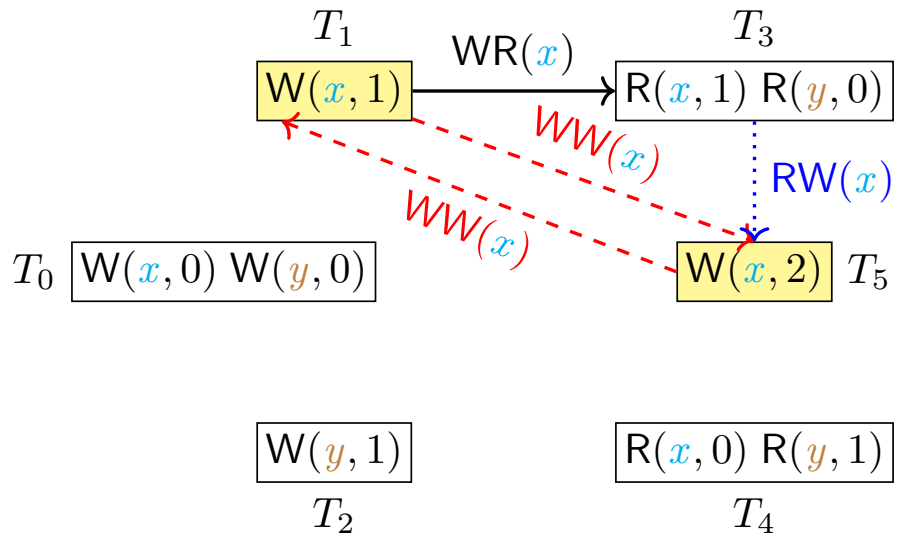


$$(\mathsf{BV}_{1,5} \wedge \mathsf{BV}_{3,5} \wedge \neg\mathsf{BV}_{5,1}) \vee (\mathsf{BV}_{5,1} \wedge \neg\mathsf{BV}_{1,5} \wedge \neg\mathsf{BV}_{3,5})$$

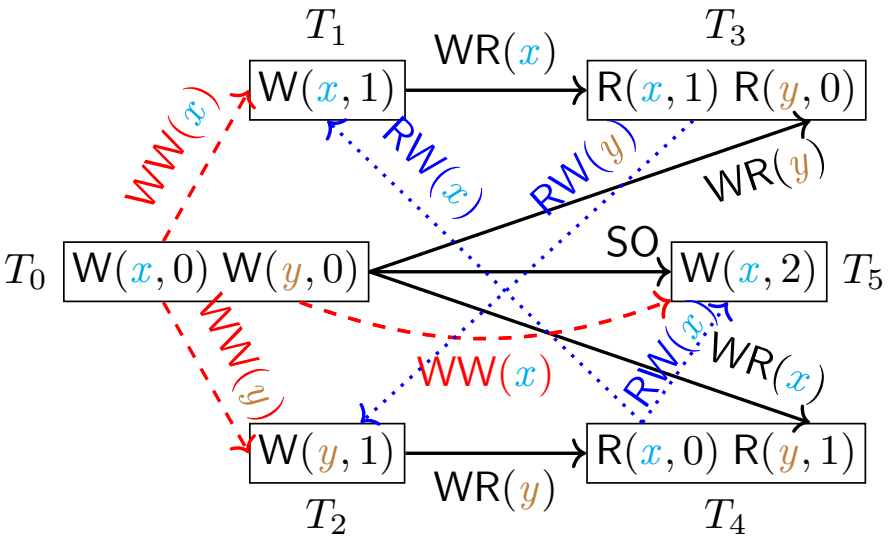
PolySI: An Illustrating Example of "Long Fork"

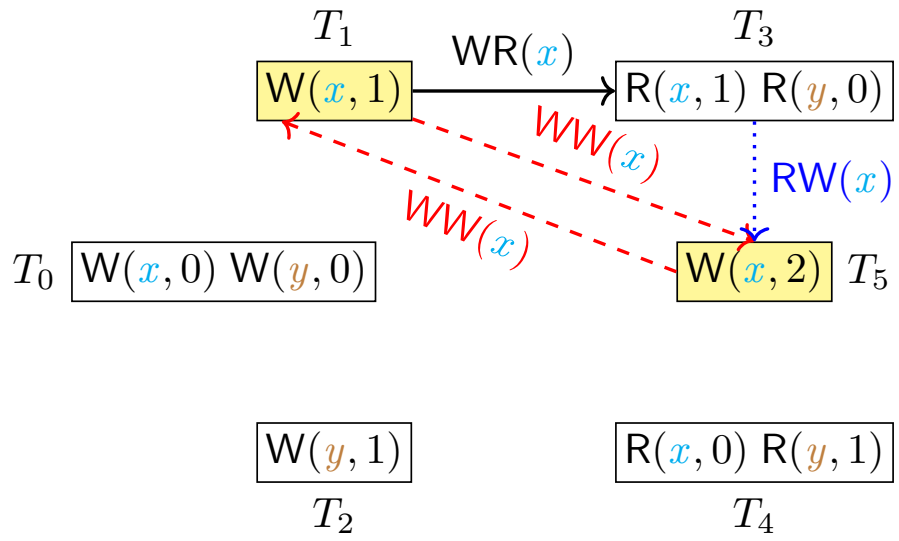




PolySI: An Illustrating Example of "Long Fork"

$((\mathsf{SO}_{\mathcal{G}} \cup \mathsf{WR}_{\mathcal{G}} \cup \mathsf{WW}_{\mathcal{G}})\ ;\ \mathsf{RW}_{\mathcal{G}}?)$ *is acyclic.*





