Efficient Black-box Checking of Snapshot Isolation in Databases

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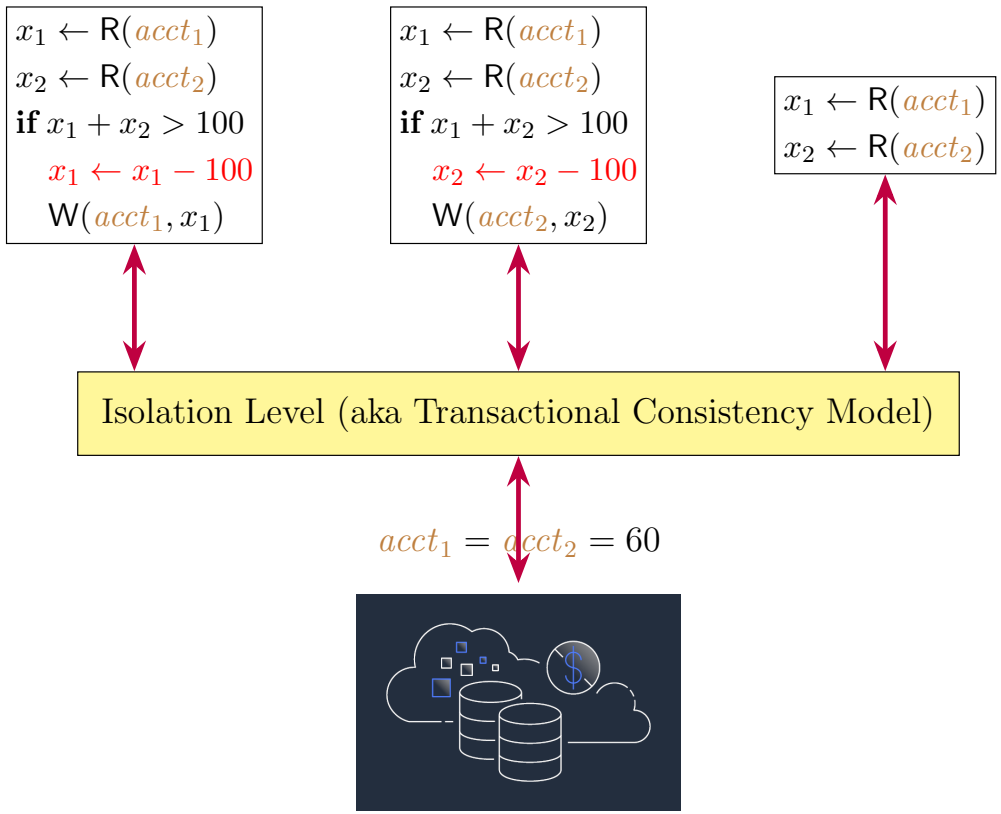
Transaction and Isolation Level

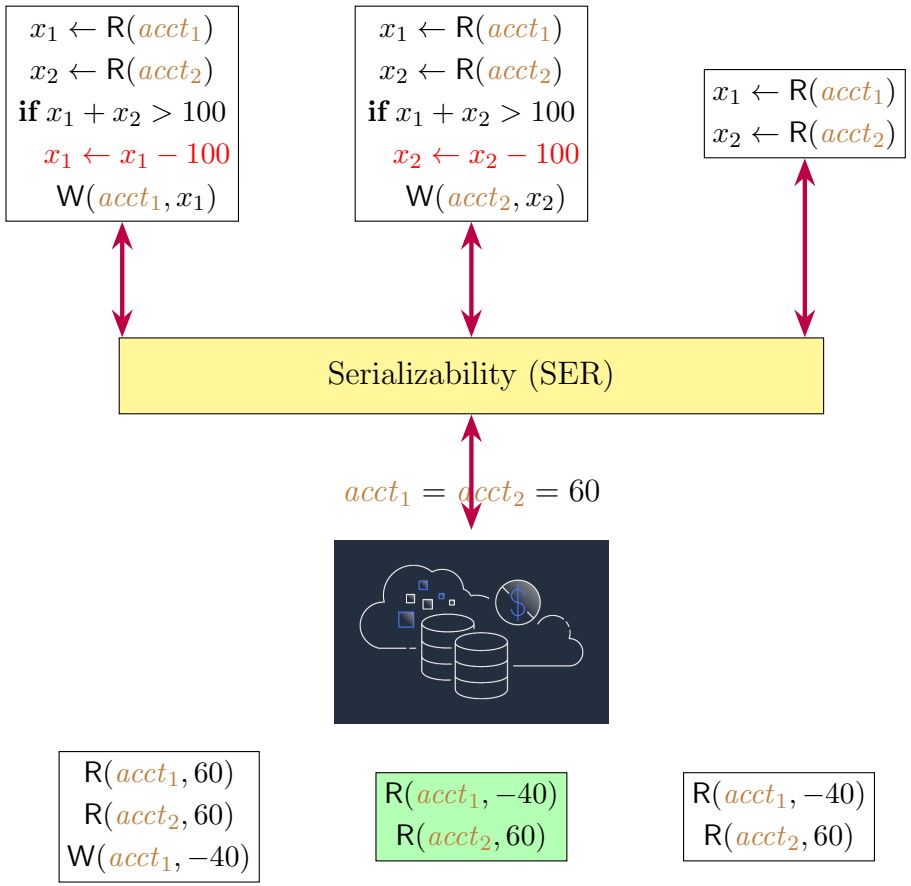
A transaction is a *group* of operations that are executed atomically.



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

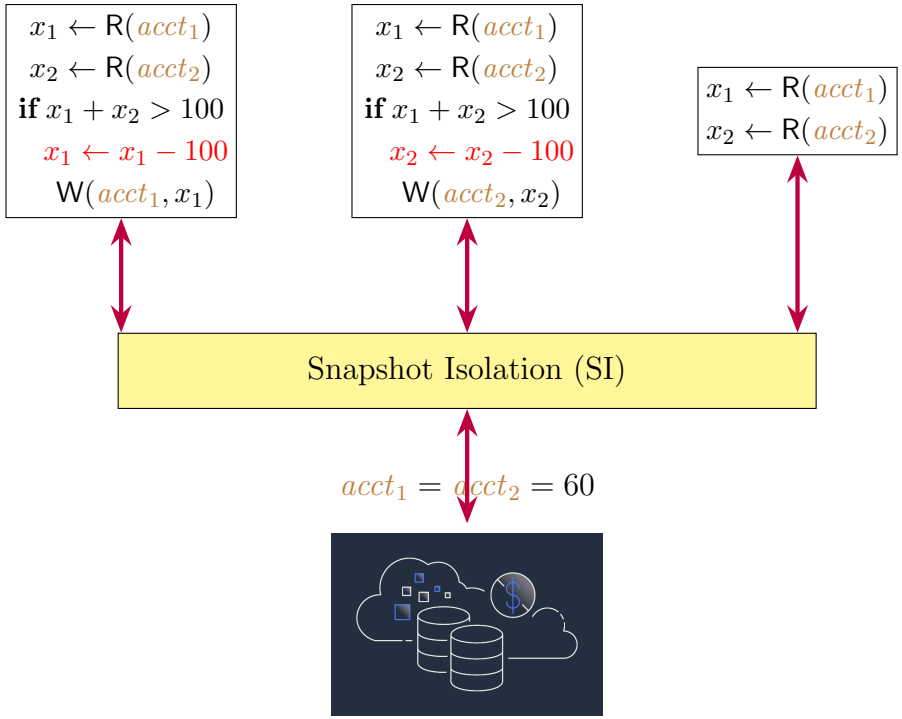
Serializability (SER)

All transactions appear to be executed in some total order.



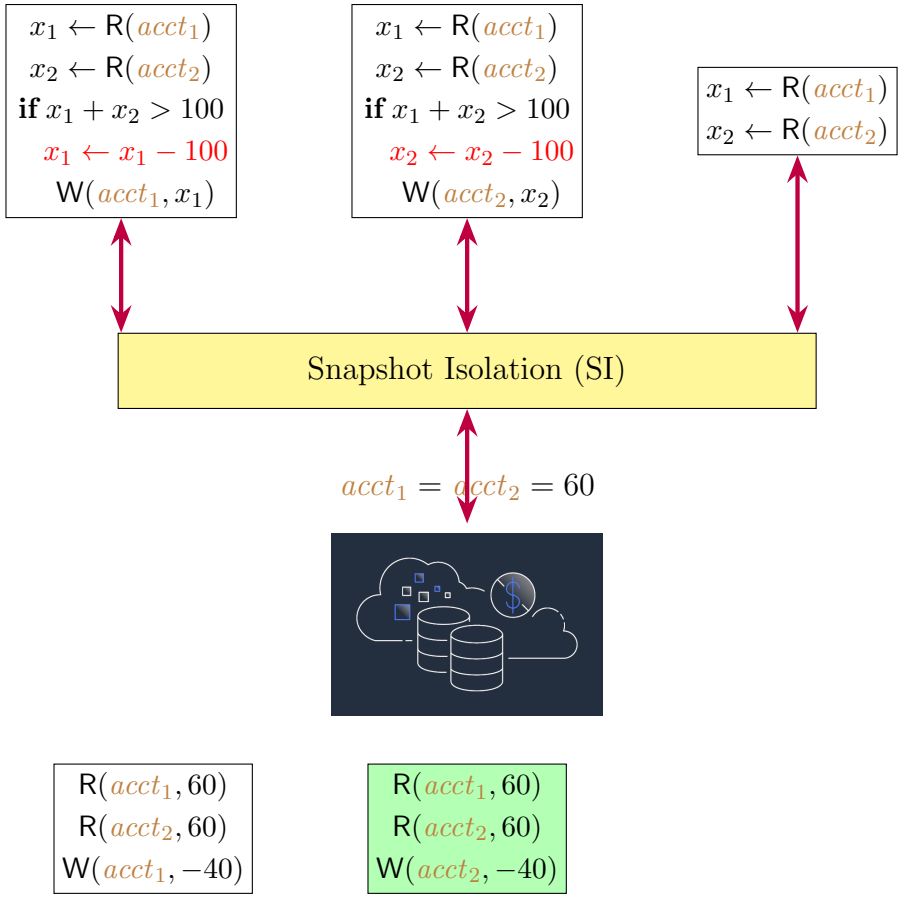
Implementing SER is too expensive.

Snapshot Isolation (SI)



Snapshot Read: Each transaction reads data from a *snapshot* as of the time the transaction started.

Snapshot Isolation (SI)



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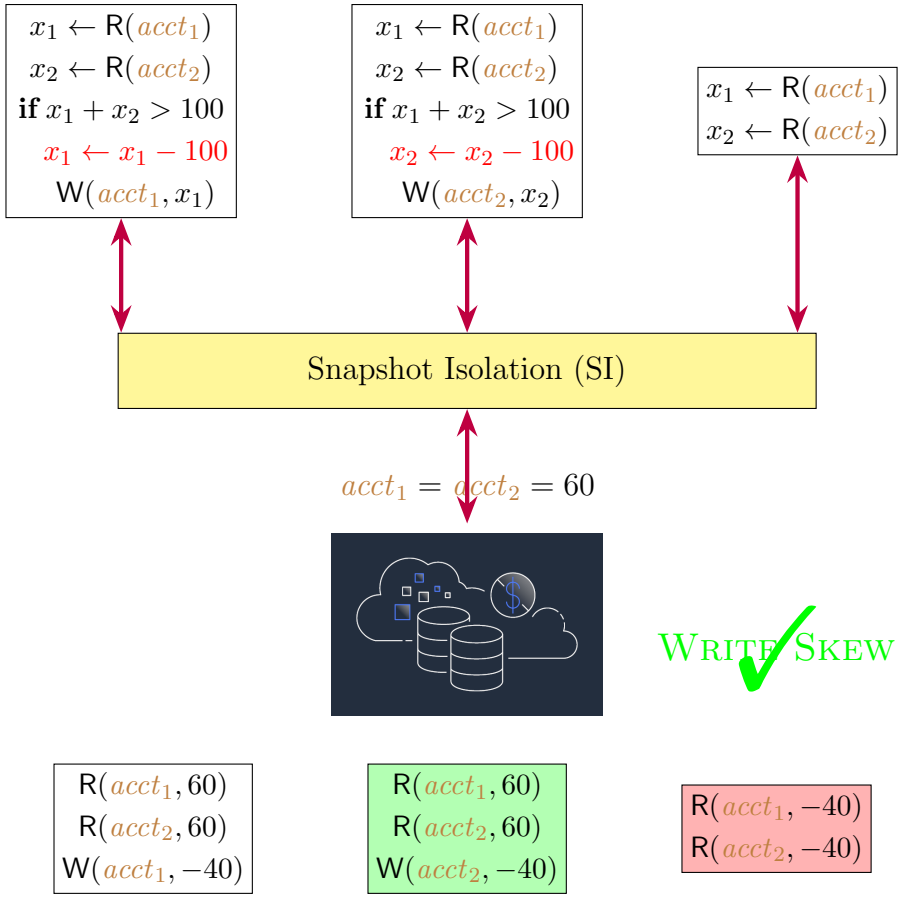

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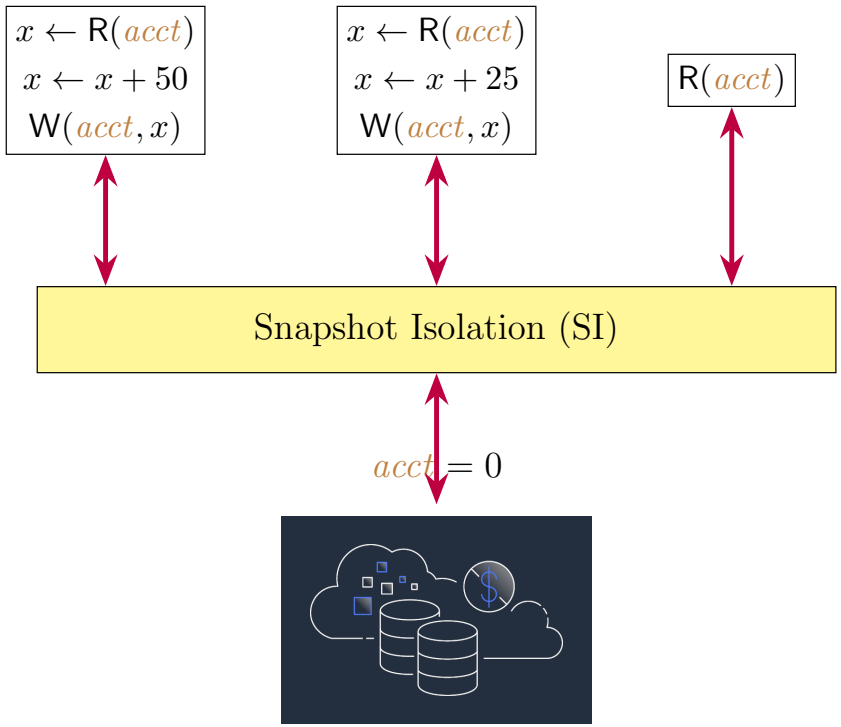
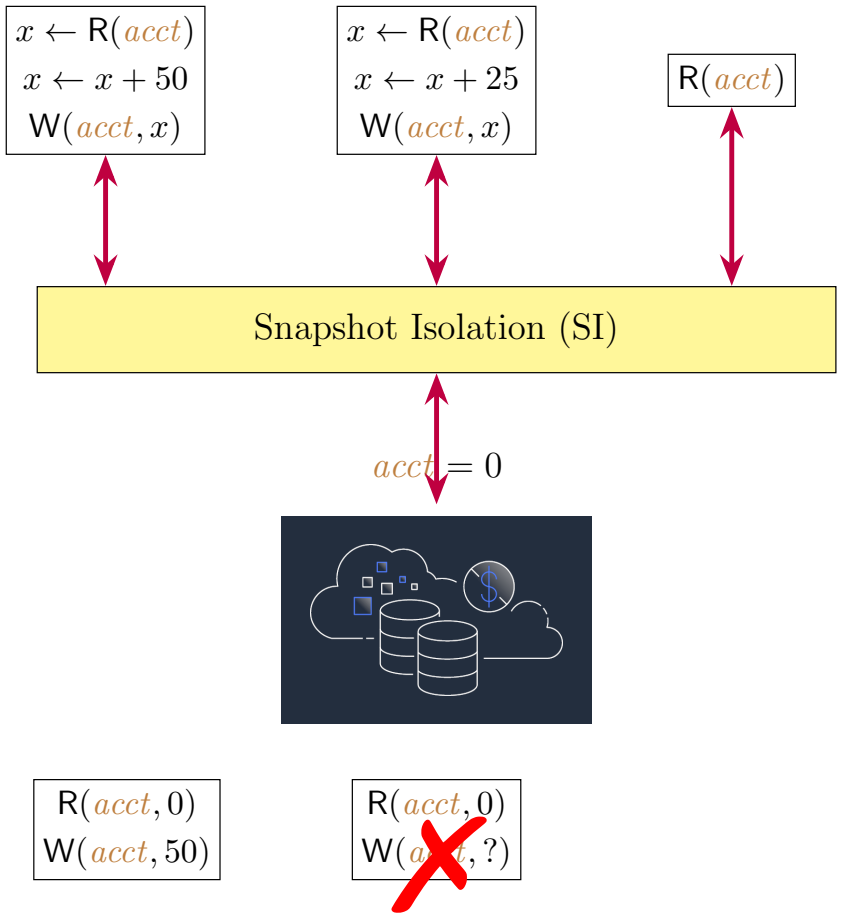


Snapshot Write: Concurrent transactions *cannot* write to the same key. One of them must be aborted.

Snapshot Isolation (SI)



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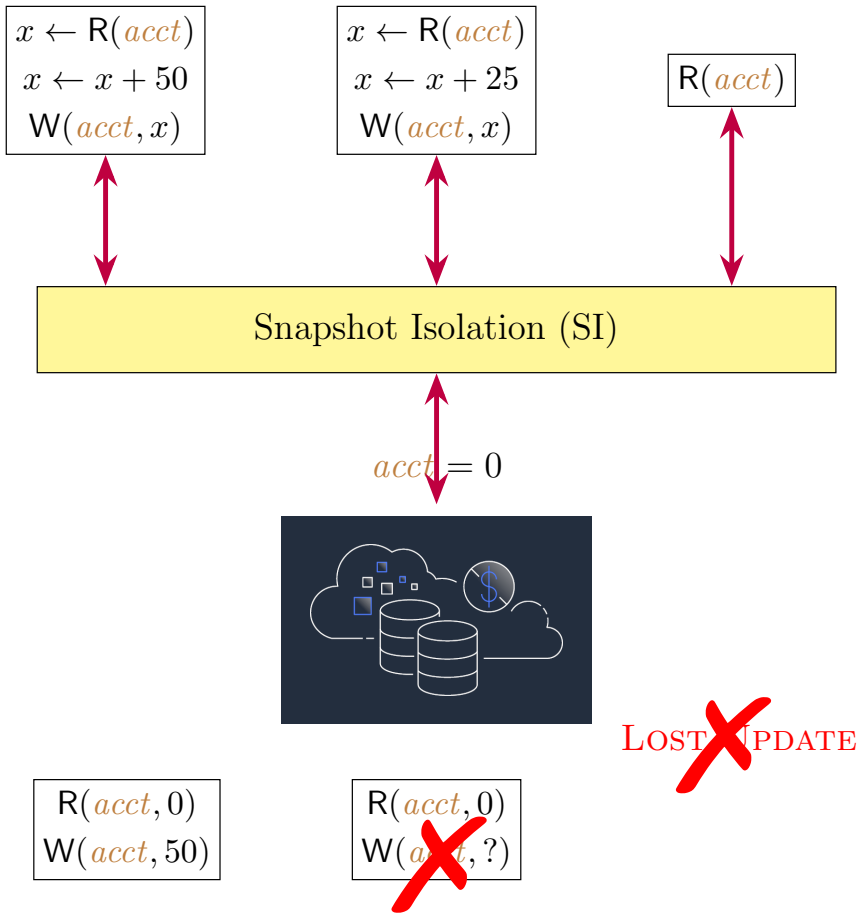


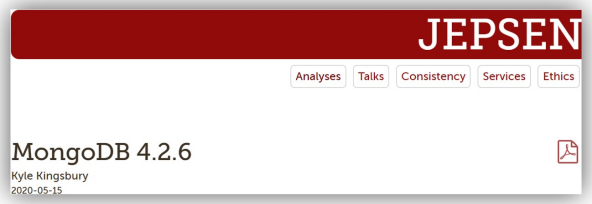
Snapshot Write: Concurrent transactions *cannot* write to the same key. One of them must be aborted.

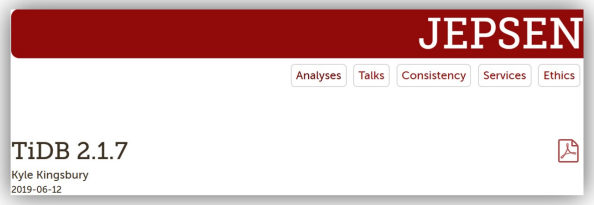
Database systems and Snapshot Isolation

Many database systems implement SI.

Database Systems and Snapshot Isolation

Database systems may fail to provide SI correctly.





Elle: Inferring Isolation Anomalies from Experimental Observations

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Peter Alvaro
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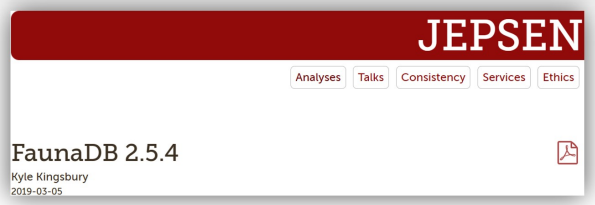
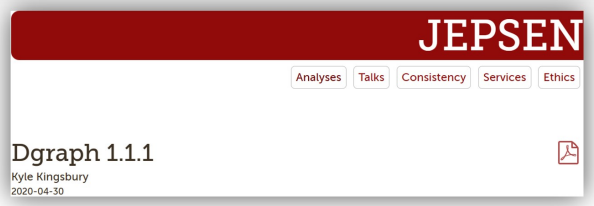
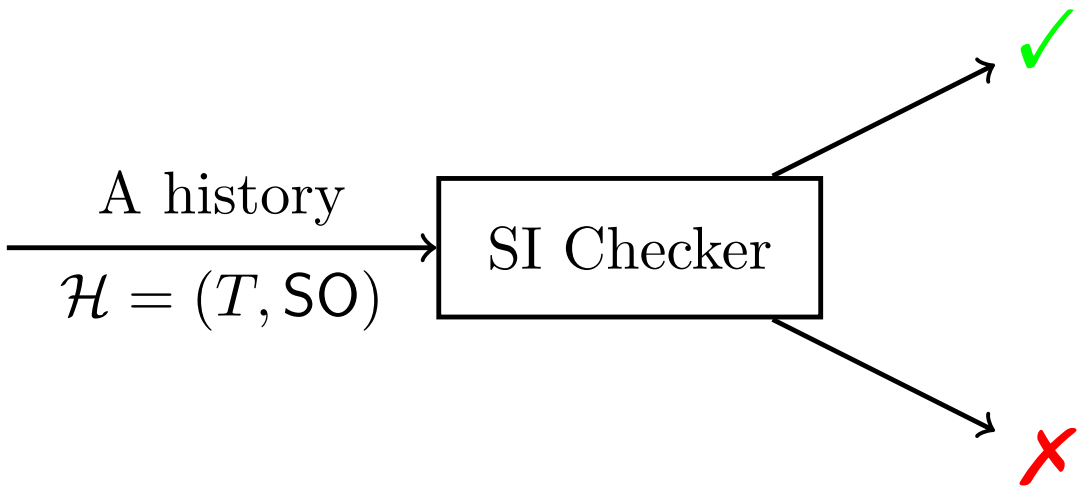




The SI Checking Problem

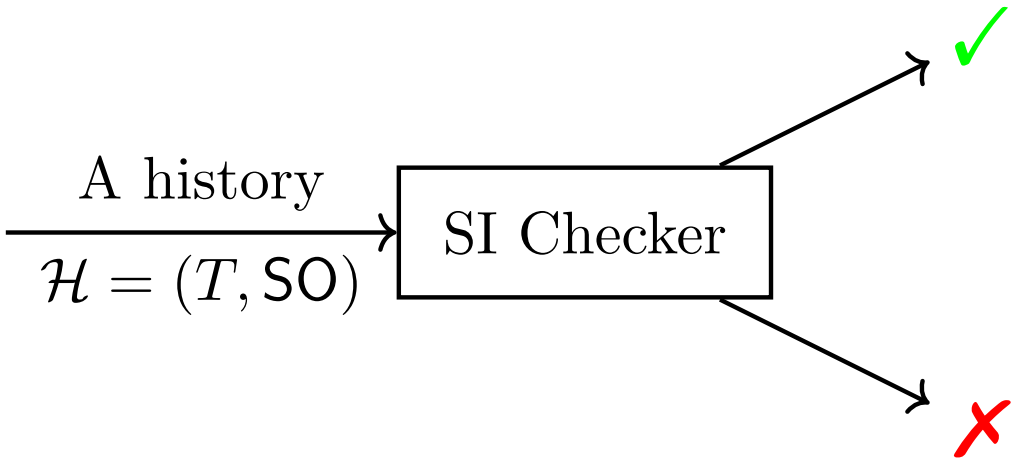
Definition (The SI Checking Problem)

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



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

The SI Checking Problem



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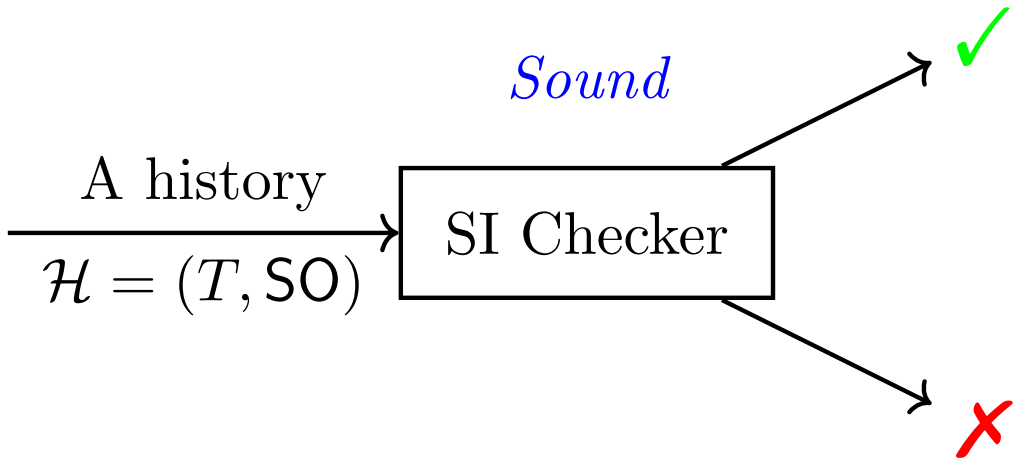
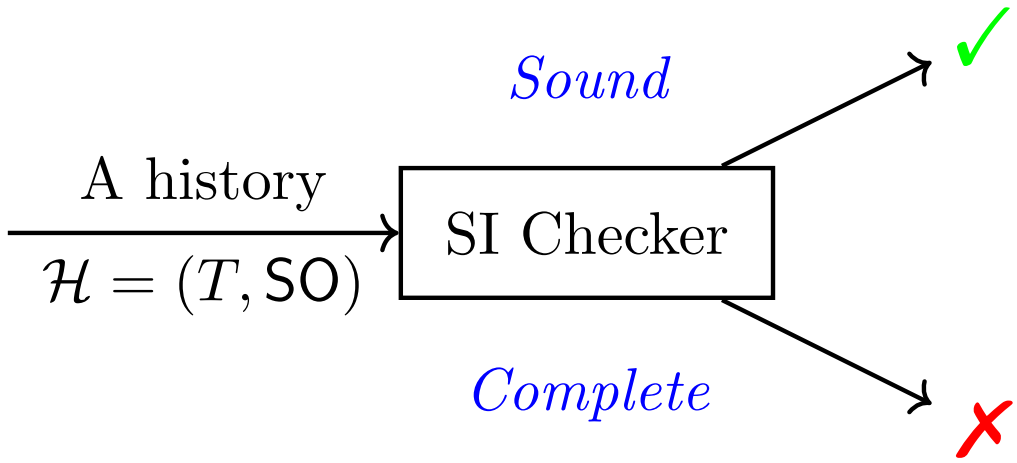


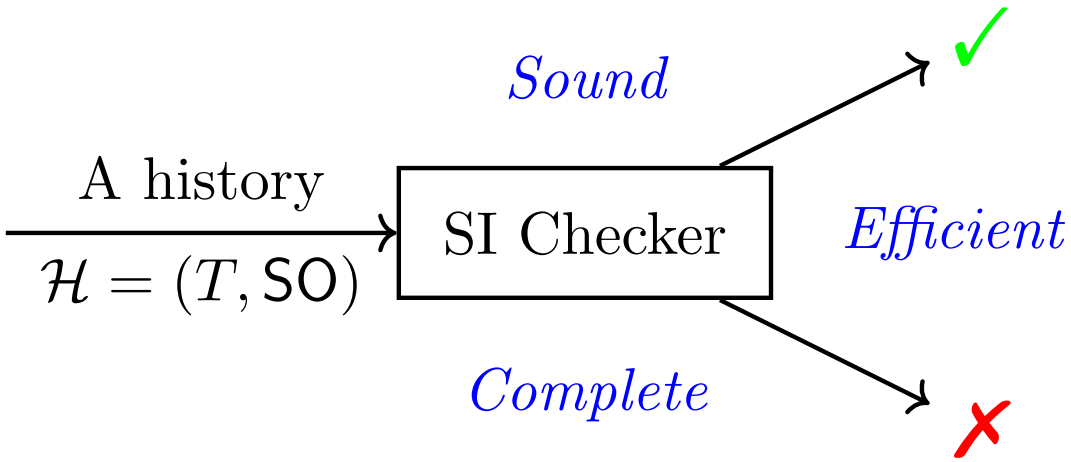
Sound: If the checker says ✗, then the history does *not* satisfy SI.

The SI Checking Problem



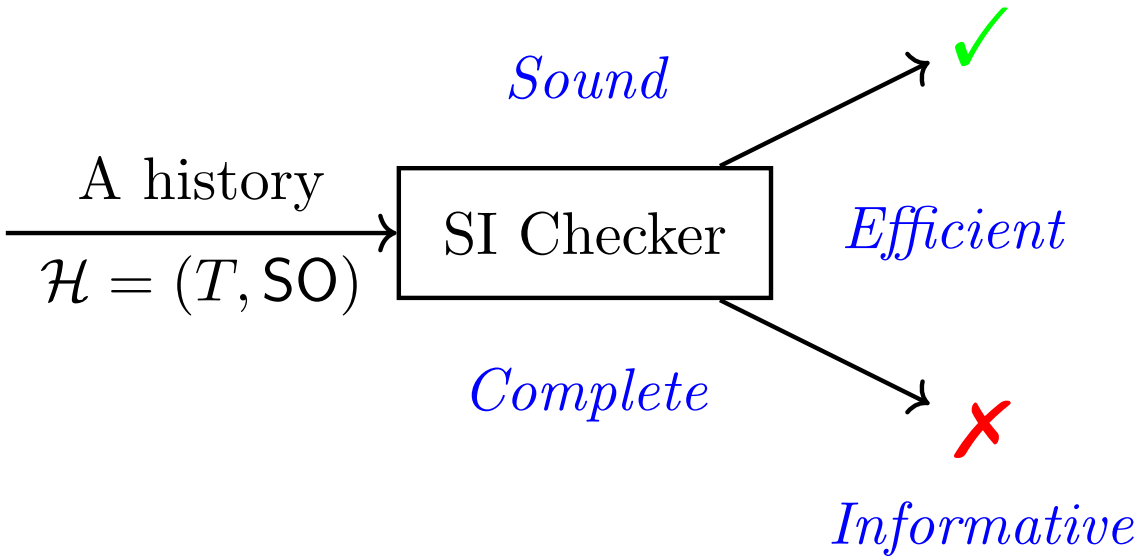
Complete: If the checker says ✓, then the history *satisfies* SI.

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 finds violations.

Related Work

dbcop [Biswas and Enea, 2019] checker for SI

not practically efficient;

not informative, returning only "False" upon violations

[a] https://github.com/jepsen-io/elle/issues/17 (fixed now)

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Cobra [Tan et al., 2020] state-of-the-art checker for SER

SI checking is *harder* than SER checking.

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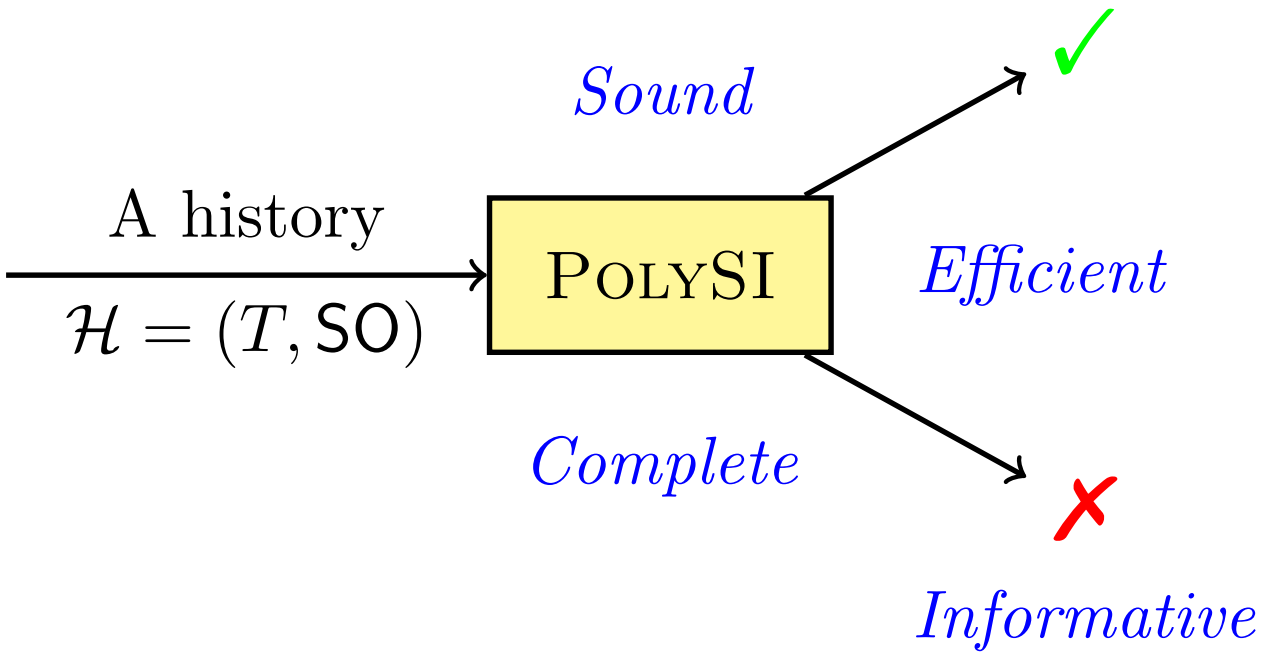
Contribution: the PolySI Checker



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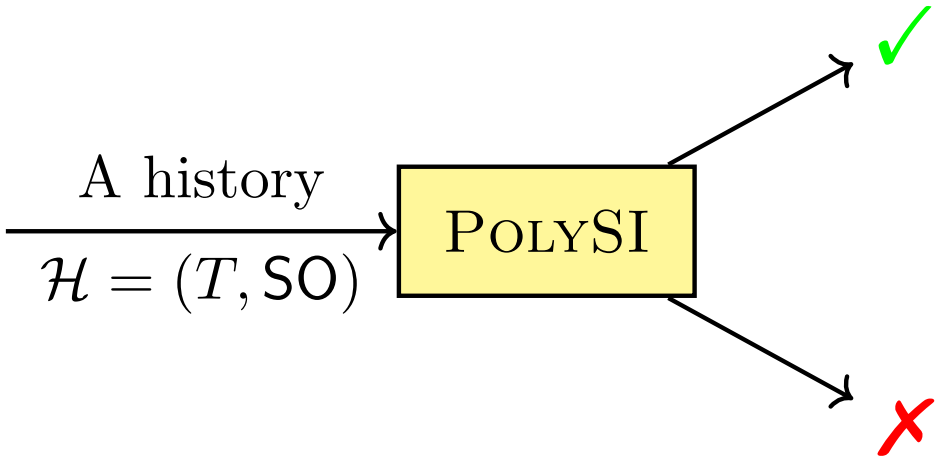

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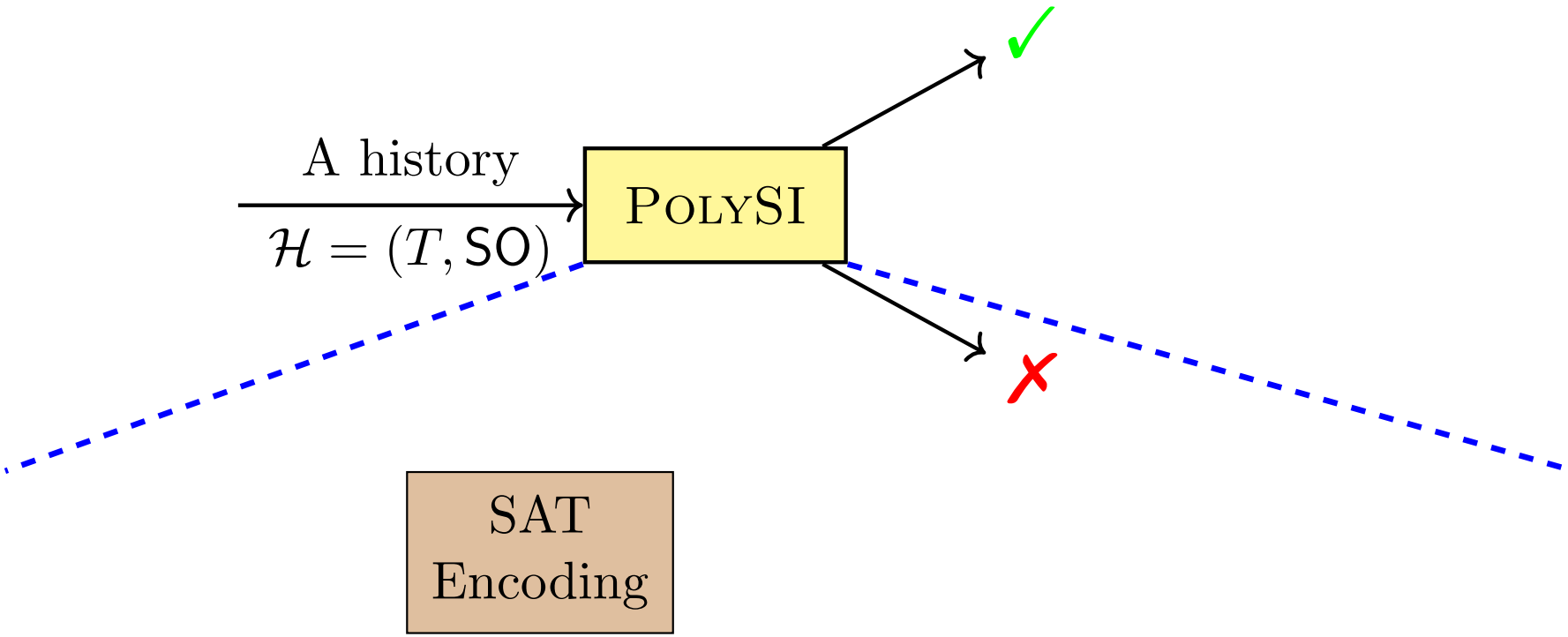
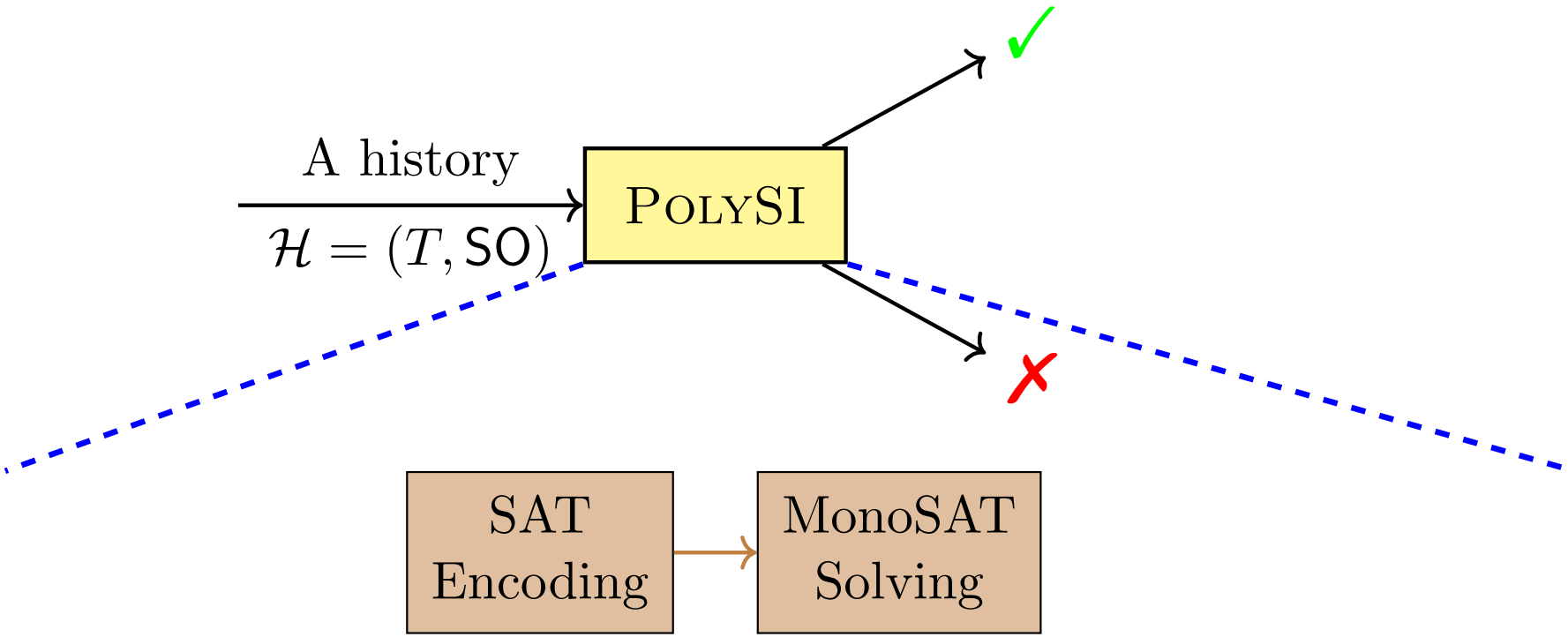