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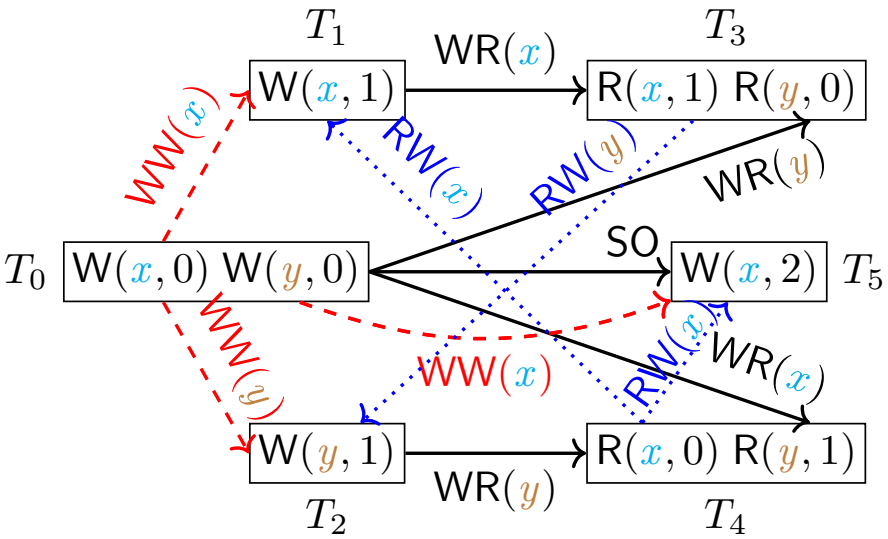

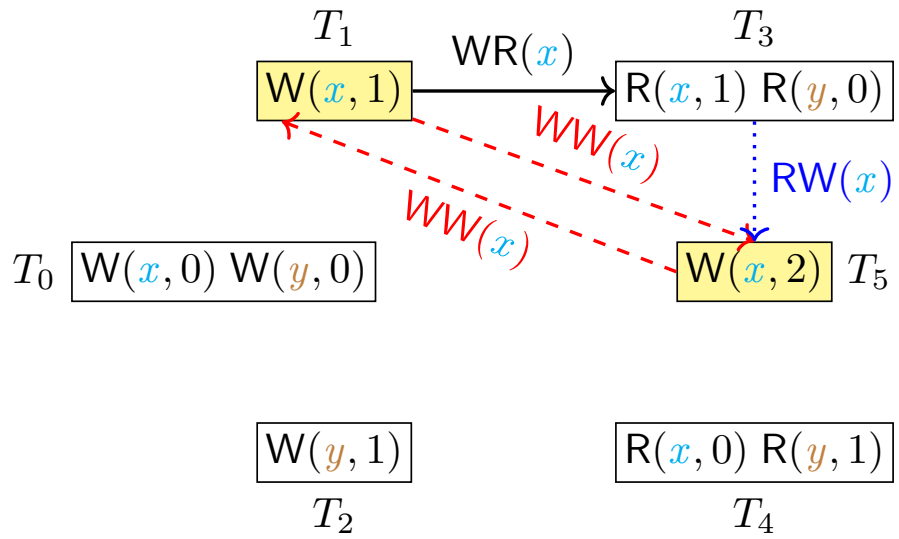

We need to encode the "composition (;)" of dependency edges.

PolySI: An Illustrating Example of "Long Fork"

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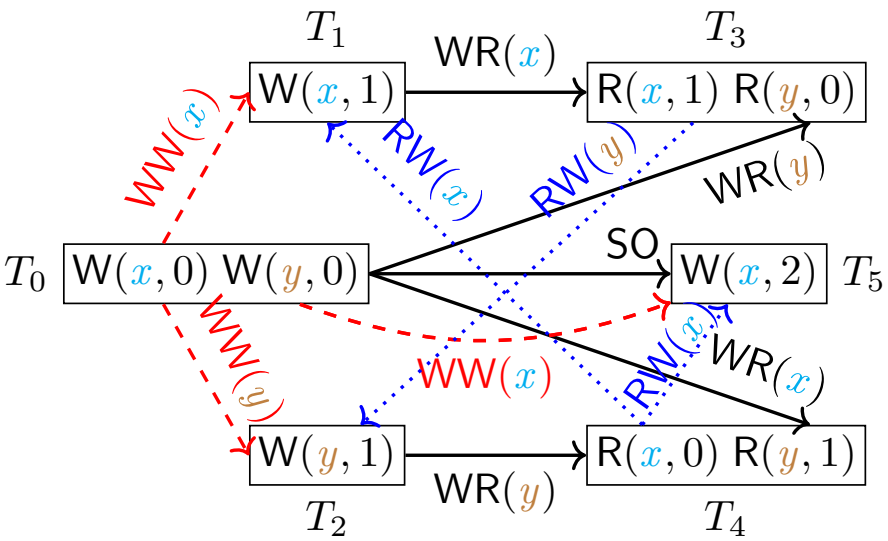

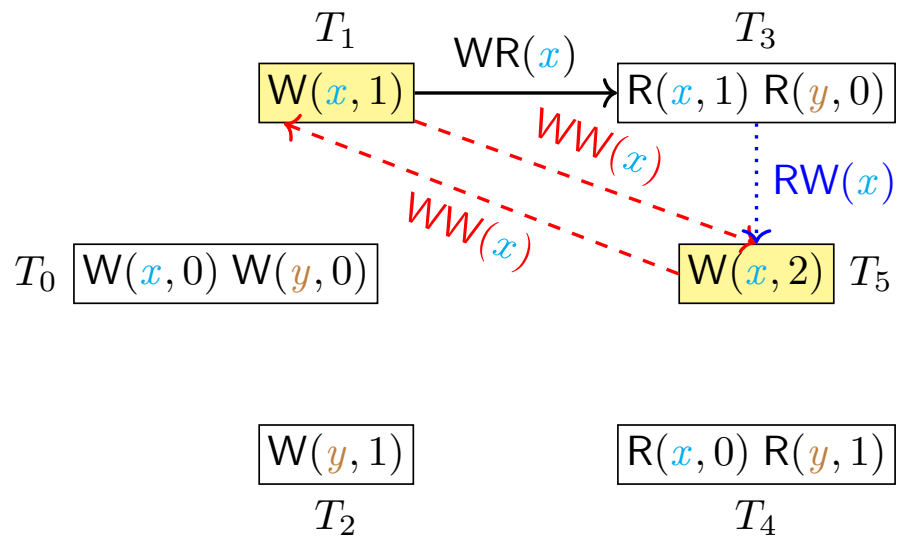

We need to encode the "composition (;)" of dependency edges.

$$T_1 \xrightarrow{\mathsf{WR}} T_3 \xrightarrow{\mathsf{RW}} T_2 : \; \mathsf{BV}^{I}_{1,2} = \mathsf{BV}_{1,3} \wedge \mathsf{BV}_{3,2} \quad (I \text{ for the induced graph})$$

PolySI: An Illustrating Example of "Long Fork"