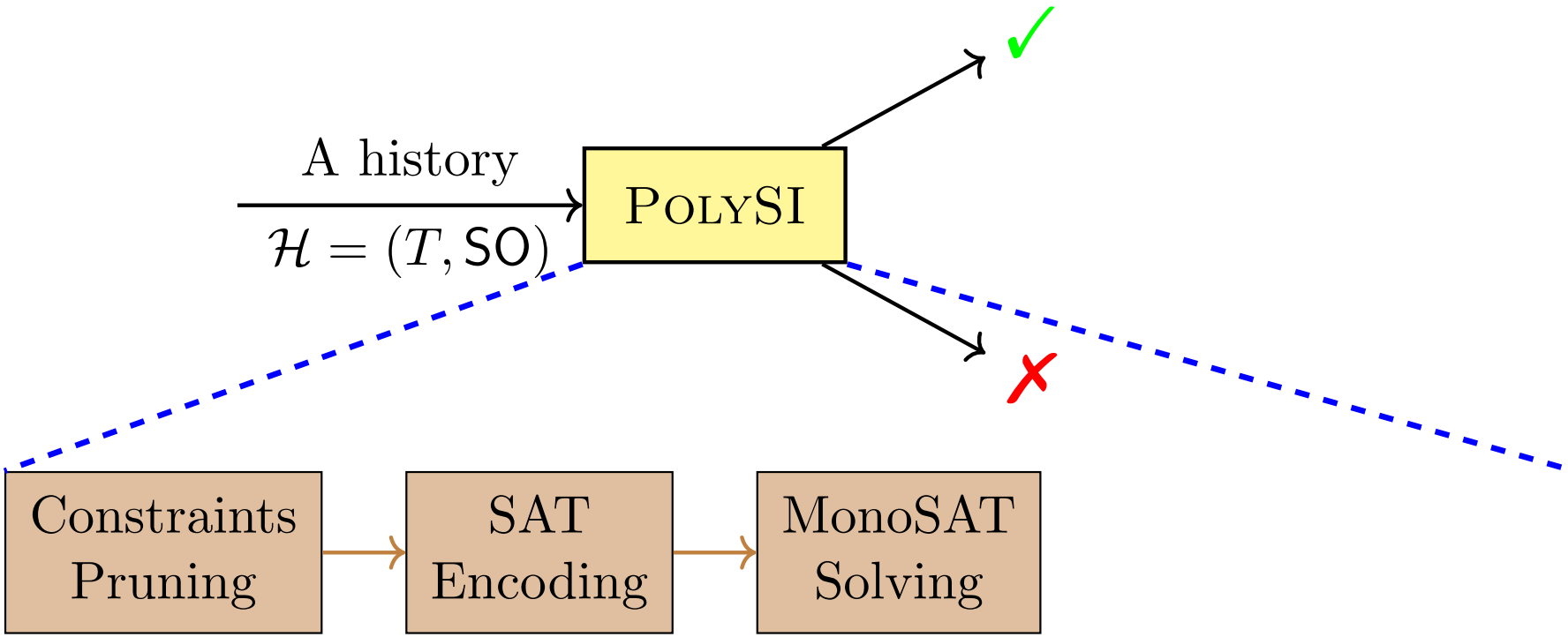
Sound & Complete: polygraph based characterization of SI

Contribution: the PolySI Checker



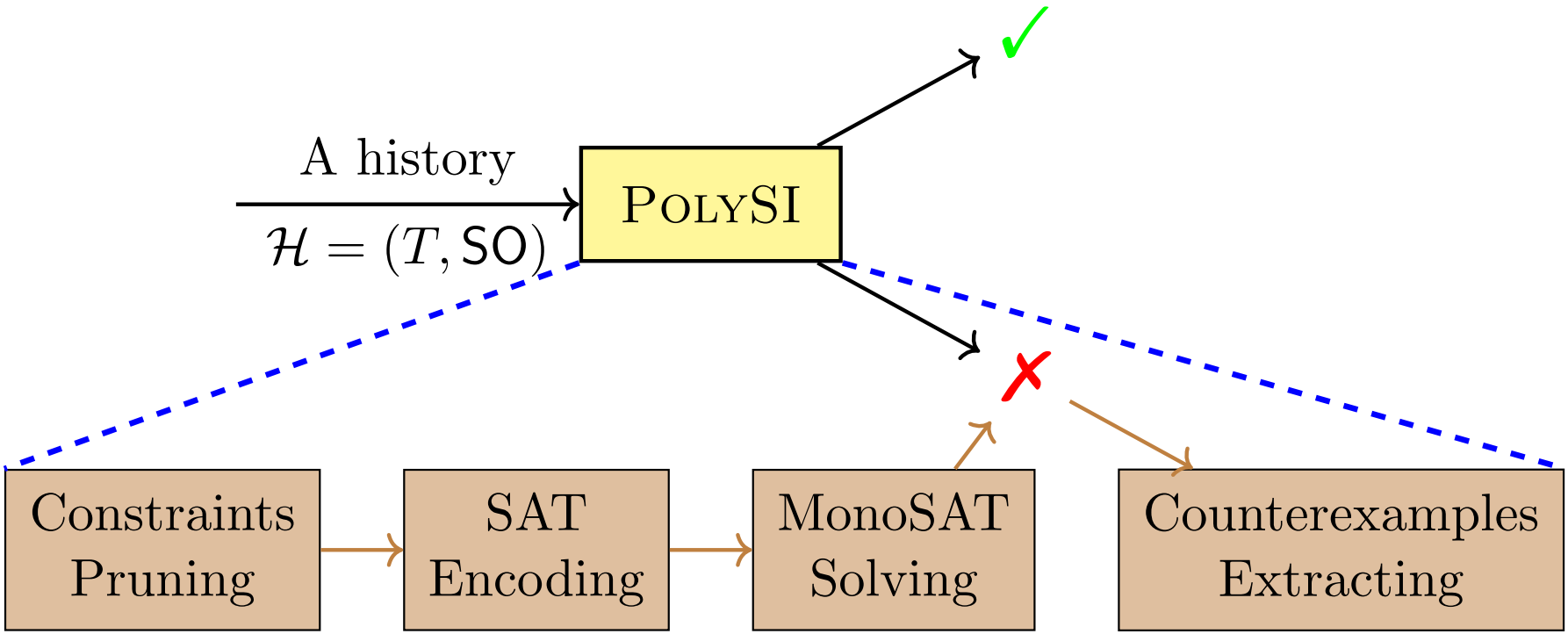
Efficient: utilizing MonoSAT solver optimized for graph problems

Contribution: the PolySI Checker



Efficient: domain-specific pruning before encoding

Contribution: the PolySI Checker



Informative: extract counterexamples from the UNSAT core

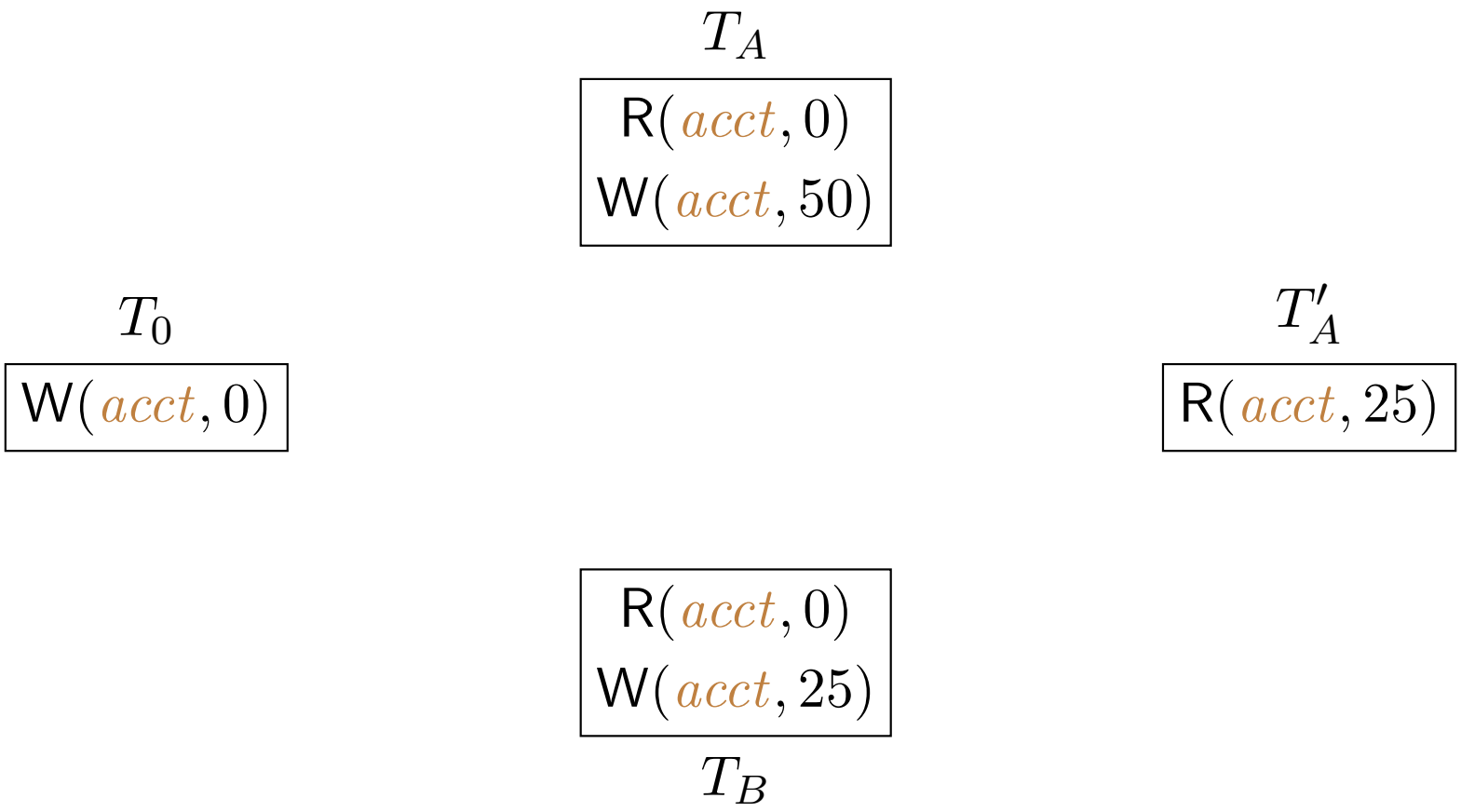
PolySI: Polygraph based Characterization of SI

Before this, we first review the *dependency graph* based characterization of SI [Cerone and Gotsman, 2018].

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

Informally, a history satisfies SI if and 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



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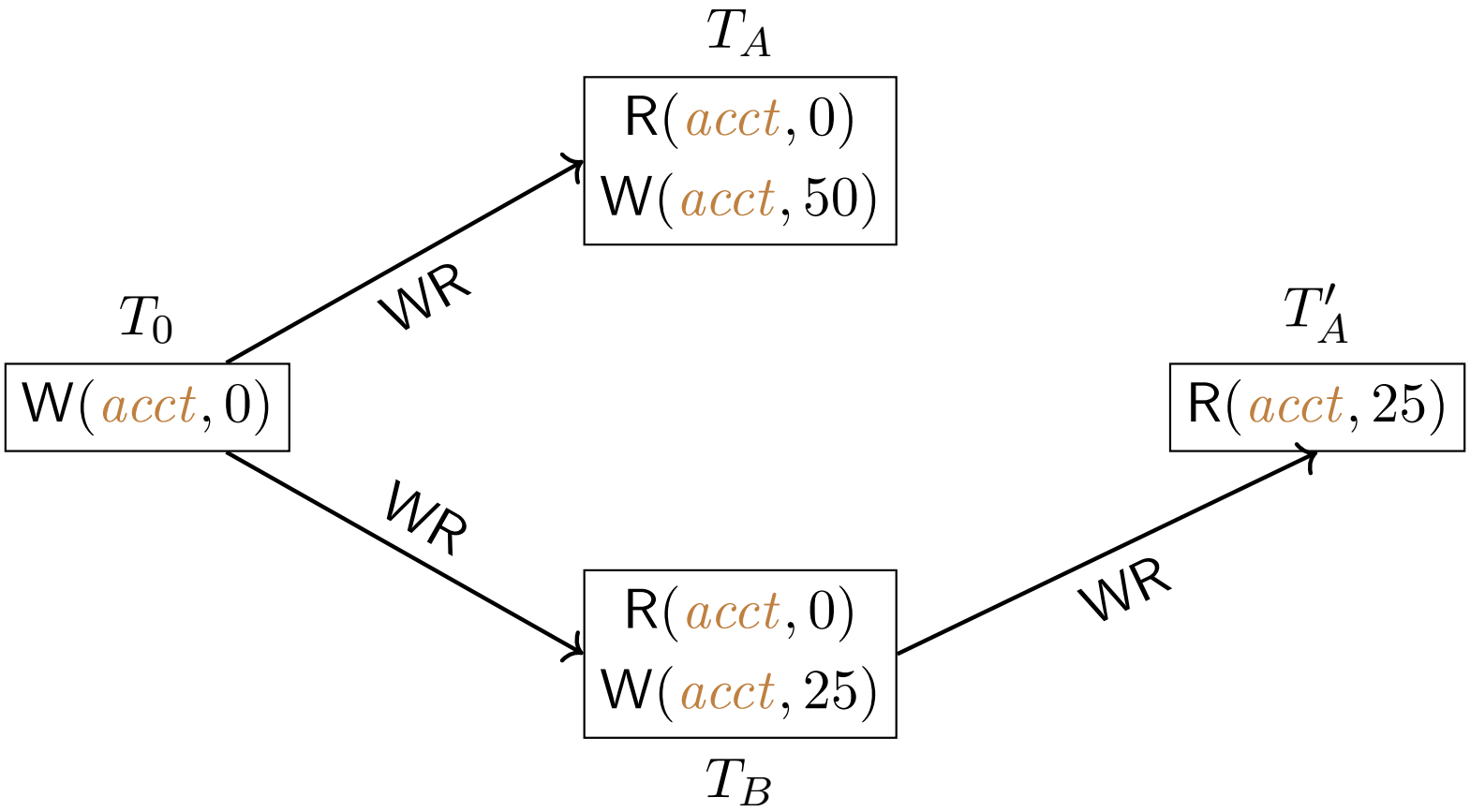
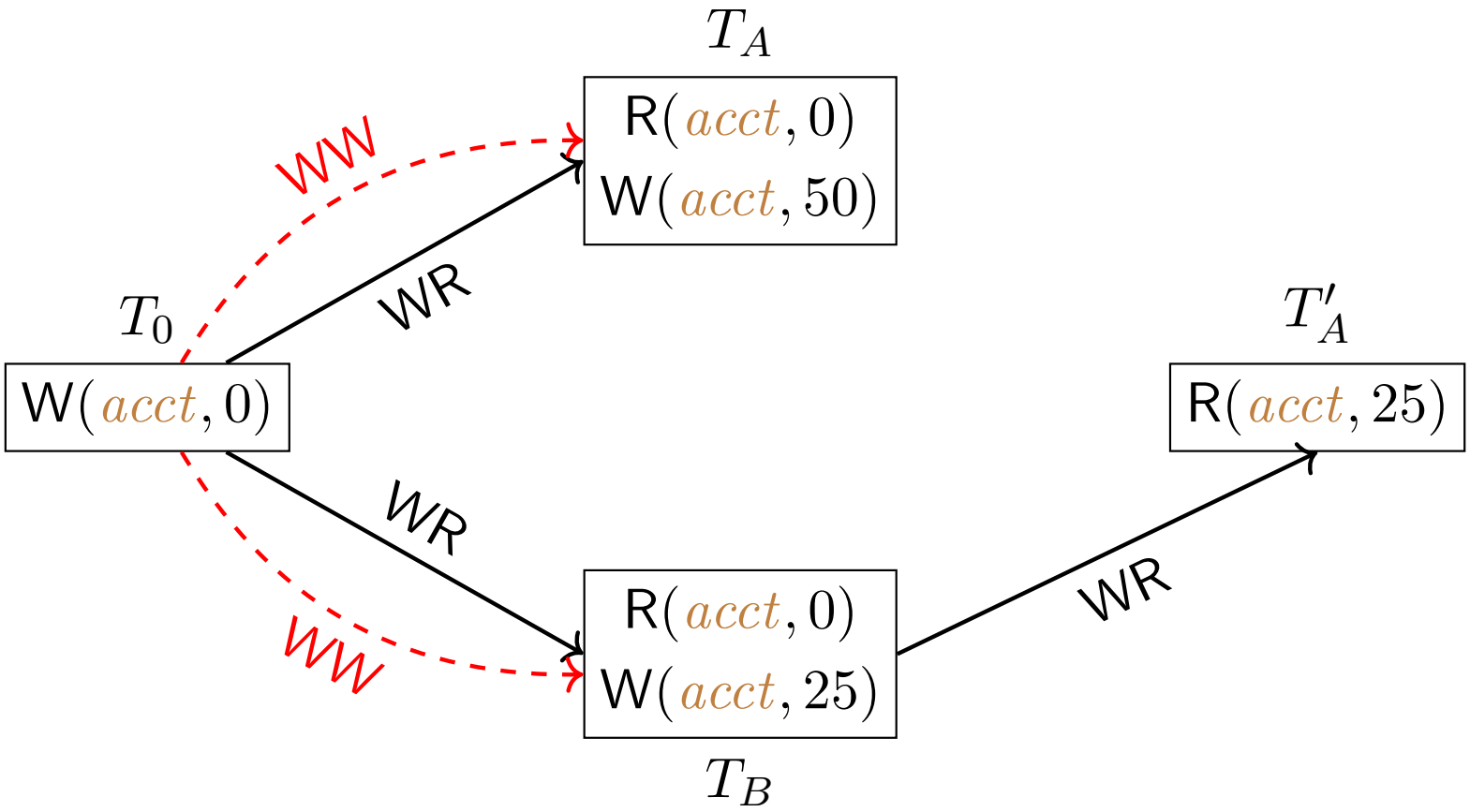


WR: "write-read" dependency capturing the "read-from" relation

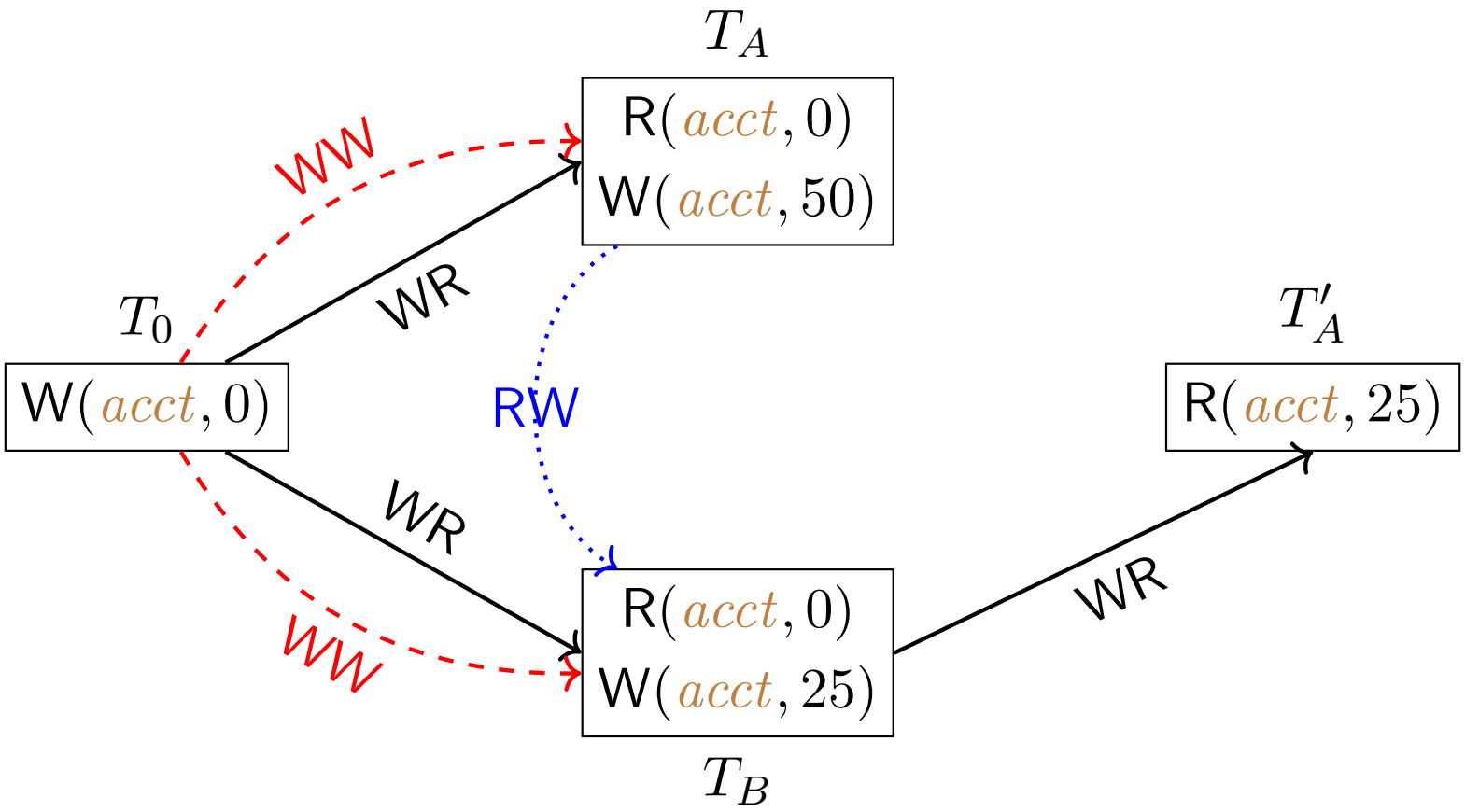
Dependency Graph based Characterization of SI



WW: "write-write" dependency capturing the version order on *acct*

Dependency Graph based Characterization of SI

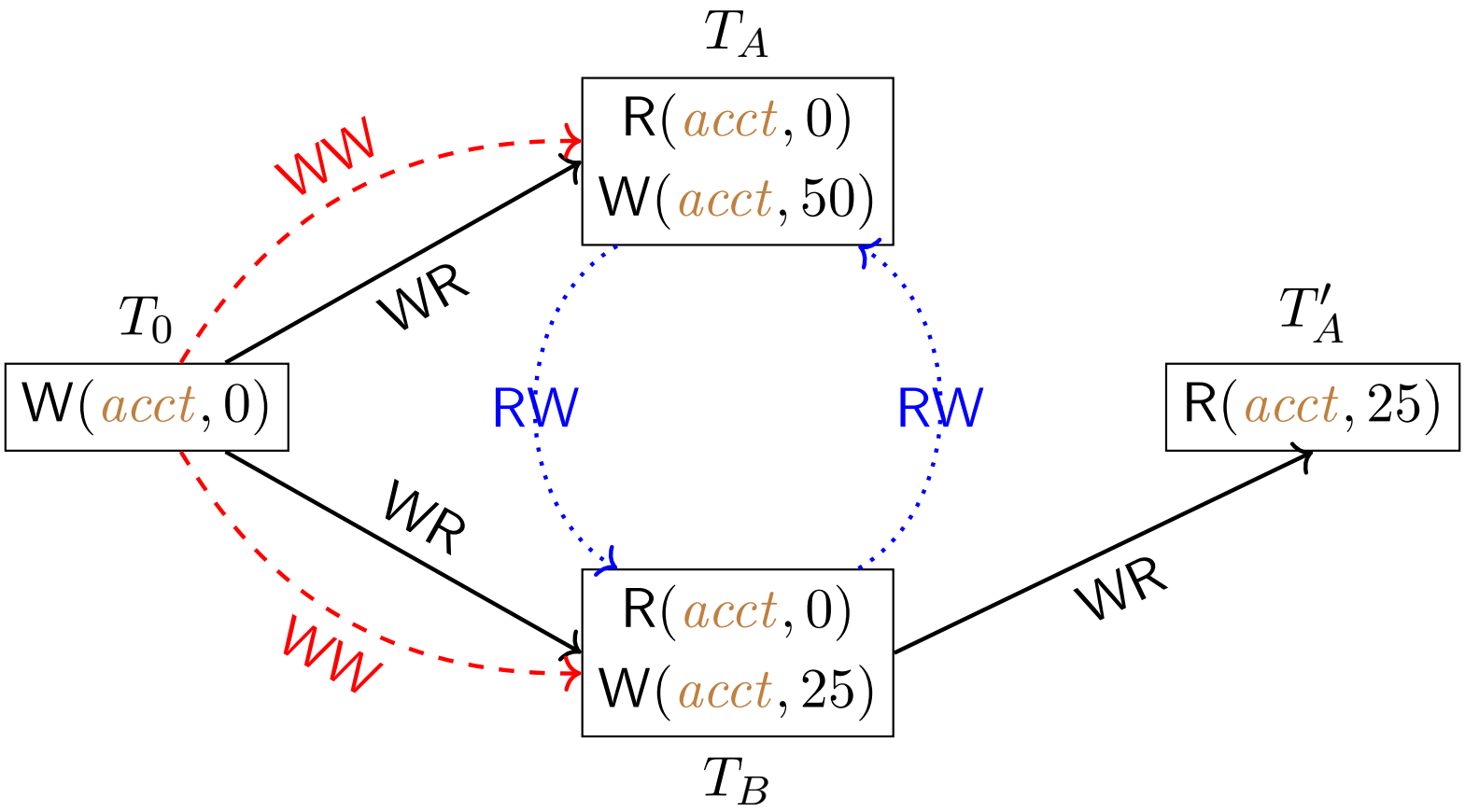
T_A reads from T_0 which is overwritten by T_B



RW: "read-write" dependency

Dependency Graph based Characterization of SI

T_B reads from T_0 which is overwritten by T_A



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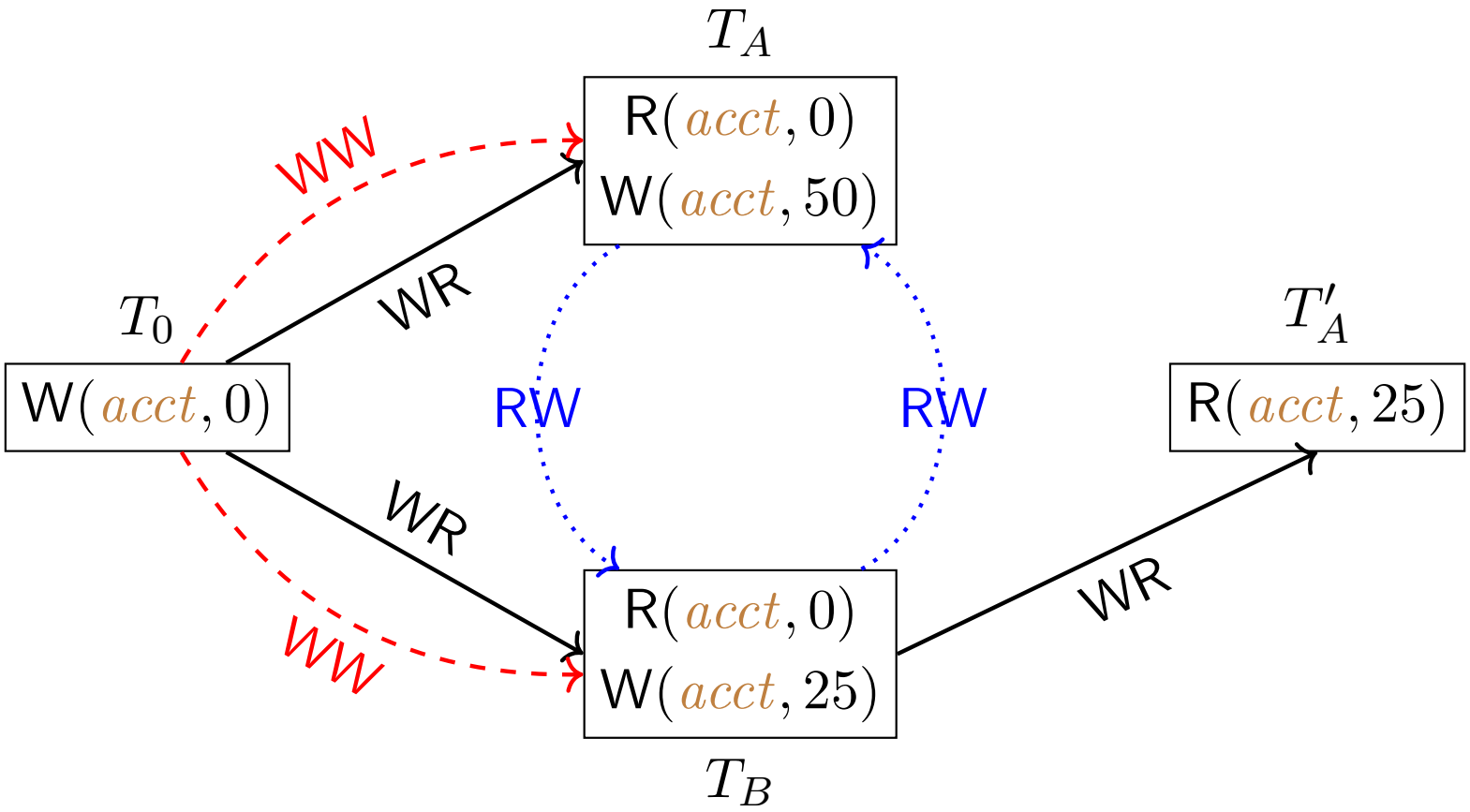
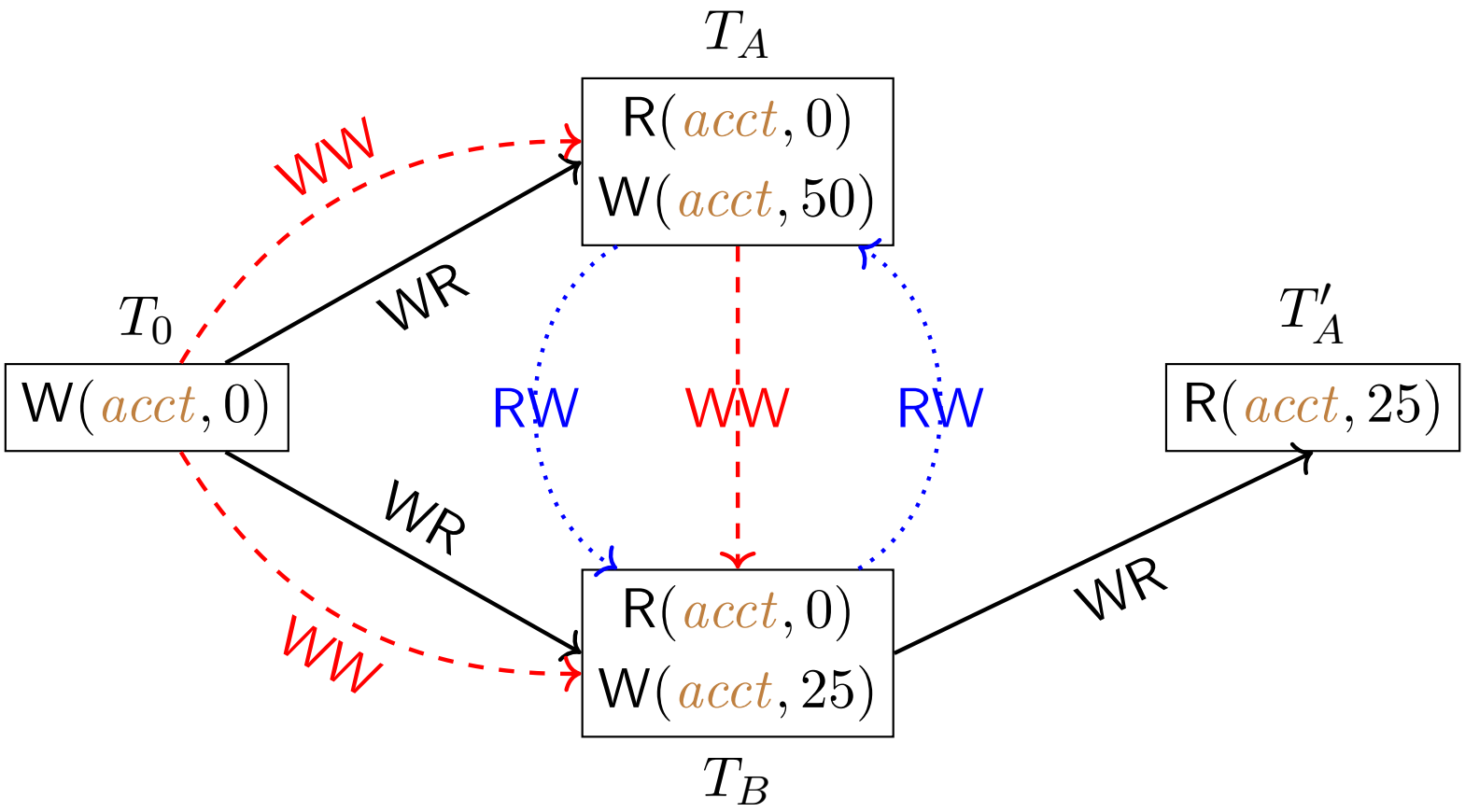


The cycle $T_A \xrightarrow{\text{RW}} T_B \xrightarrow{\text{RW}} T_A$ is allowed by SI.

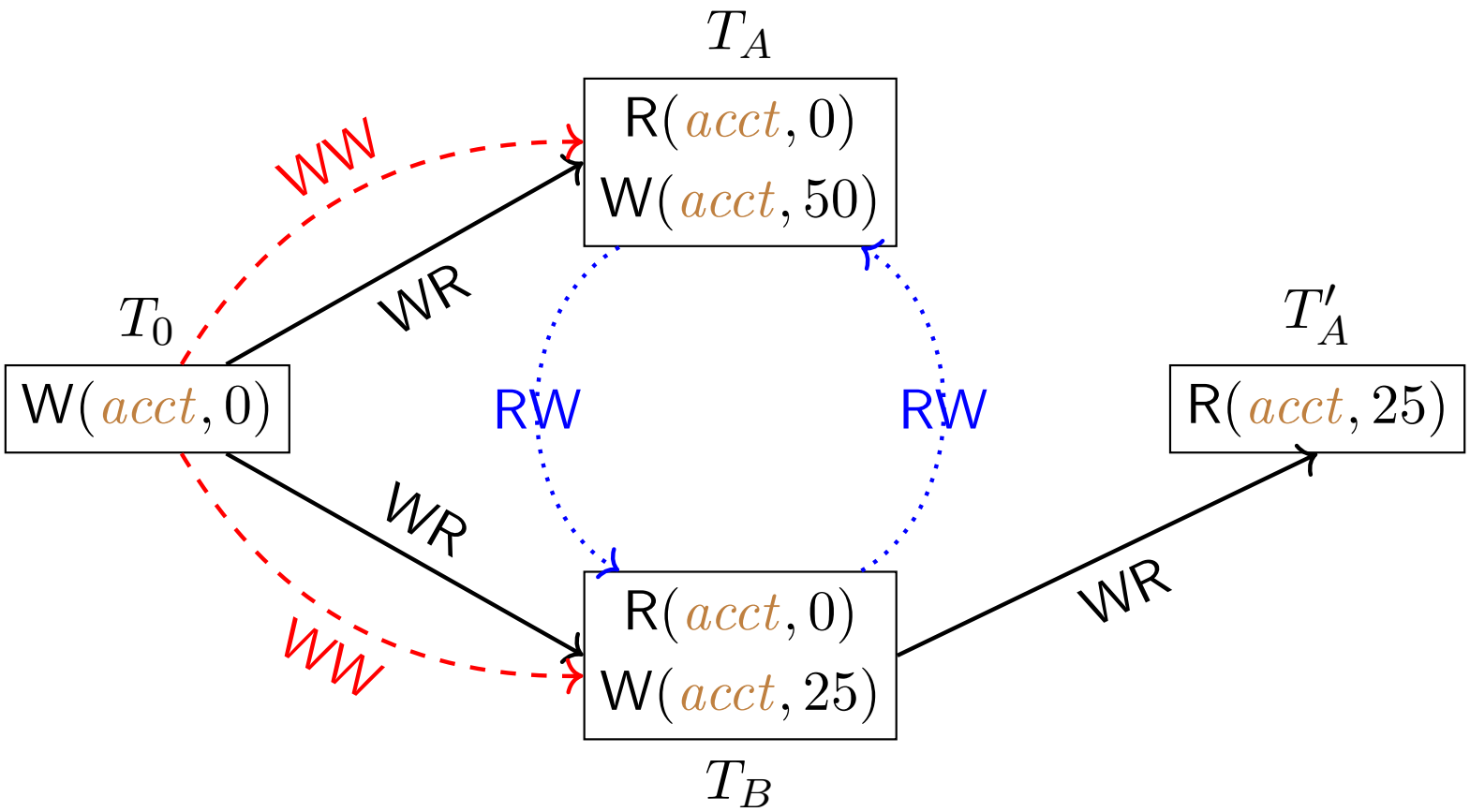
Dependency Graph based Characterization of SI