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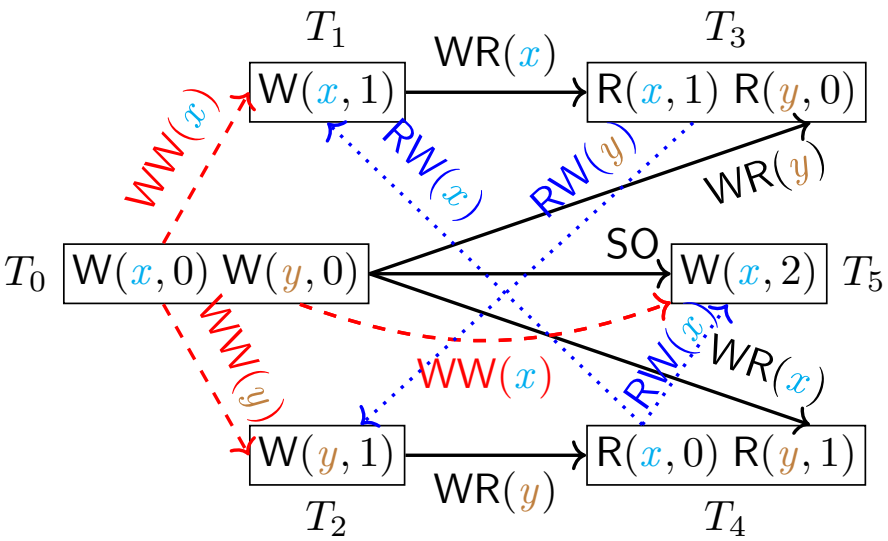

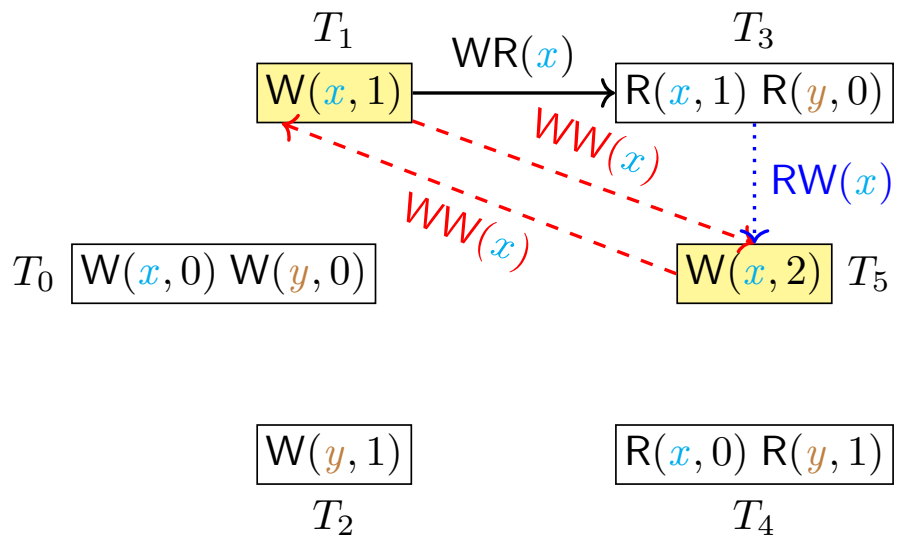

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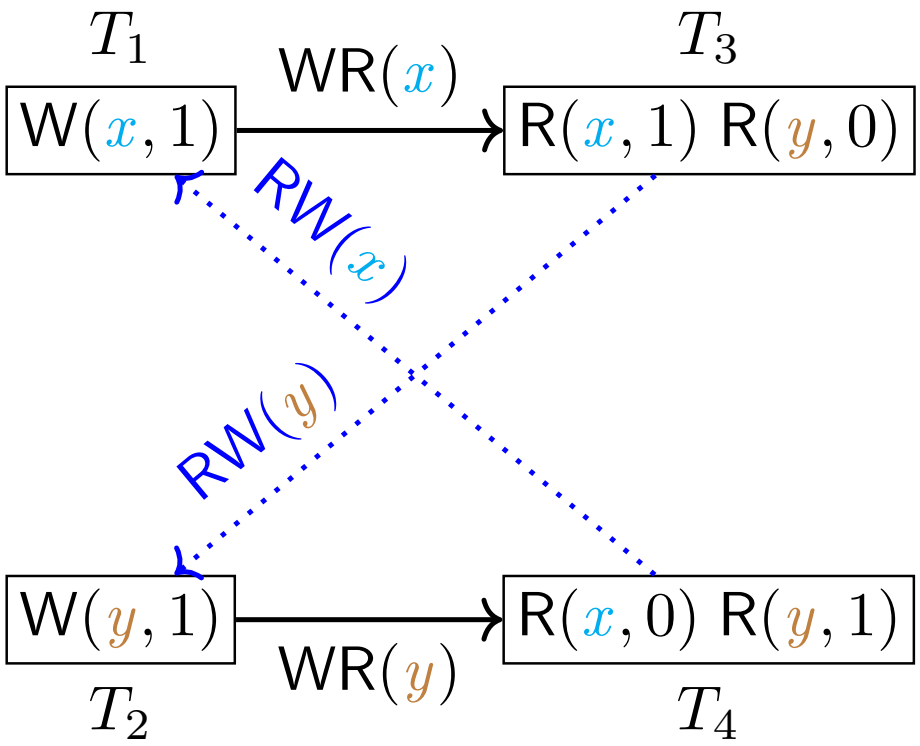
$$T_1 \xrightarrow{\mathsf{WR}} T_3 \xrightarrow{\mathsf{RW}} T_5 : \; \mathsf{BV}^{I}_{1,5} = \mathsf{BV}_{1,3} \wedge \mathsf{BV}_{3,5} \quad (I \text{ for the induced graph})$$

PolySI: An Illustrating Example of "Long Fork"

Feed the SAT formula into the MonoSAT solver [Bayless et al., 2015] optimized for *cycle detection*

Assert that the induced graph I is acyclic.

PolySI: An Illustrating Example of "Long Fork"



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?

`https://github.com/hengxin/PolySI-PVLDB2023-Artifacts`

Workloads

Table: Workload parameters and their default values.

Parameter	Default Value
#sess	20
#txns/sess	100
#ops/txn	15
#keys	10, 000
%reads	50%
distribution	zipfian

Benchmarks

RuBis: an eBay-like bidding system

TPC-C: an open standard for OLTP benchmarking

C-Twitter: a Twitter clone

GeneralRH: read-heavy workloads with 95% reads

GeneralRW: medium workloads with 50% reads

GeneralWH: write-heavy workloads with 30% reads

Use a simple database schema of a *two-column table* storing keys and values.