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



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

Dependency Graph based Characterization of SI



Dependency Graph based Characterization of SI

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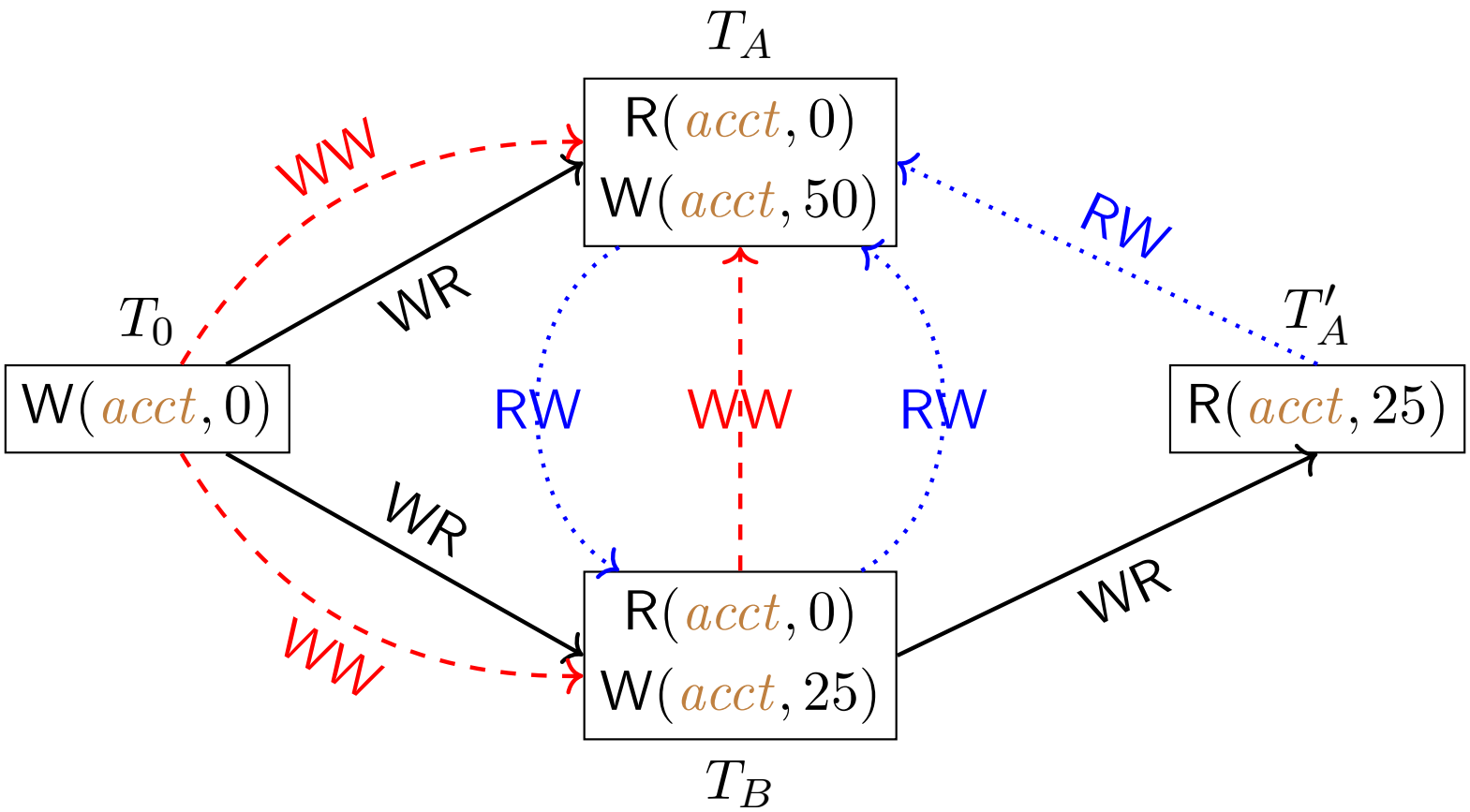
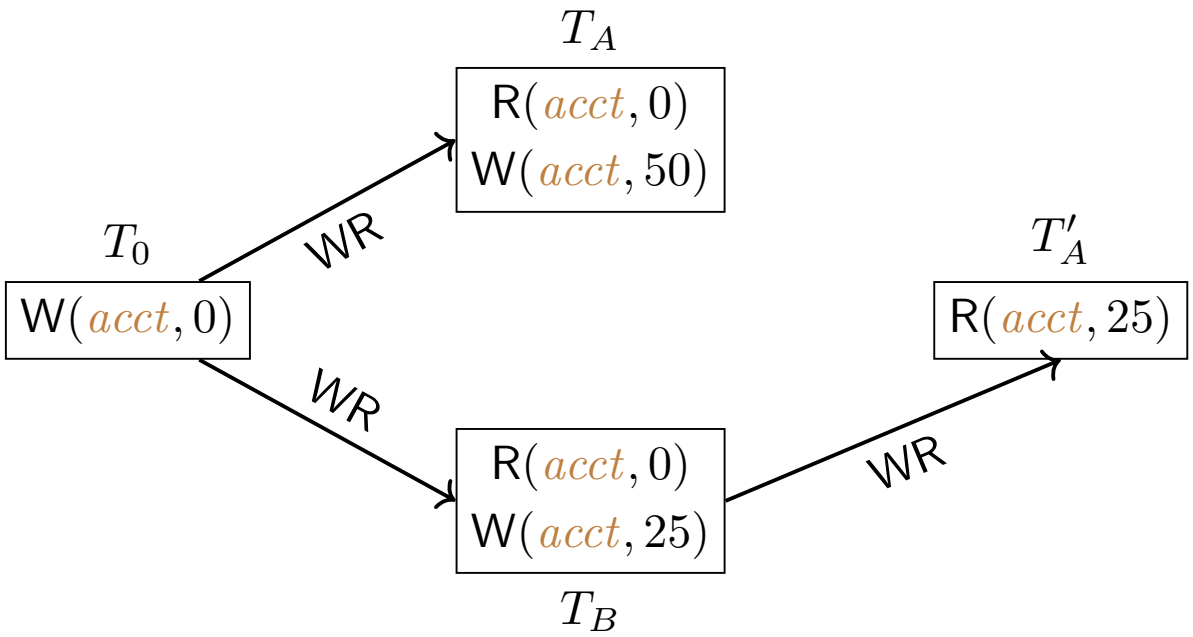


undesired cycle for SI: $T_B \xrightarrow{\text{WW}} T_A \xrightarrow{\text{RW}} T_B$

Dependency Graph based Characterization of SI

We have considered both bases $T_A \xrightarrow{\text{WW}} T_B$ and $T_B \xrightarrow{\text{WW}} T_A$, and each case leads to an undesired cycle for SI.



Therefore, this history does not satisfy SI.

Dependency Graph based Characterization of SI

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

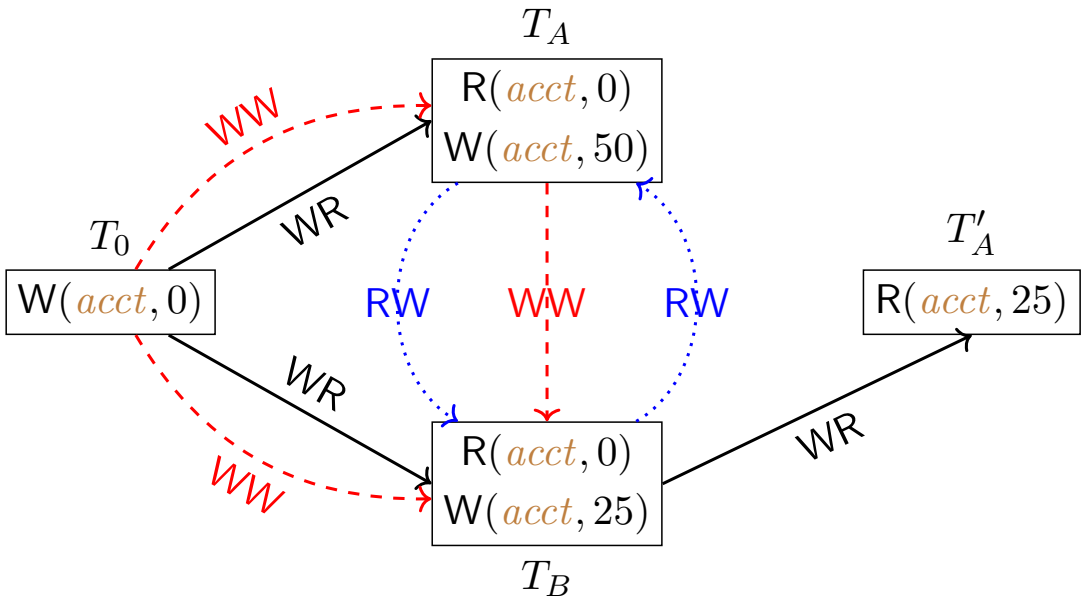
Informally, a history satisfies SI if and only if

there exists a dependency graph $\mathcal{G}$ for it such that

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

Dependency Graph based Characterization of SI

induced graph $\boxed{((\mathsf{SO}_{\mathcal{G}} \cup \mathsf{WR}_{\mathcal{G}} \cup \mathsf{WW}_{\mathcal{G}}) \; ; \; \mathsf{RW}_{\mathcal{G}}?)}$ *for* $\mathcal{G}$



Dependency Graph based Characterization of SI

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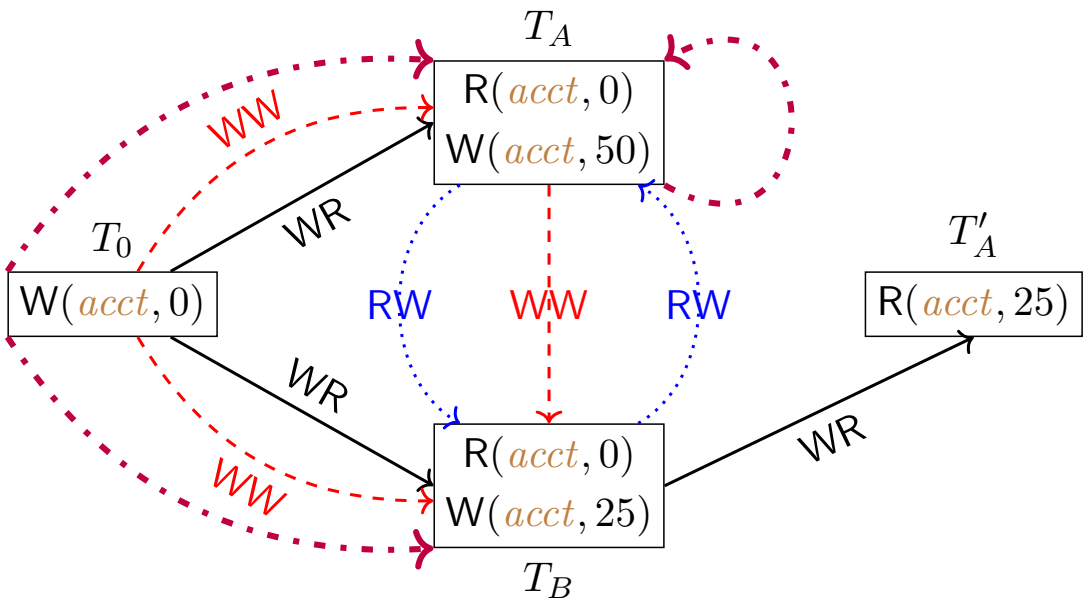

first composing (;) SO/WR/WW edges with RW edges

Dependency Graph based Characterization of SI

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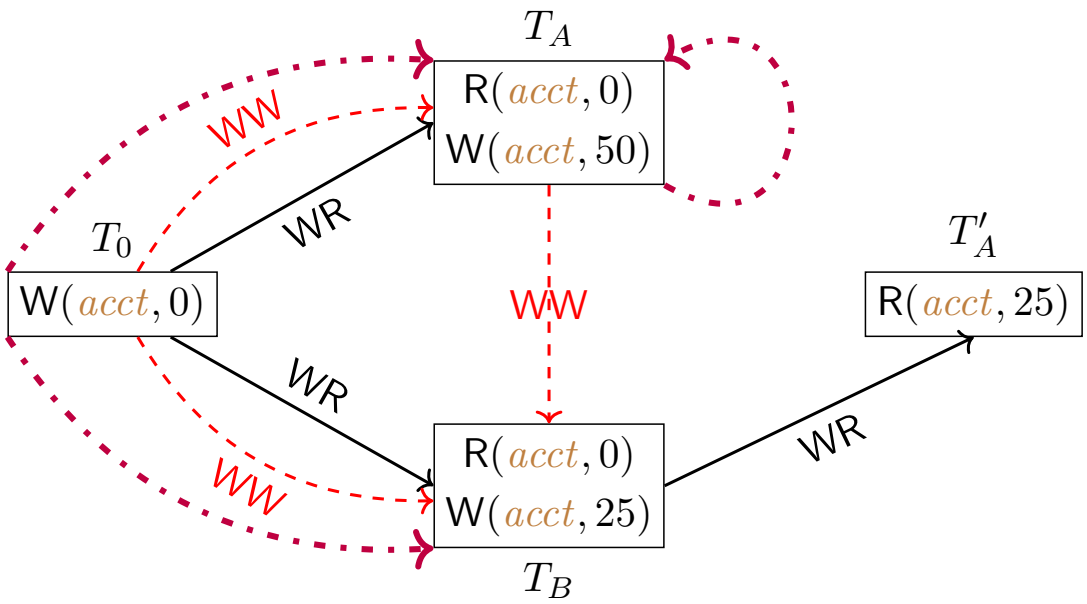
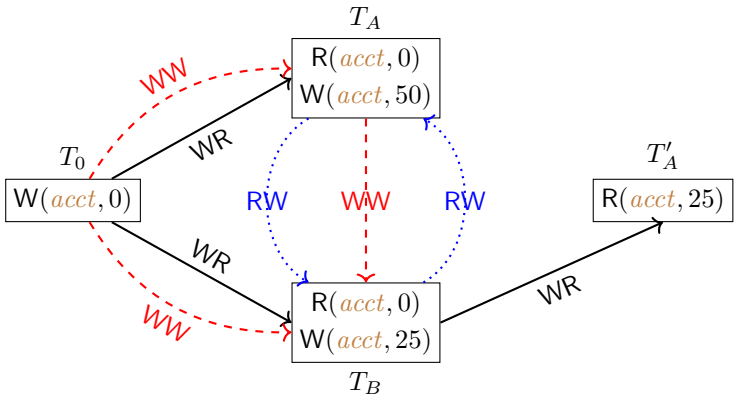


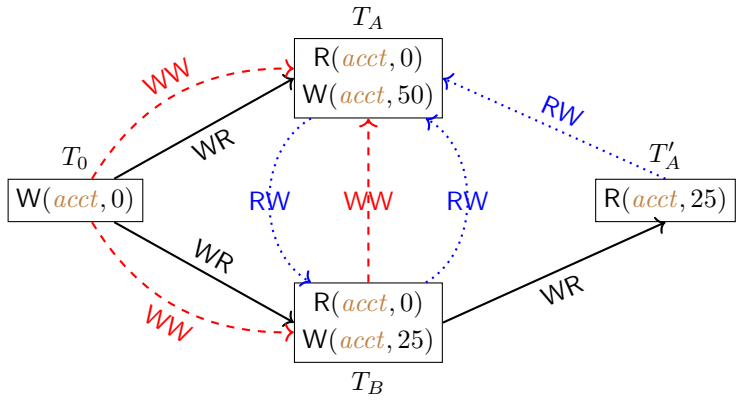
first composing (;) SO/WR/WW edges with RW edges

then deleting the RW edges

Polygraphs: A Family of Dependency Graphs

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





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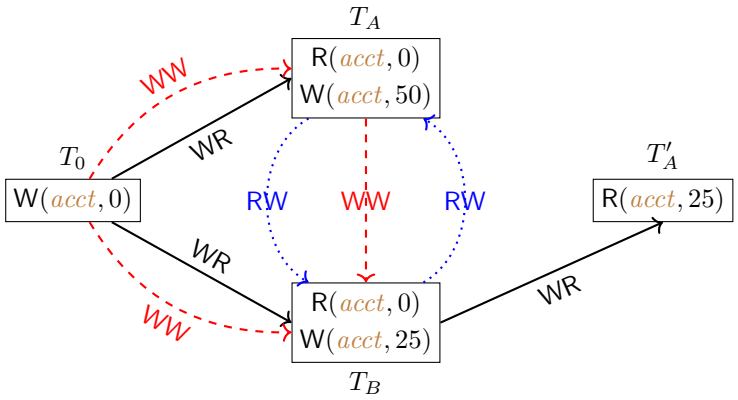
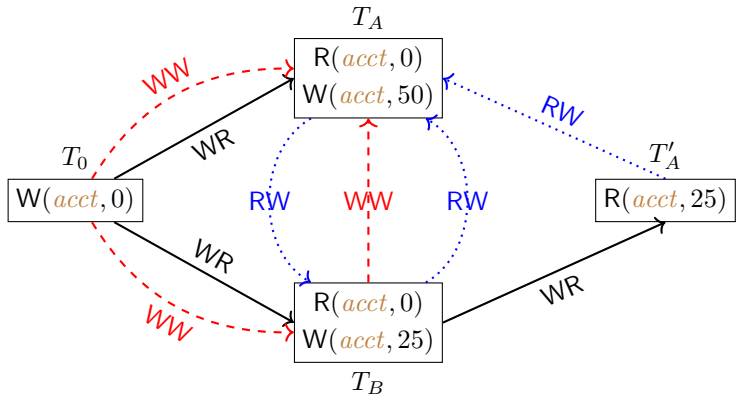
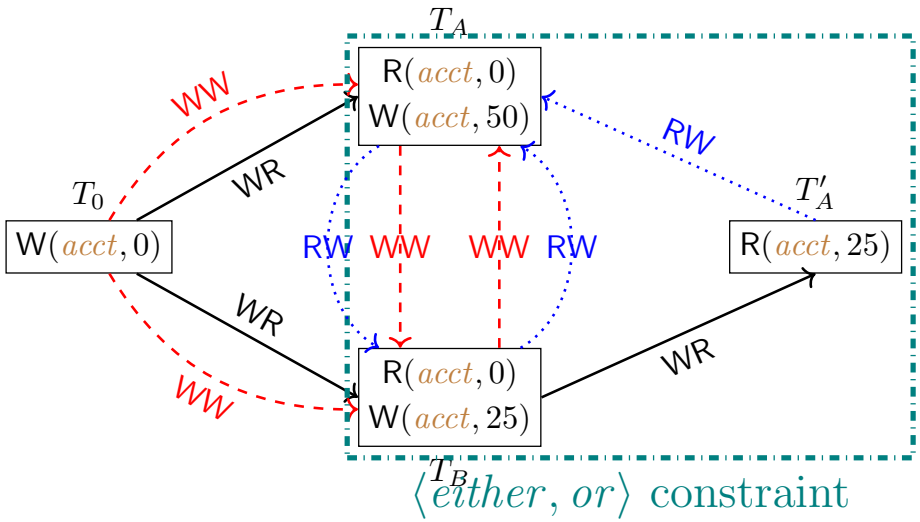
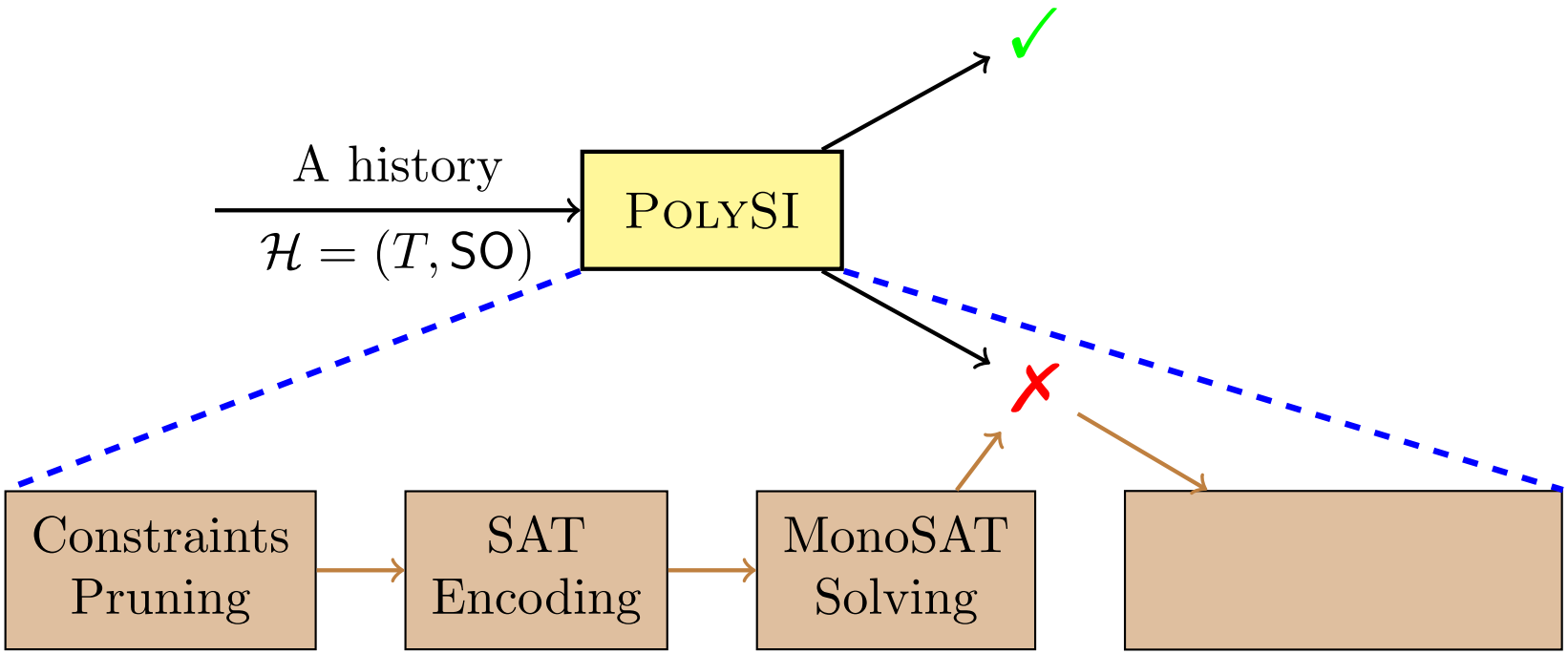






polygraph: $\langle either \triangleq \{T_A \xrightarrow{\text{WW}} T_B\}, or \triangleq \{T_B \xrightarrow{\text{WW}} T_A, T'_A \xrightarrow{\text{RW}} T_A\}\rangle$

PolySI: An Illustrating Example



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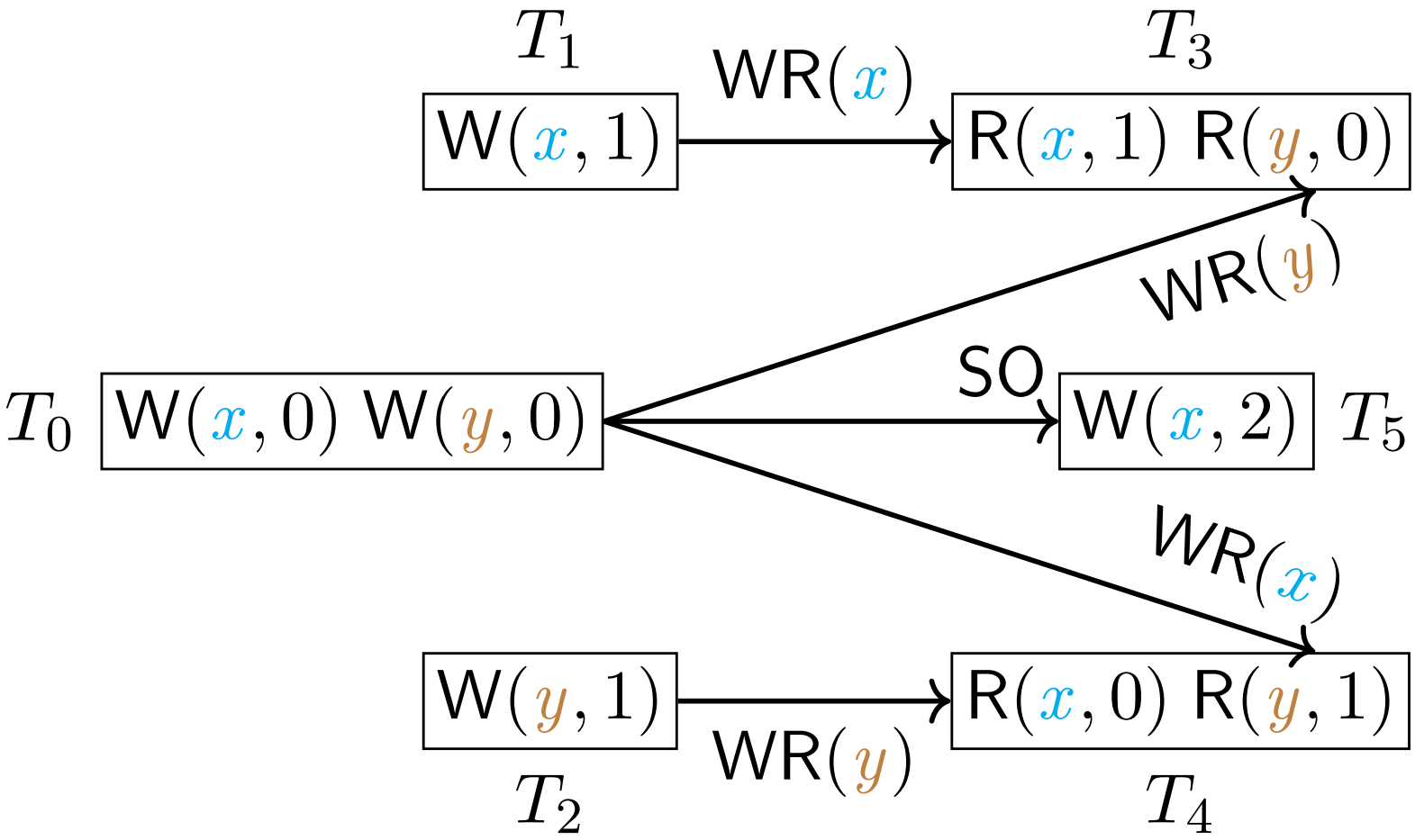
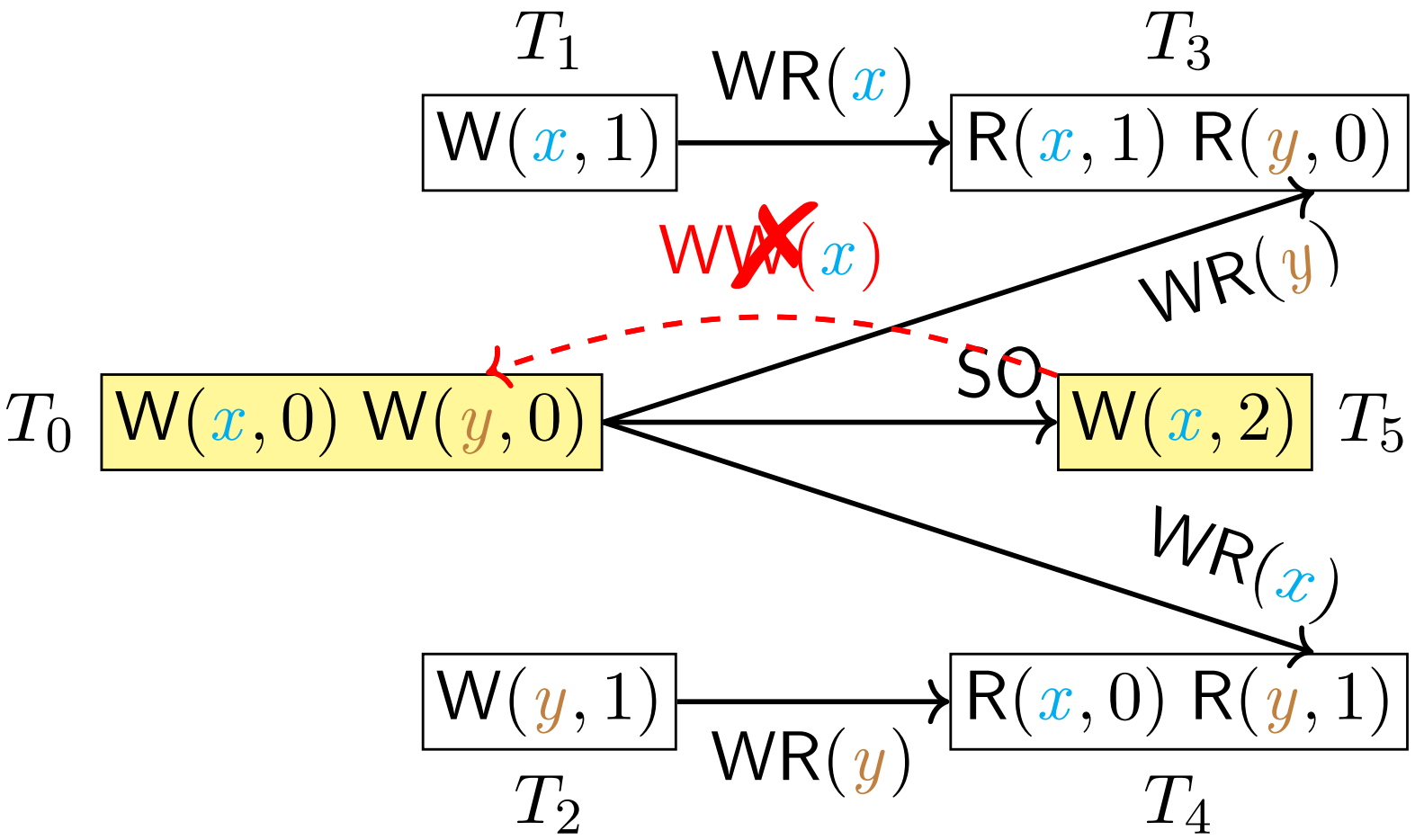


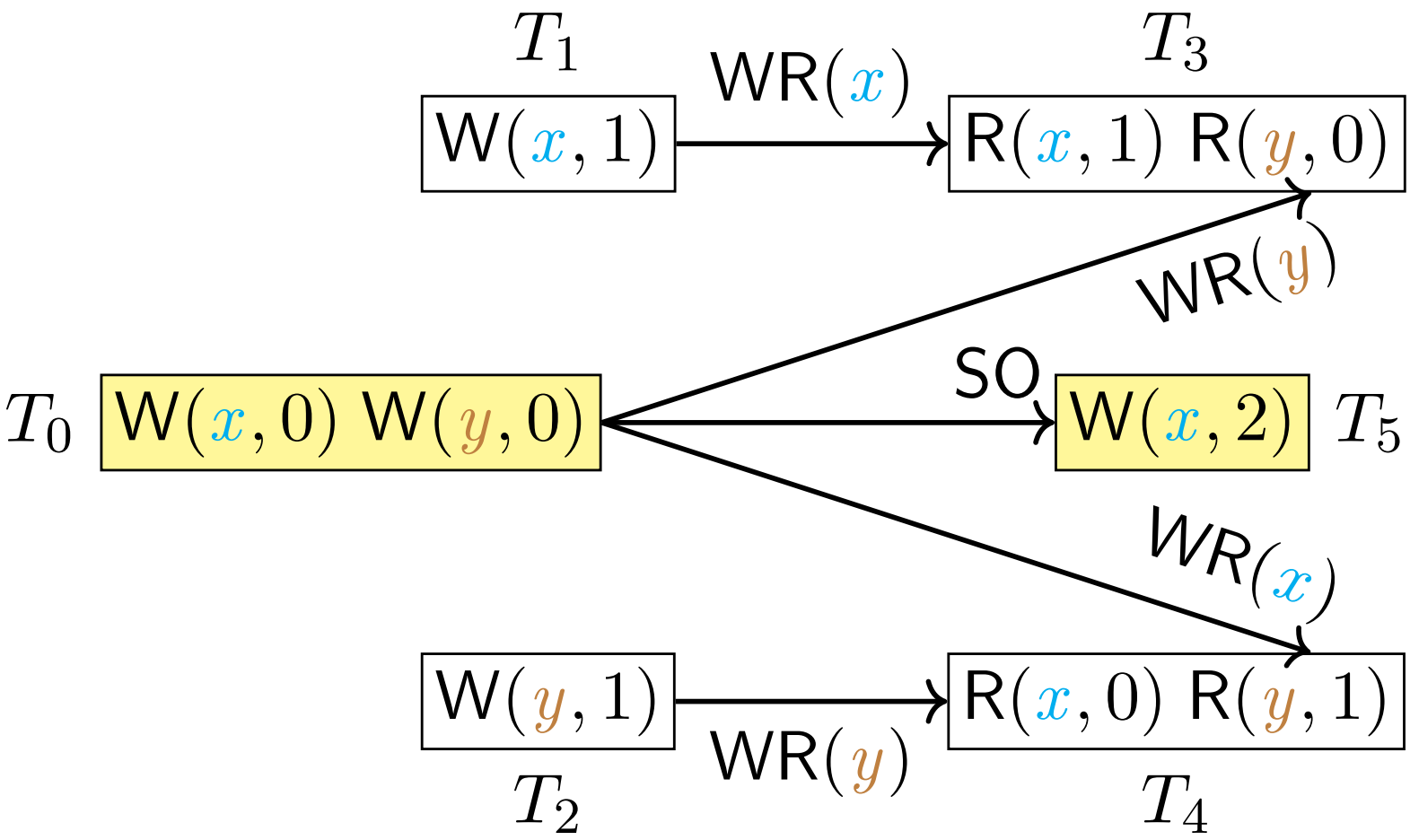
WW between T_0, T_1, and T_5 (on x) and between T_0 and T_2 (on y)

PolySI: An Illustrating Example

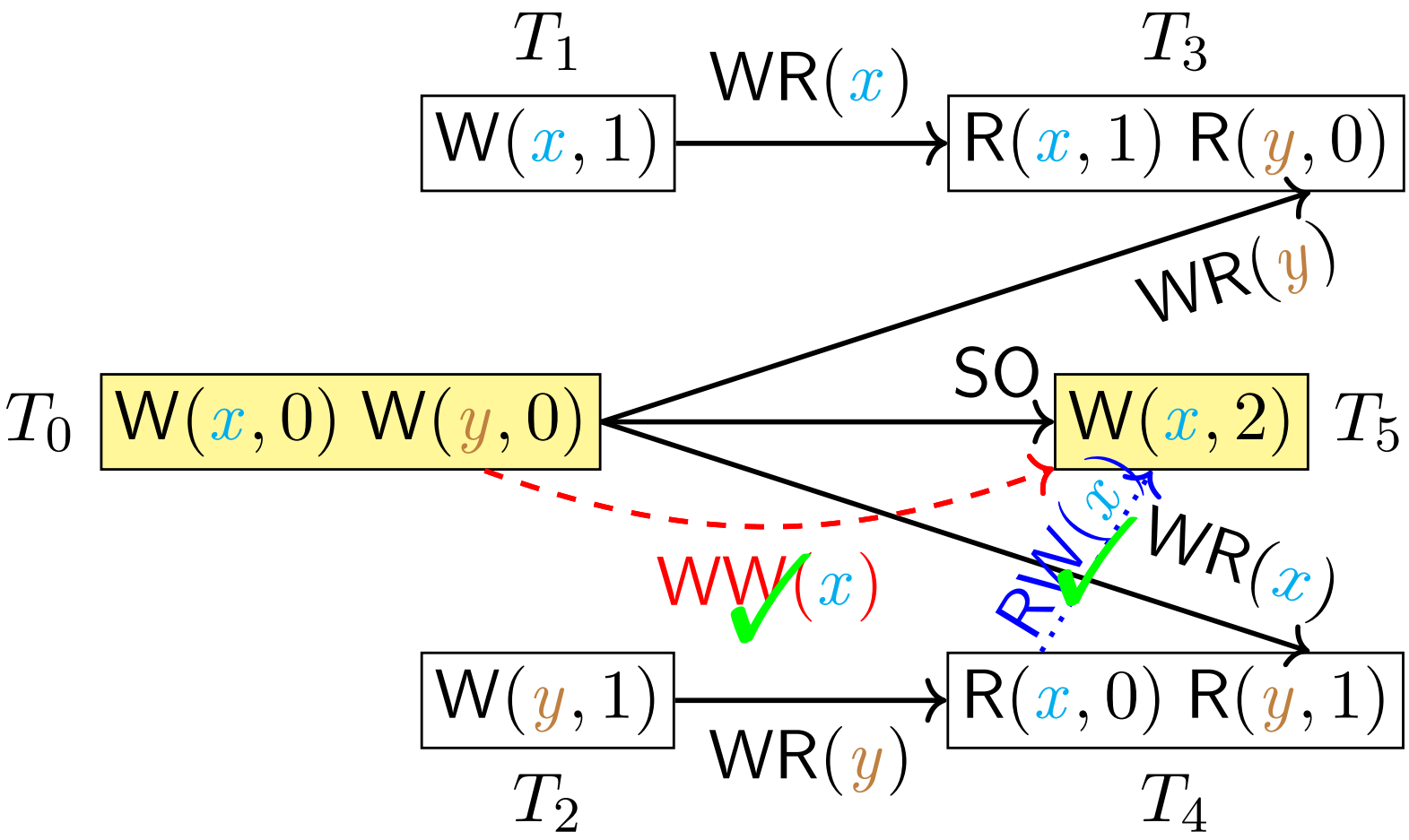


The $T_5 \xrightarrow{\mathsf{WW}(x)} T_0$ case is pruned due to $T_0 \xrightarrow{\mathsf{SO}} T_5 \xrightarrow{\mathsf{WW}(x)} T_0$.

PolySI: An Illustrating Example

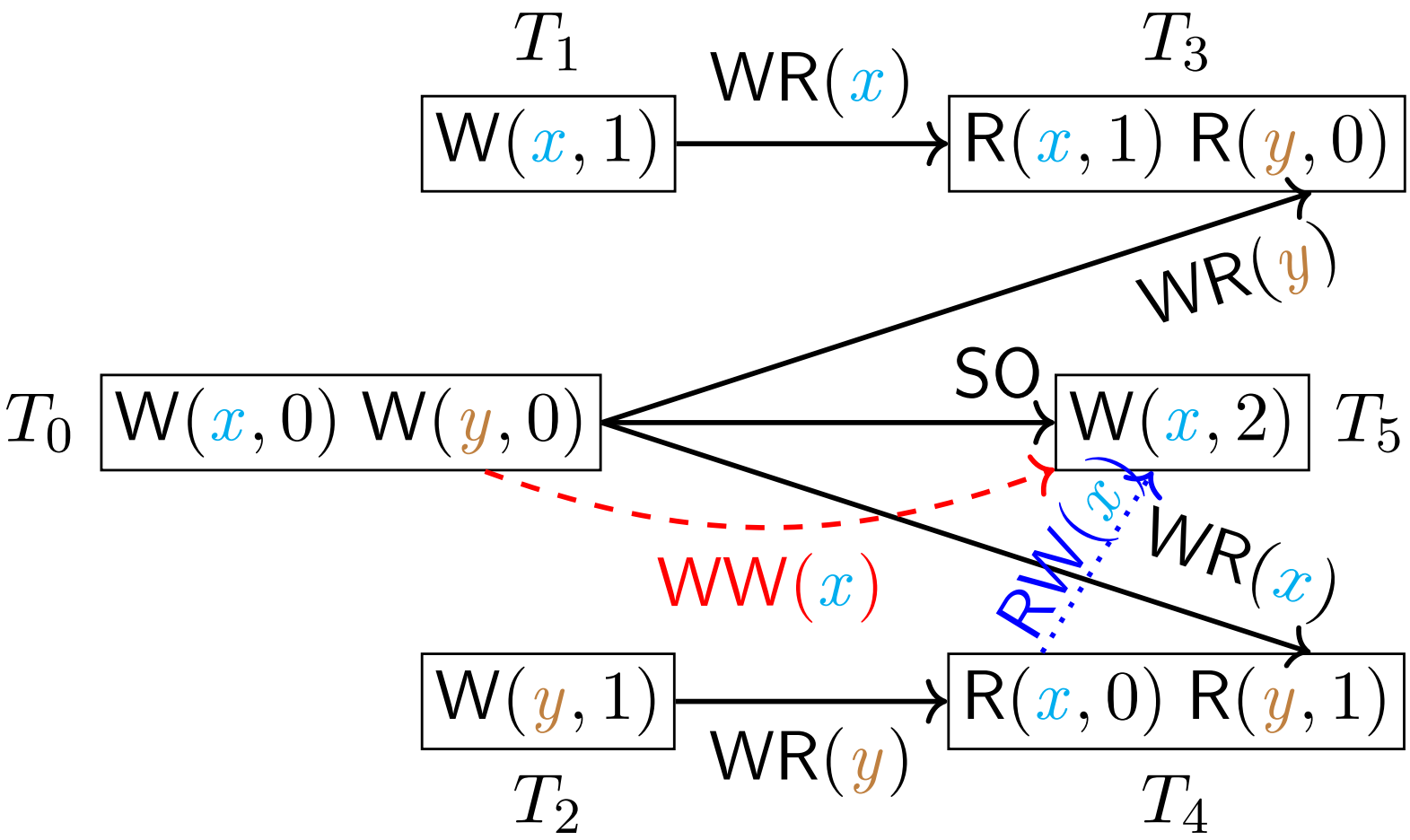


PolySI: An Illustrating Example

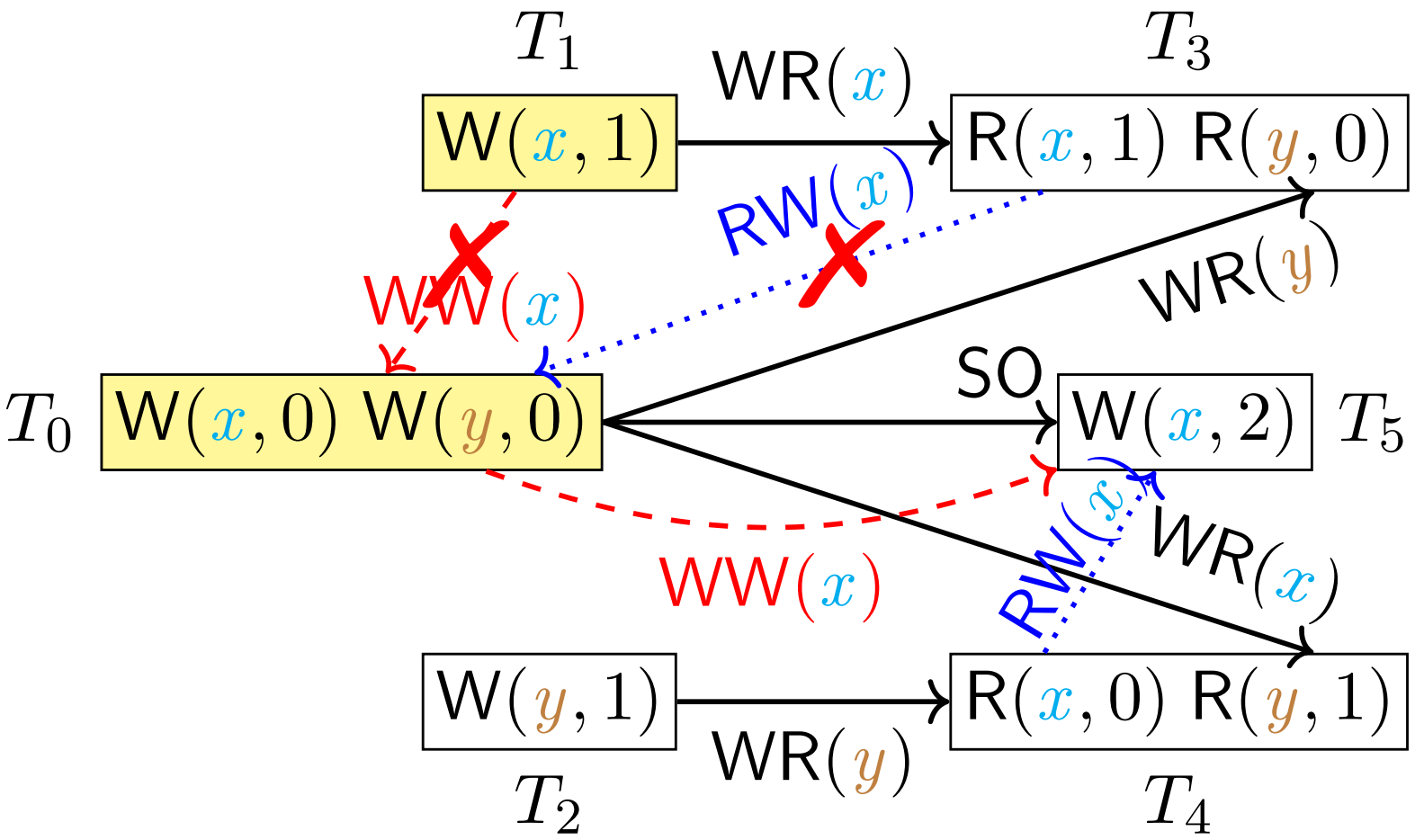


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_5$ case becomes known.