Finding SI Violations

Table: Reproducing known SI violations.

Database	GitHub Stars	Kind	Release
CockroachDB	25.1k	Relational	v2.1.0, v2.1.6
MySQL-Galera	381	Relational	v25.3.26
YugabyteDB	6.7k	Multi-model	v1.1.10.0

An extensive collection of 2477 anomalous histories

[Biswas and Enea, 2019; Darnell, Accessed February 14, 2023; Jepsen, Accessed February 14, 2023]

Finding SI Violations

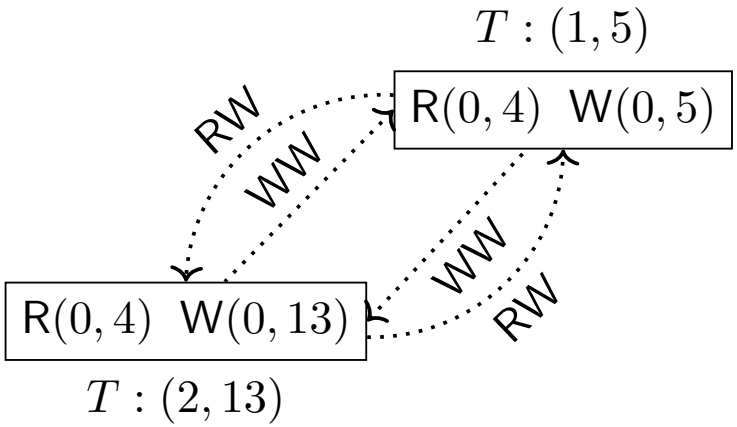
Dgraph: helped the Dgraph team confirm some of their suspicions about their latest release

Table: Detecting new violations.

Database	**GitHub Stars**	**Kind**	**Release**
Dgraph	18.2k	Graph	v21.12.0
MariaDB-Galera	4.4k	Relational	v10.7.3
YugabyteDB	6.7k	Multi-model	v2.11.1.0

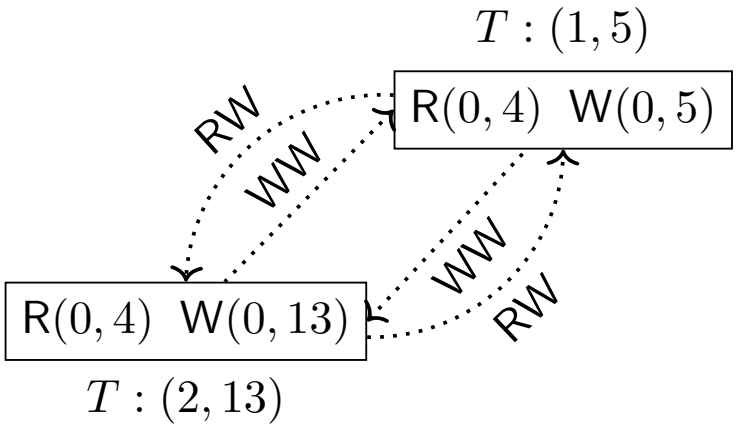
Galera: confirmed the incorrect claim on preventing "lost updates" for transactions issued on different cluster nodes

Understanding Violations (Lost Update)

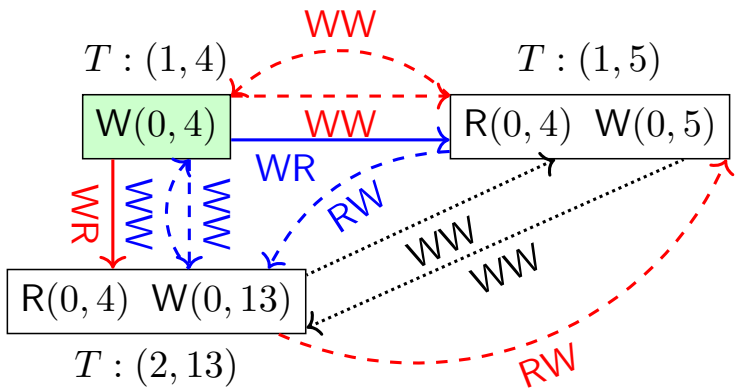


(a) Original output

Understanding Violations (Lost Update)

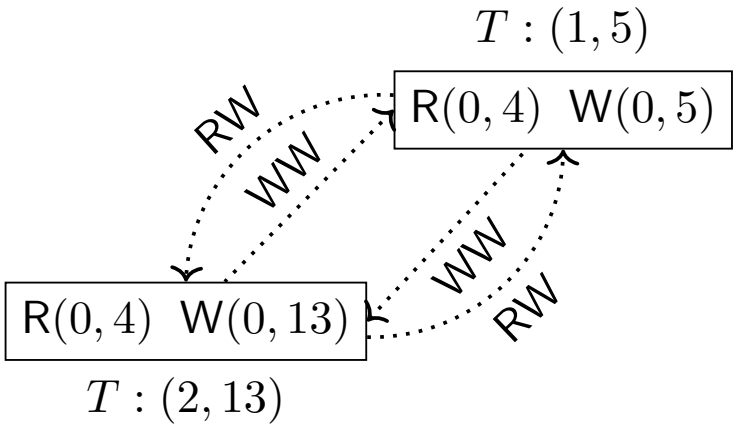


(a) Original output

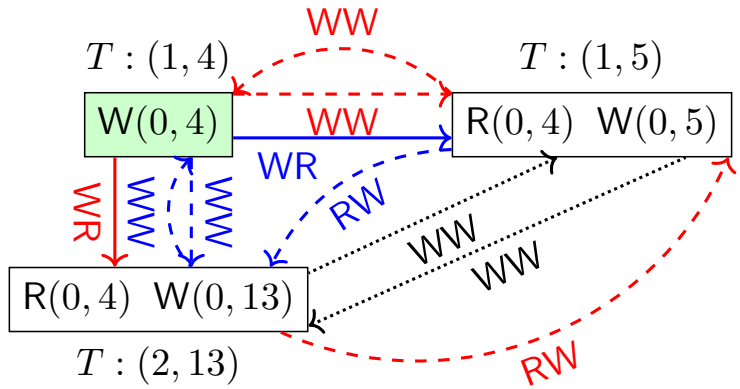


(b) Missing participants

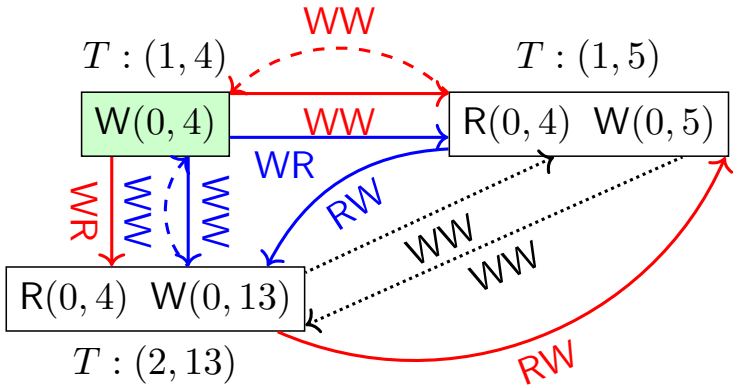
Understanding Violations (Lost Update)



(a) Original output

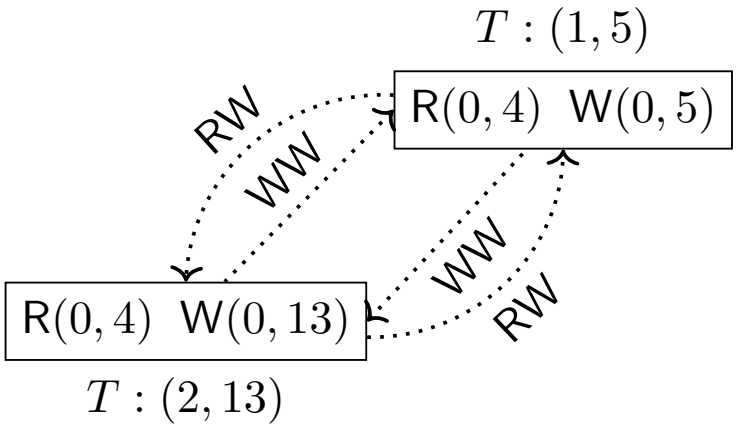


(b) Missing participants

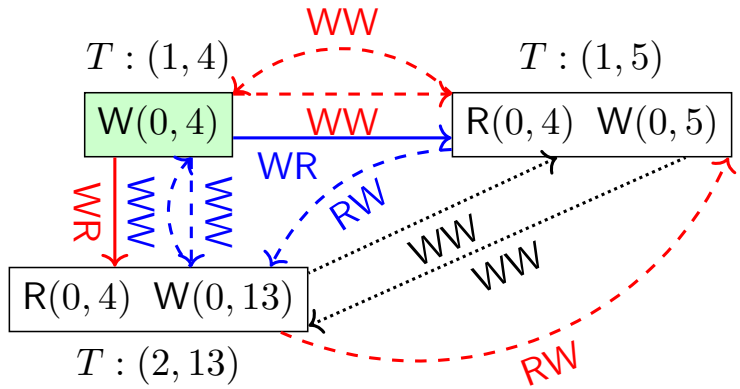


(c) Recovered scenario

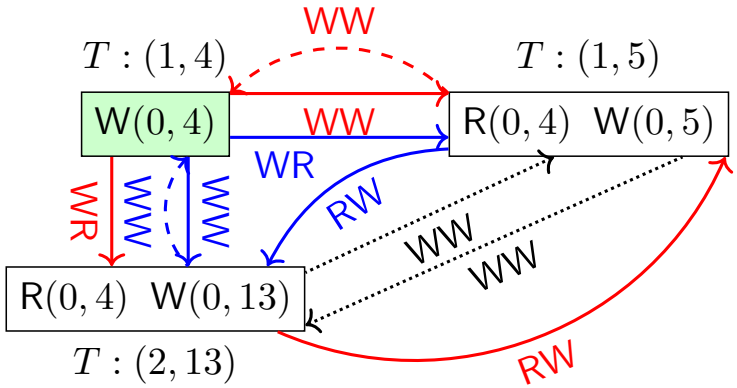
Understanding Violations (Lost Update)