PolySI: An Illustrating Example

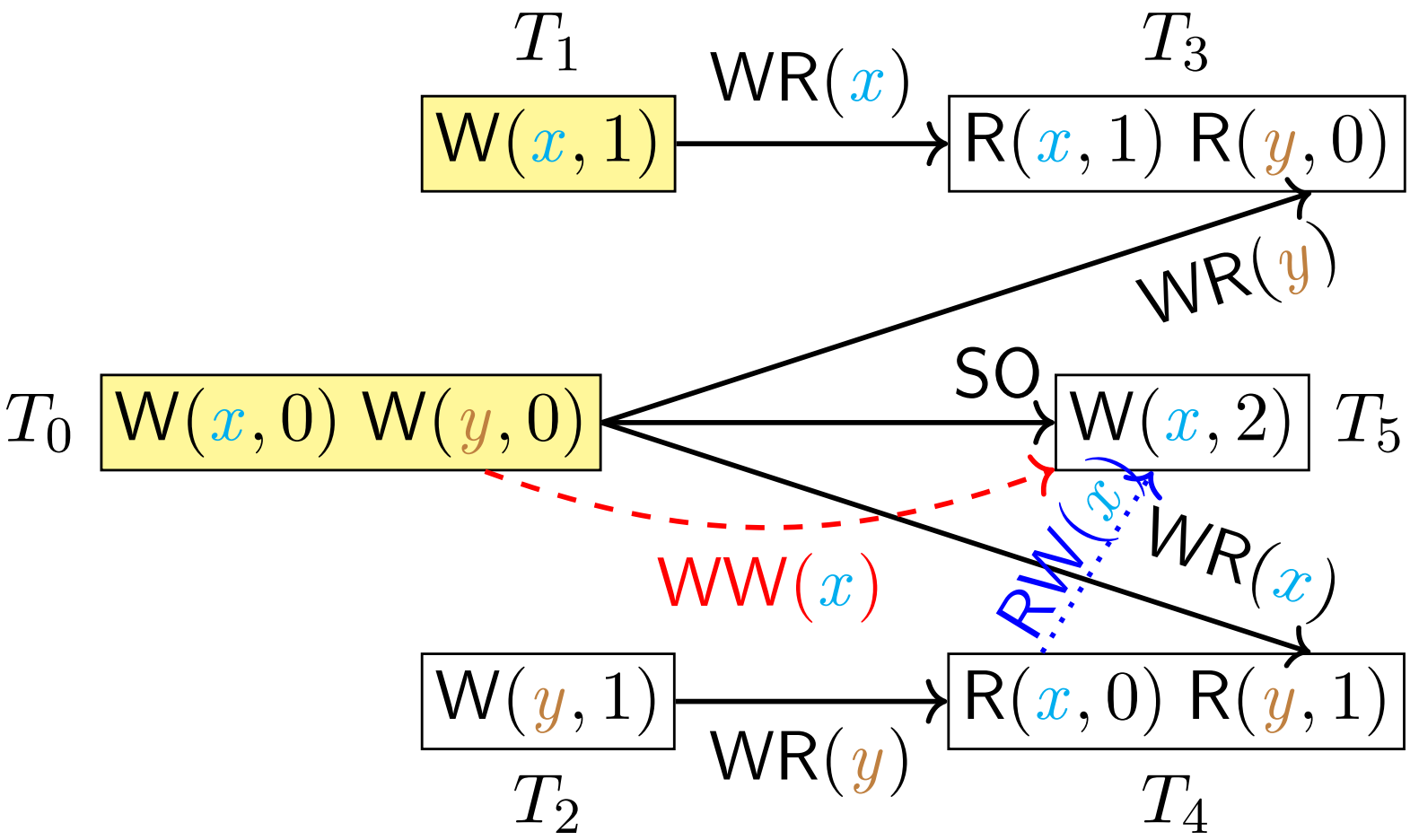


PolySI: An Illustrating Example

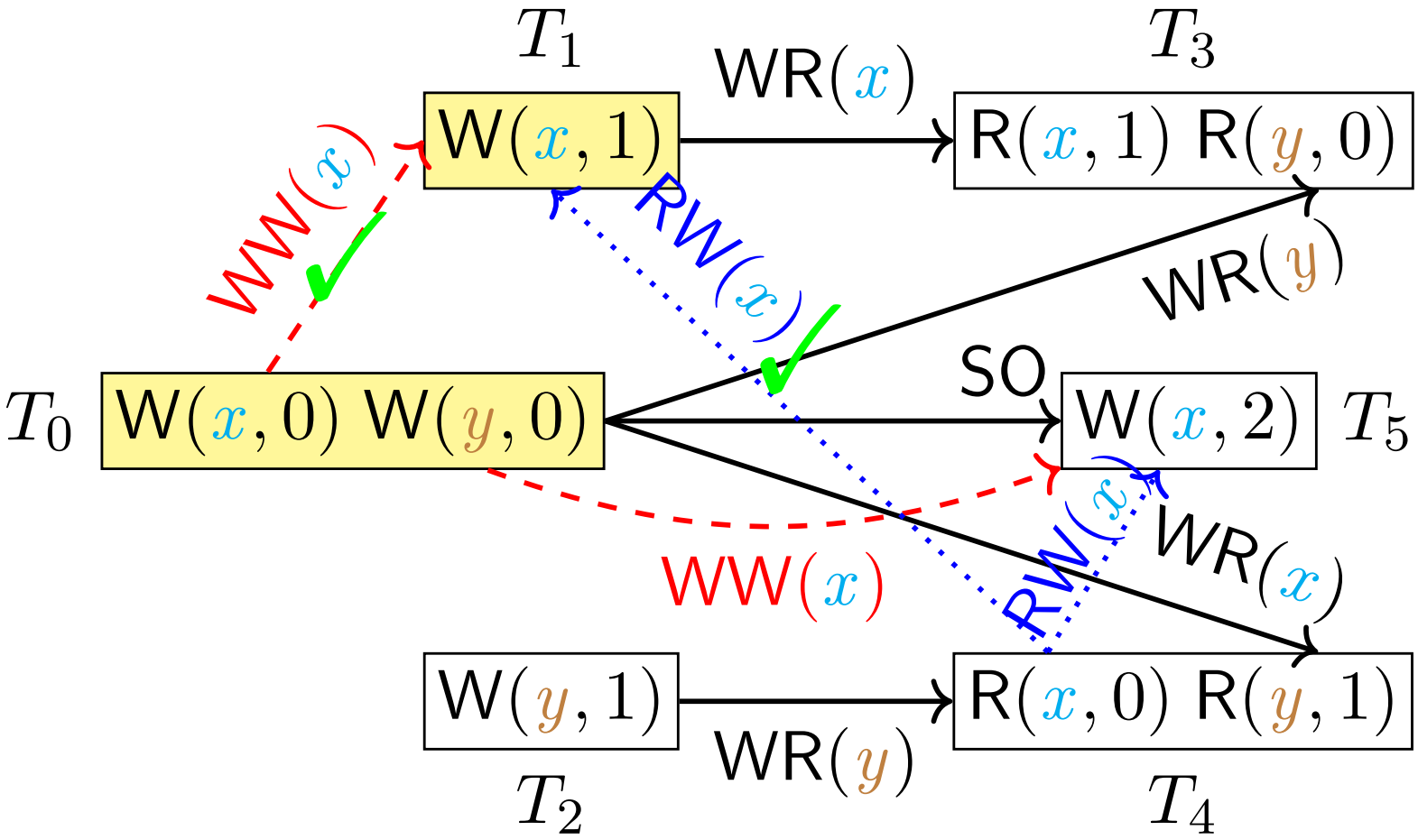


The $T_1 \xrightarrow{\mathsf{WW}(x)} T_0$ case is pruned due to $T_3 \xrightarrow{\mathsf{RW}(x)} T_0 \xrightarrow{\mathsf{WR}(y)} T_3$.

PolySI: An Illustrating Example

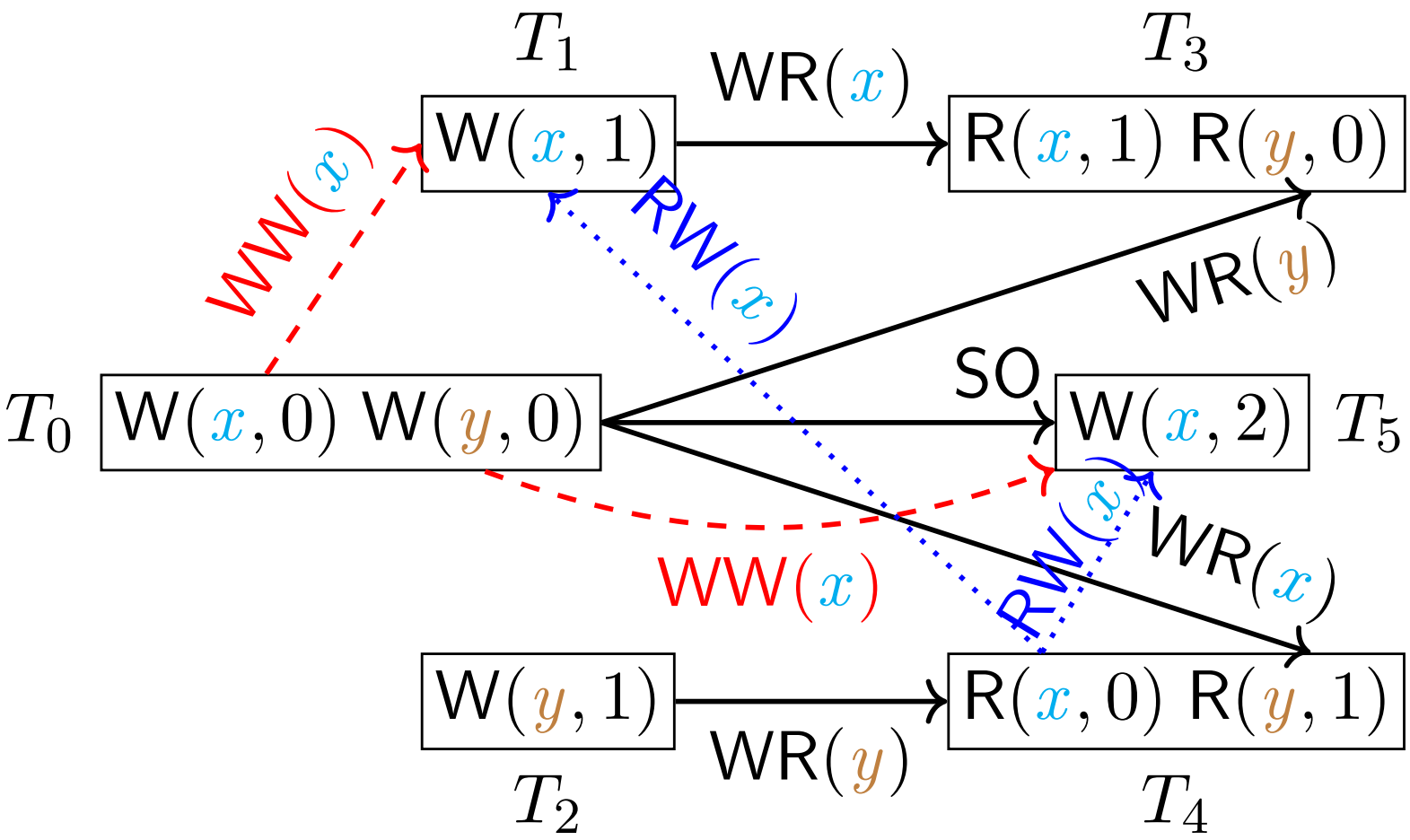


PolySI: An Illustrating Example

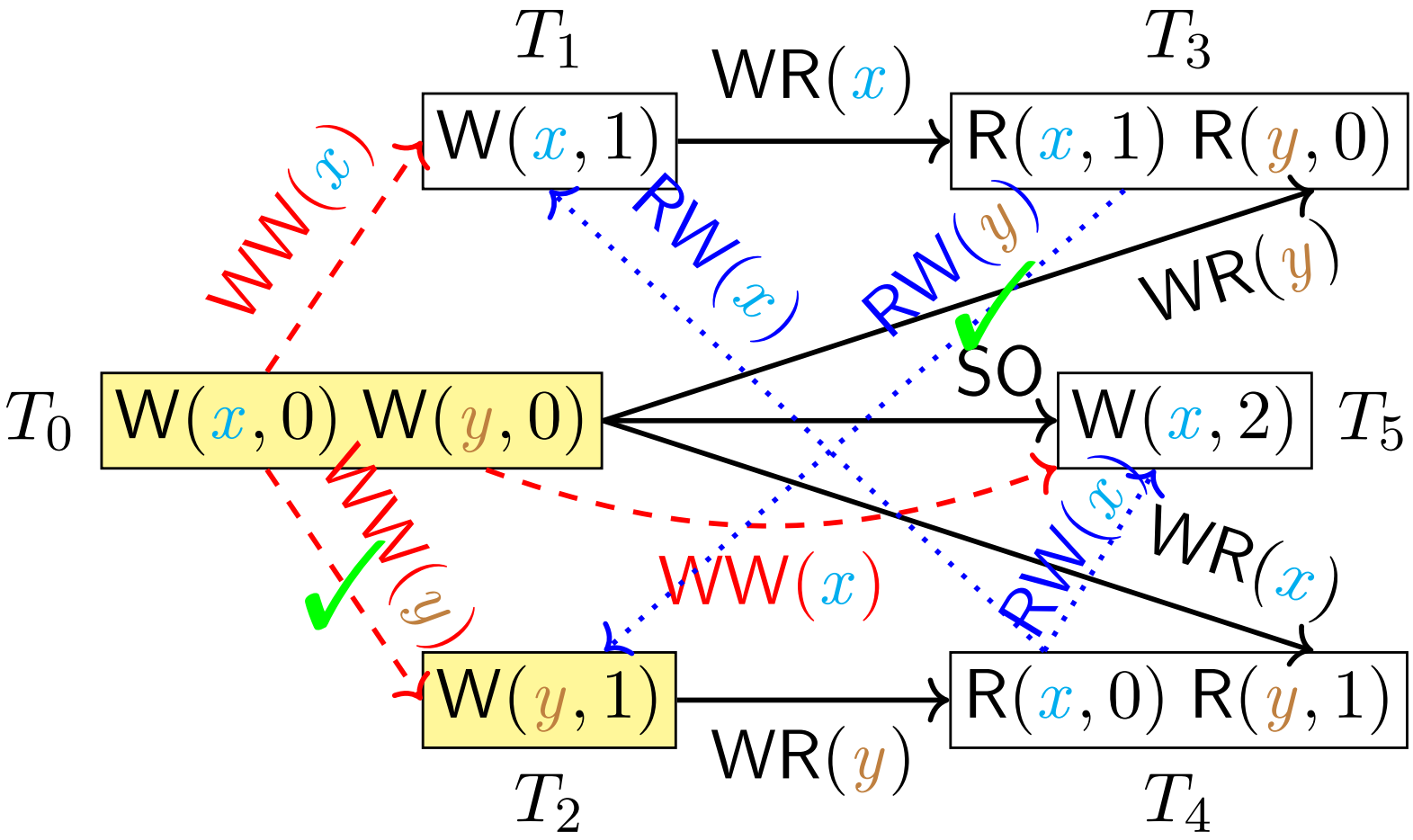


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_1$ case becomes known.