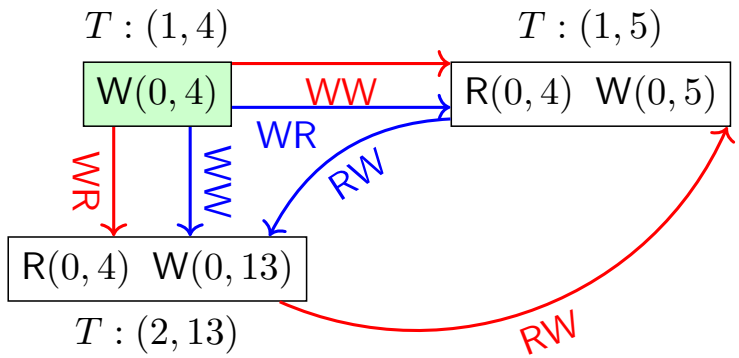
(a) Original output



(b) Missing participants



(c) Recovered scenario



(d) Finalized scenario

Performance Evaluation

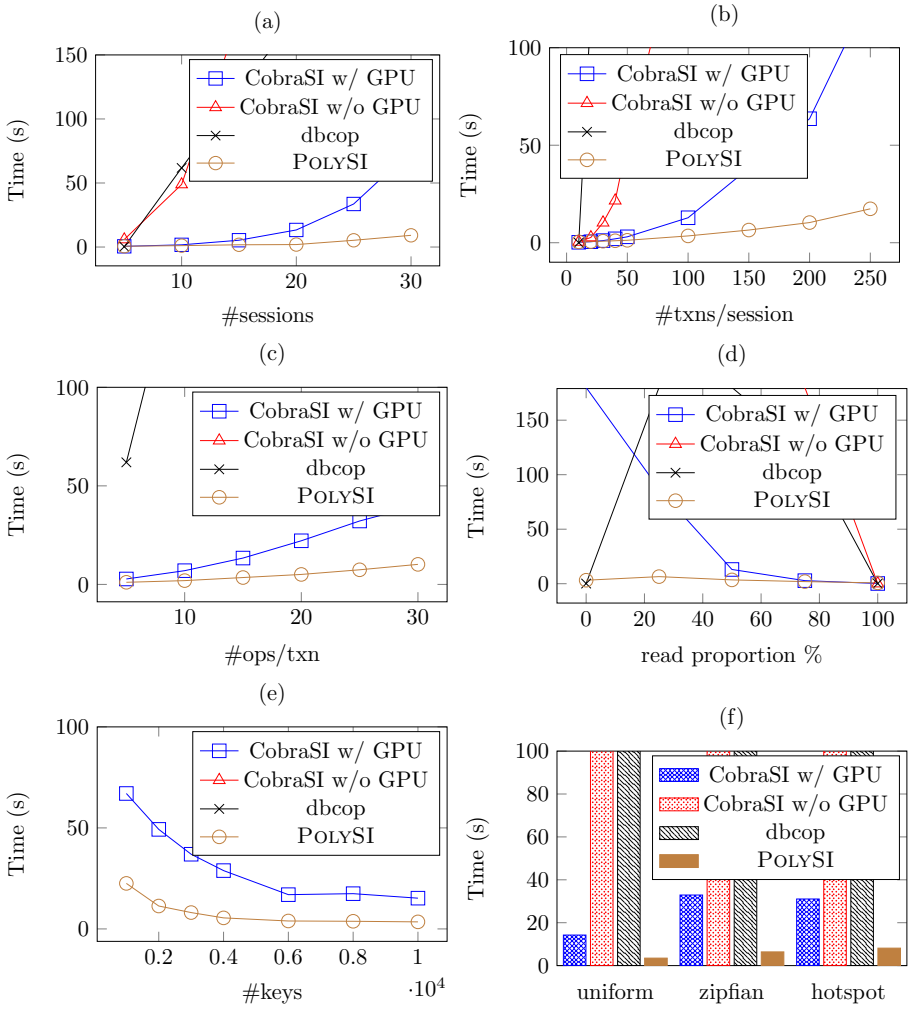
dbcop [Biswas and Enea, 2019]: the state-of-the-art SI checker without using SAT solvers

Cobra [Tan et al., 2020]: the state-of-the-art SER checker using both MonoSAT and GPU; as a baseline

CobraSI: reducing SI checking to SER checking [Biswas and Enea, 2019] to leverage Cobra with/without GPU

Performance Evaluation: Runtime

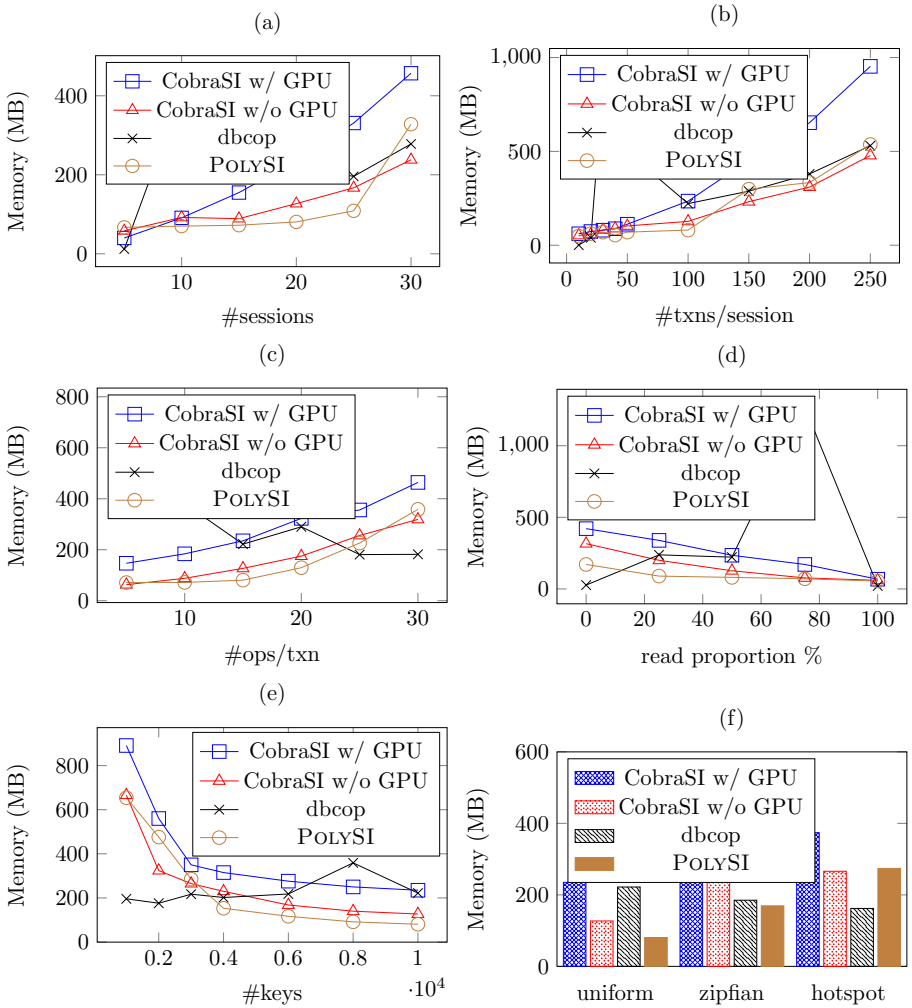
PolySI significantly outperforms the competitors.



All the input histories extracted from PostgreSQL satisfy SI.

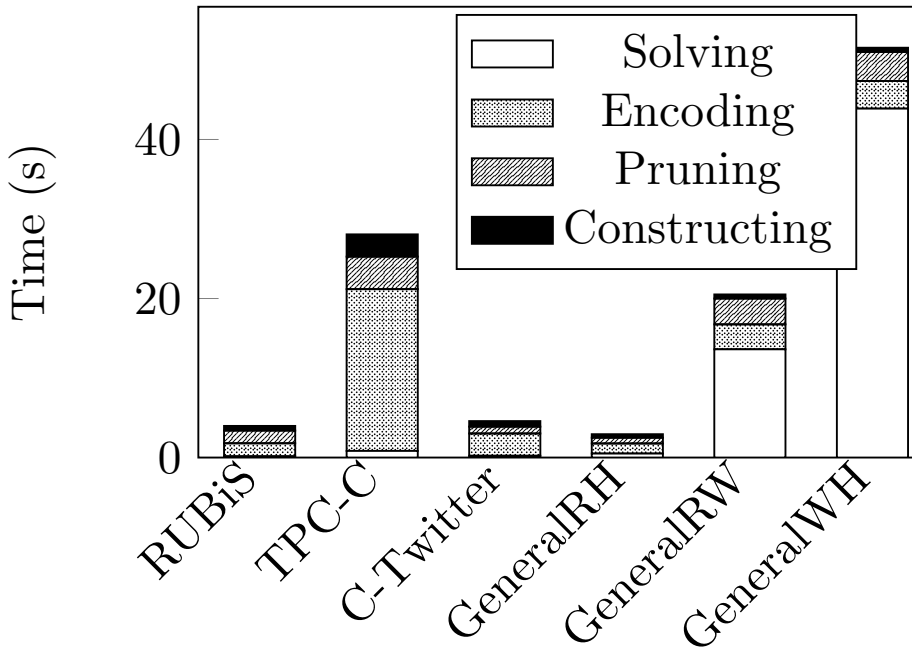
Performance Evaluation: Memory

PolySI consumes less memory.



Performance Evaluation: Decomposition

TPC-C incurs more overhead in *encoding* as the number of operations in total is 5x more than the others.



The solving time depends on the remaining constraints and unknown dependencies *after pruning*.

Performance Evaluation: Pruning

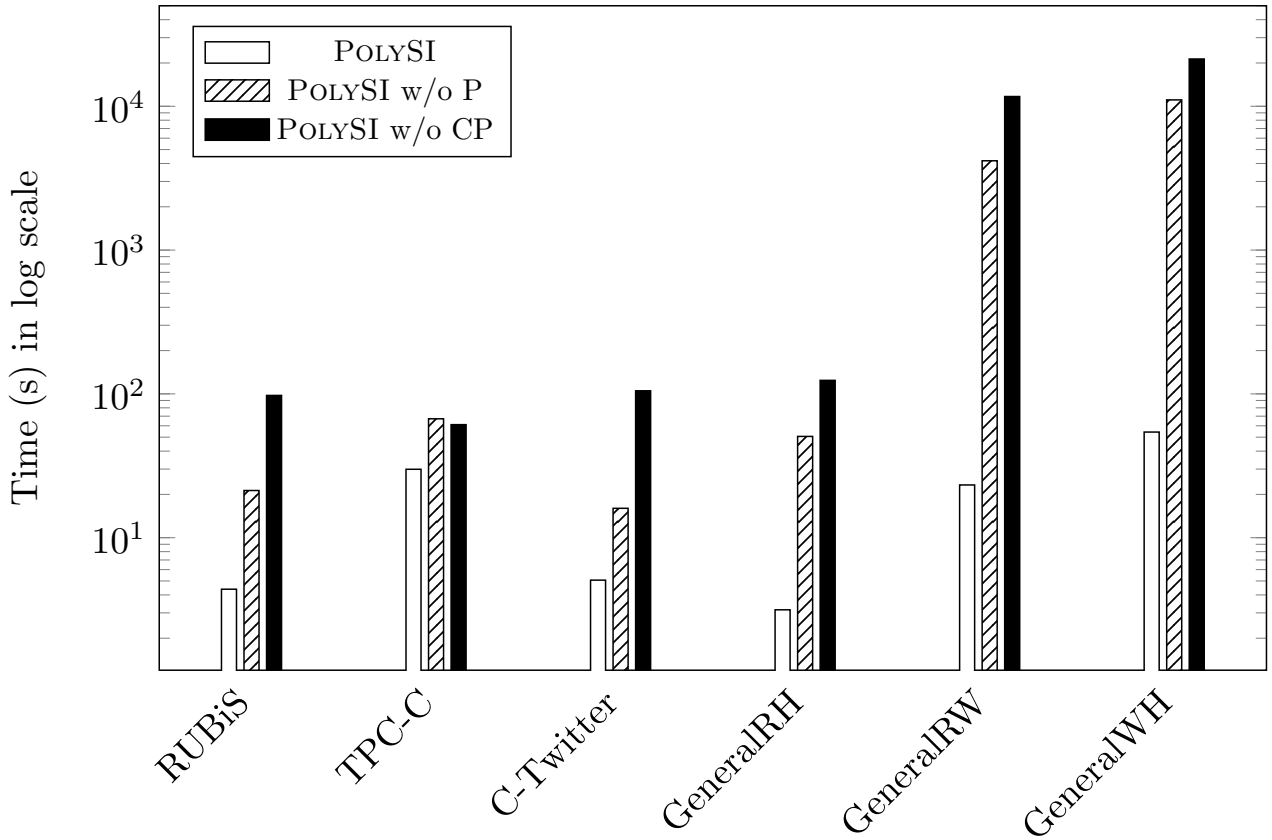
PolySI can effectively prune a huge number of constraints.

Benchmark	#cons. before P	#cons. after P	#unk. dep. before P	#unk. dep. after P
TPC-C	386k	0	3628k	0
GeneralRH	4k	29	39k	77
RUBiS	14k	149	171k	839
C-Twitter	59k	277	307k	776
GeneralRW	90k	2565	401k	5435
GeneralWH	167k	6962	468k	14376

TPC-C: read-only transactions + RMW transactions

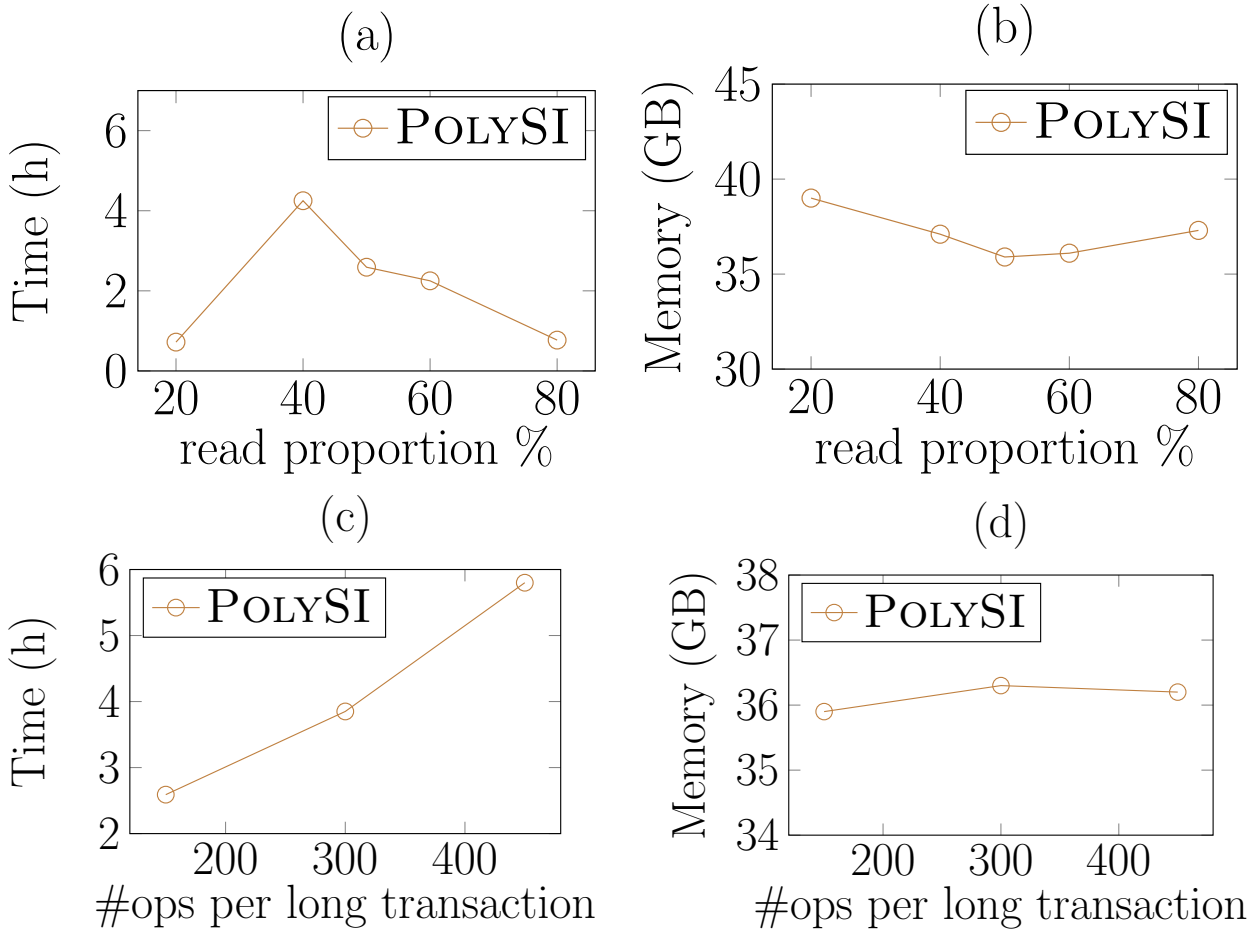
Performance Evaluation: Differential Analysis

Pruning is crucial to the efficiency of PolySI.

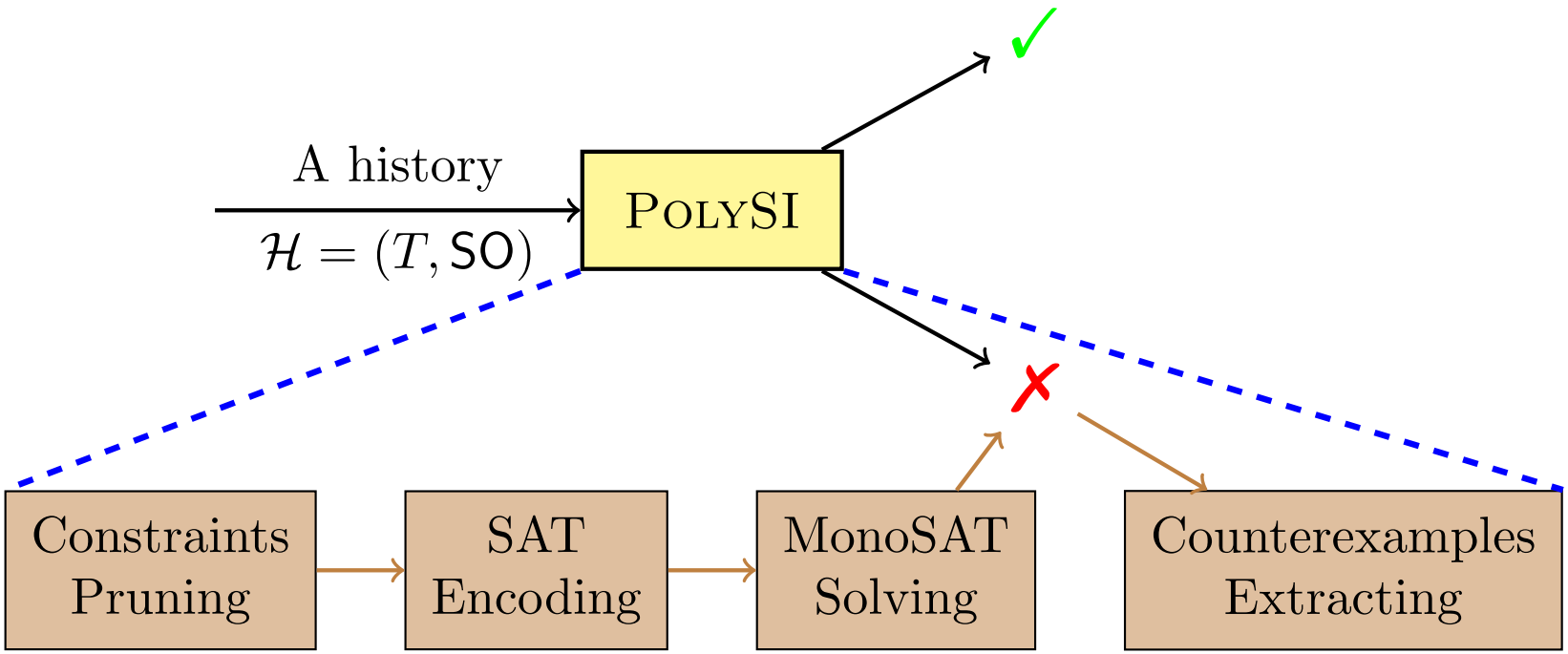


Performance Evaluation: Scalability

several hours and 35 $\sim$ 40GB memory for checking 1M transactions



Conclusion


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

Future Work

PolySI uses MonoSAT as a black-box.

Working on a **theory solver** dedicated to isolation level checking, which is deeply integrated with SAT solvers [He, Sun, and Fan, 2021].

Hengfeng Wei (hfwei@nju.edu.cn)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