PolySI: An Illustrating Example



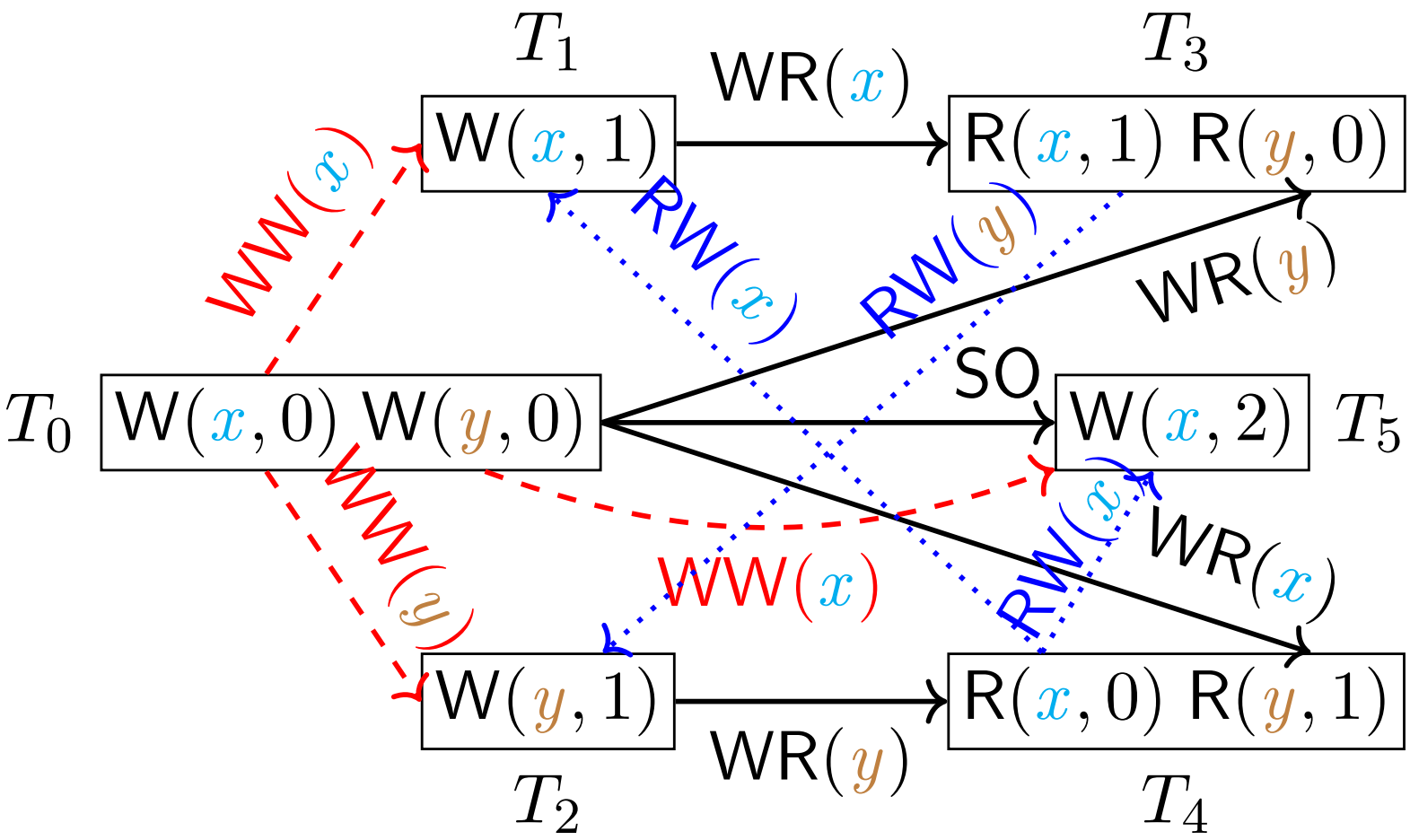
PolySI: An Illustrating Example



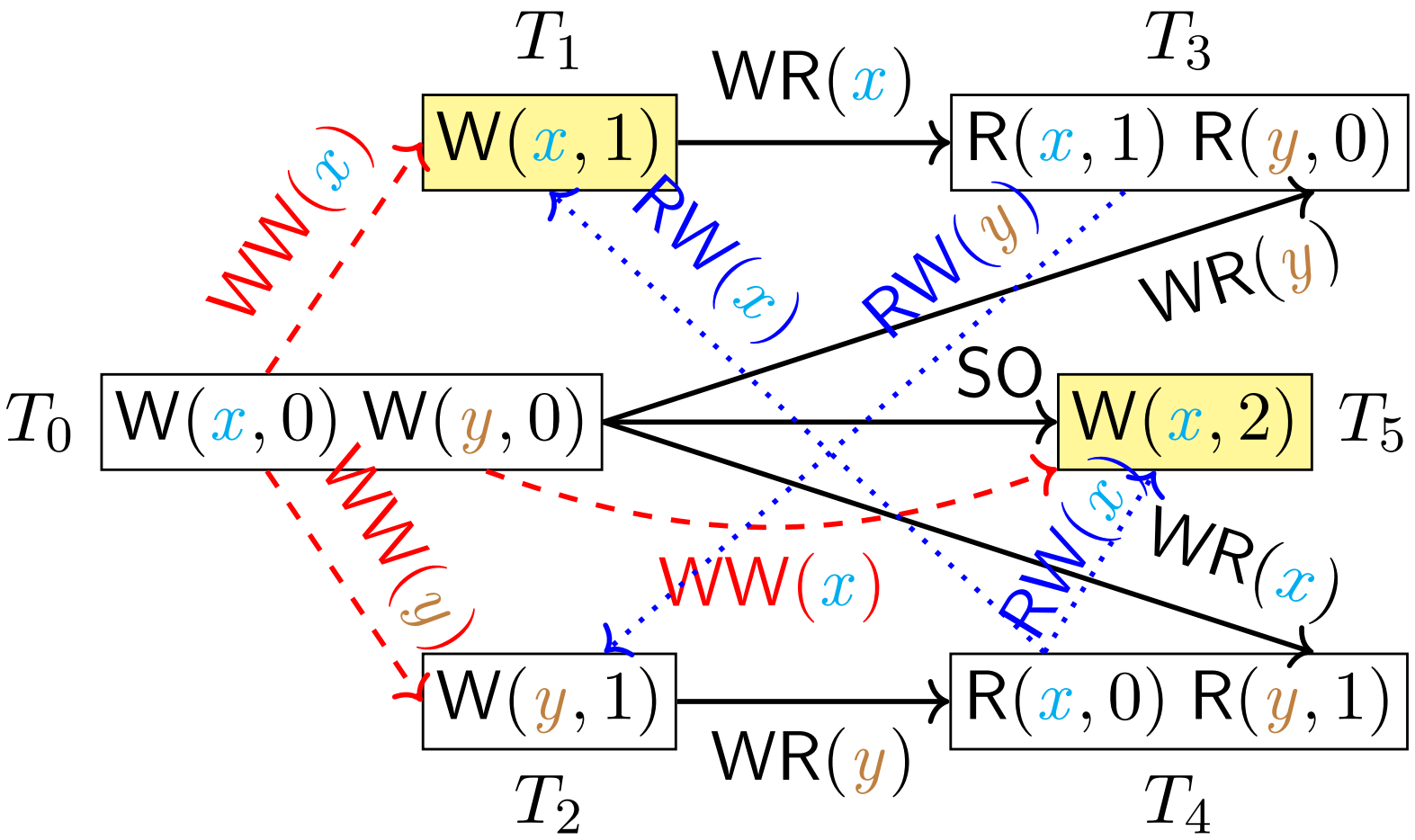
The $T_2 \xrightarrow{\mathsf{WW}(y)} T_0$ case is pruned,

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

PolySI: An Illustrating Example

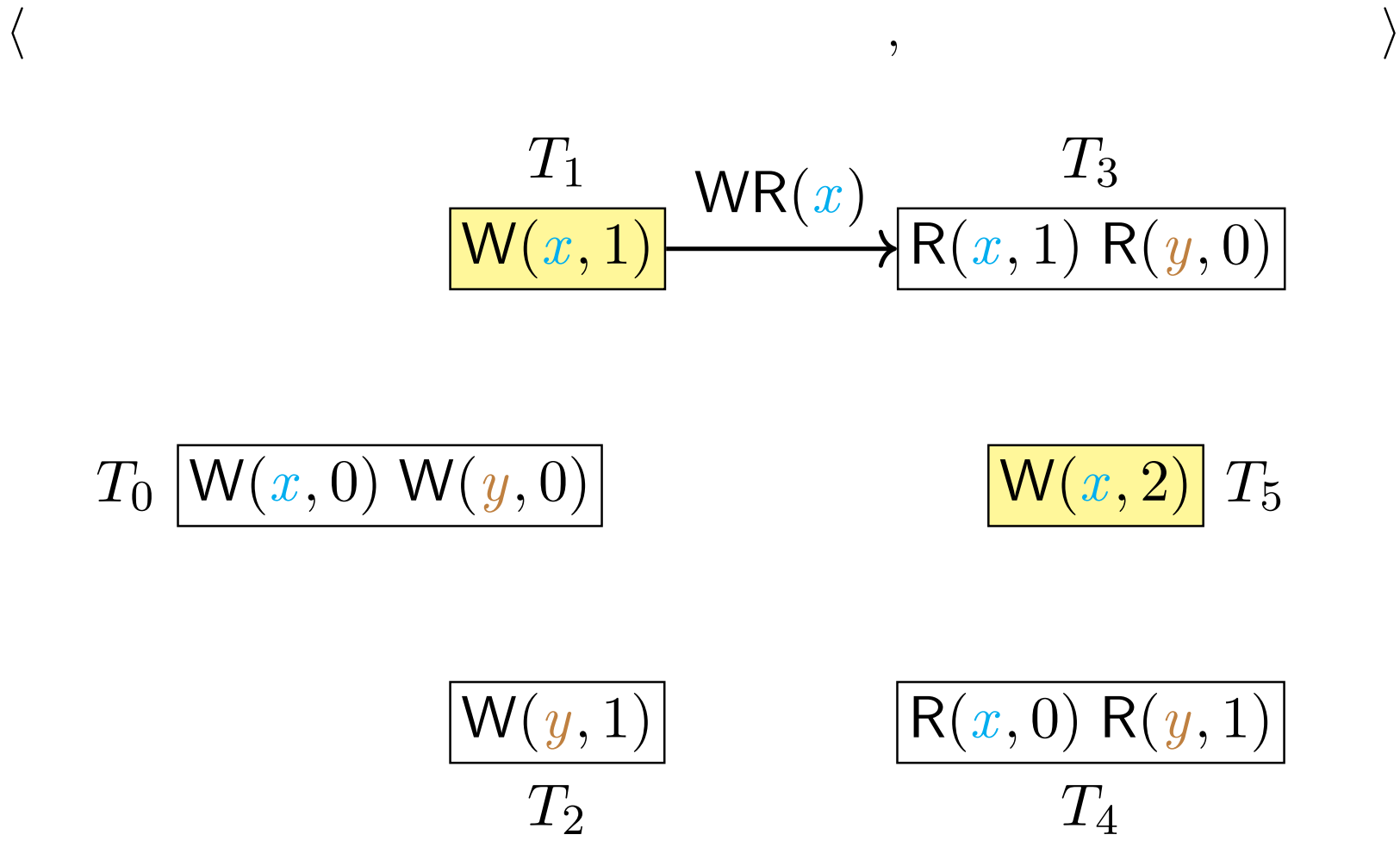


PolySI: An Illustrating Example



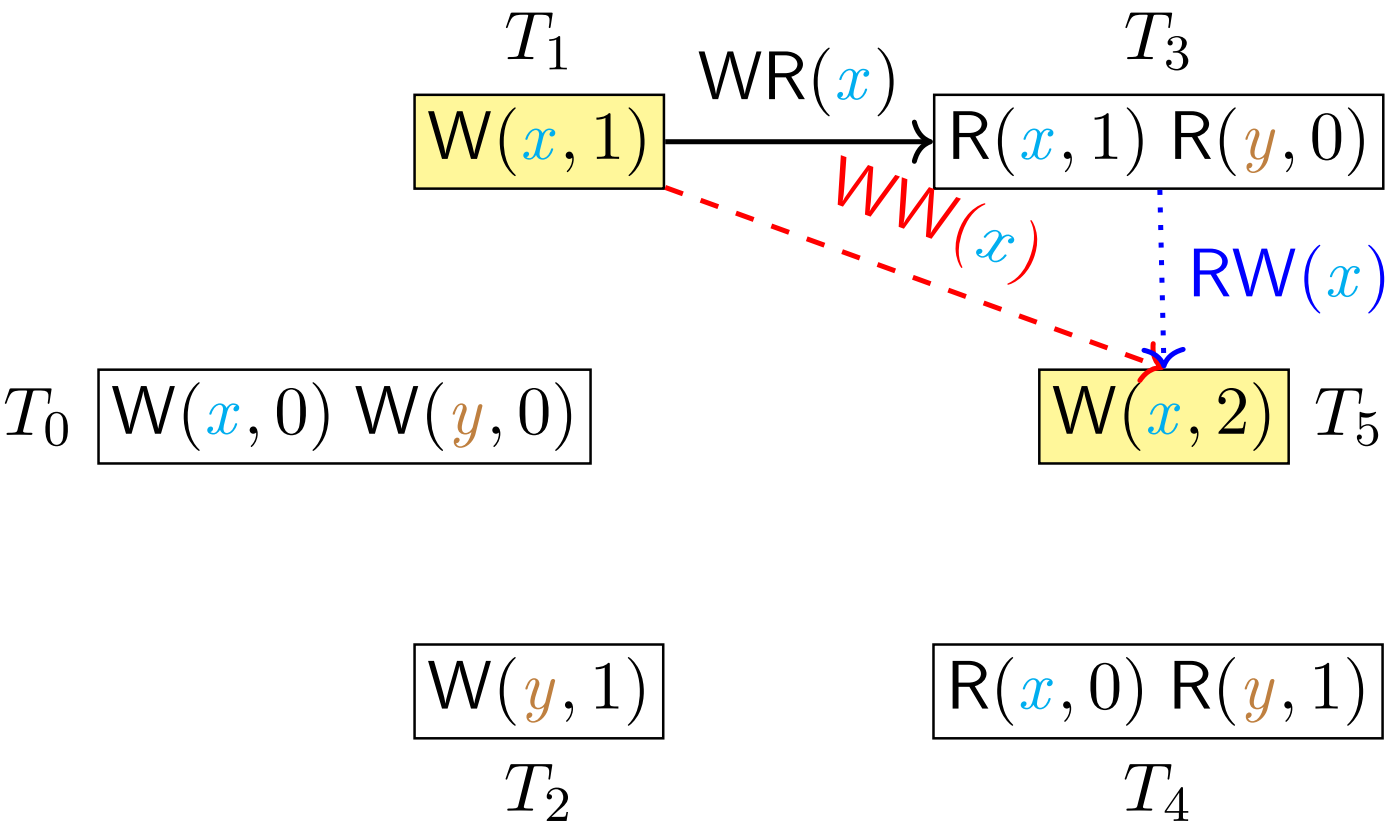
The WW order between T_1 and T_5 is still uncertain after pruning.

PolySI: An Illustrating Example



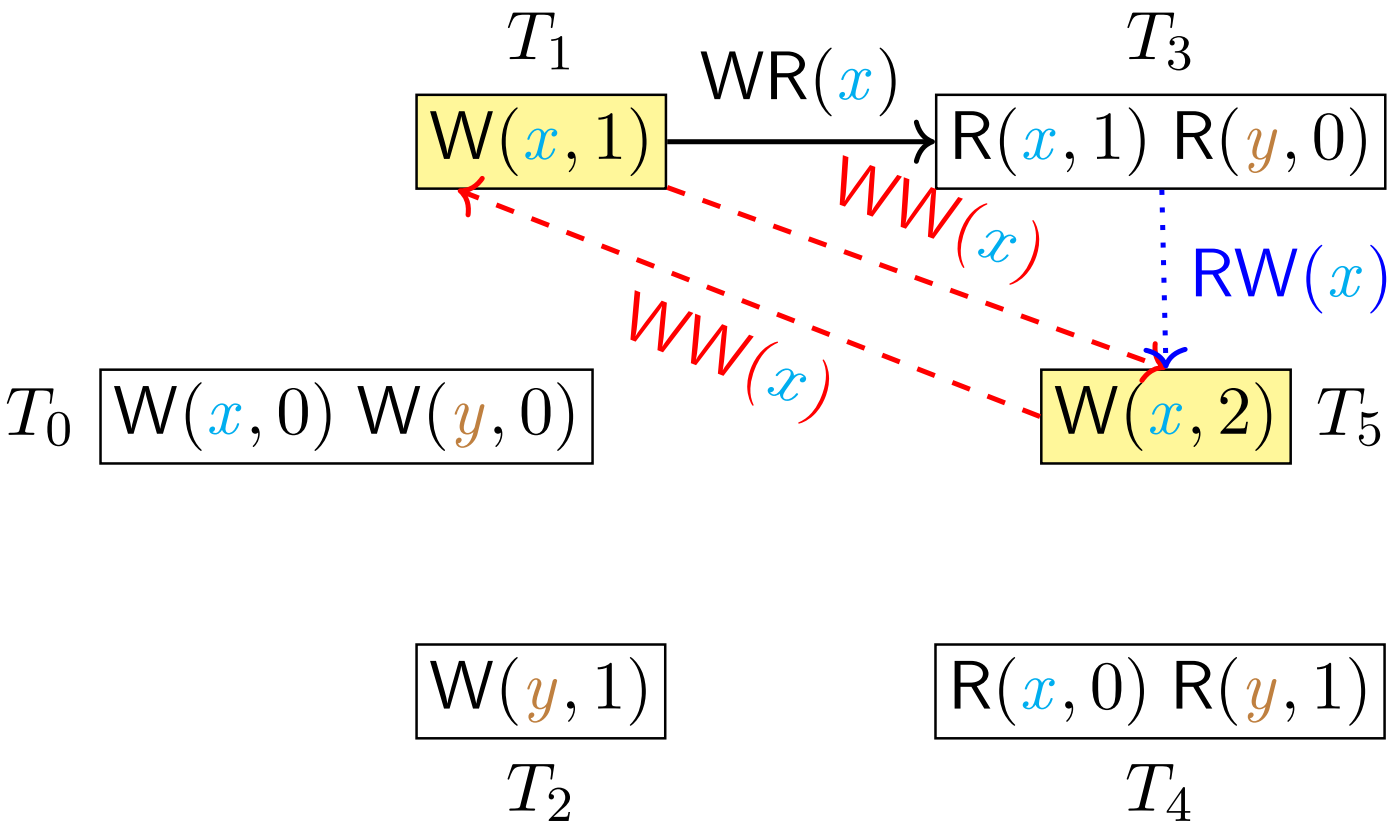
PolySI: An Illustrating Example

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



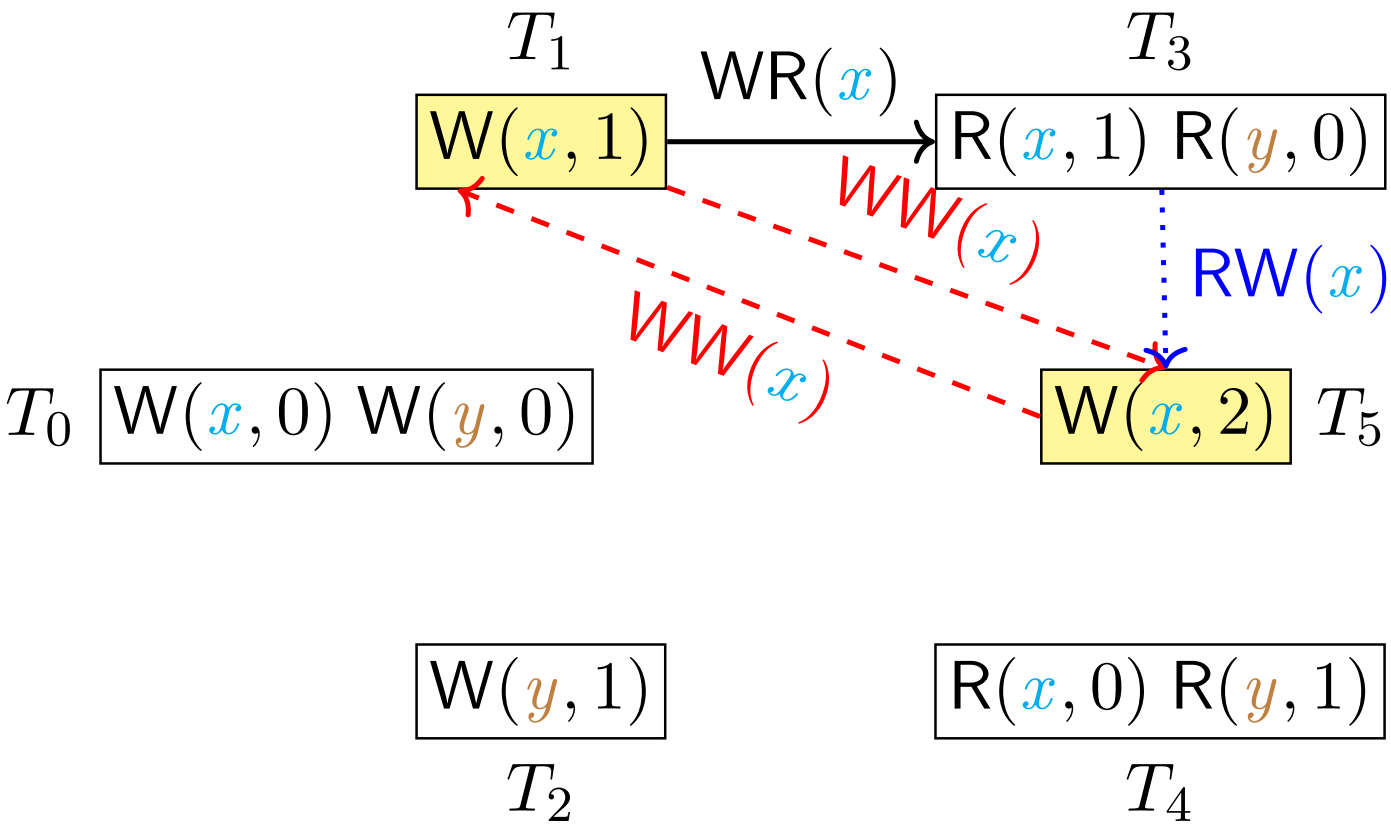
PolySI: An Illustrating Example

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



PolySI: An Illustrating Example

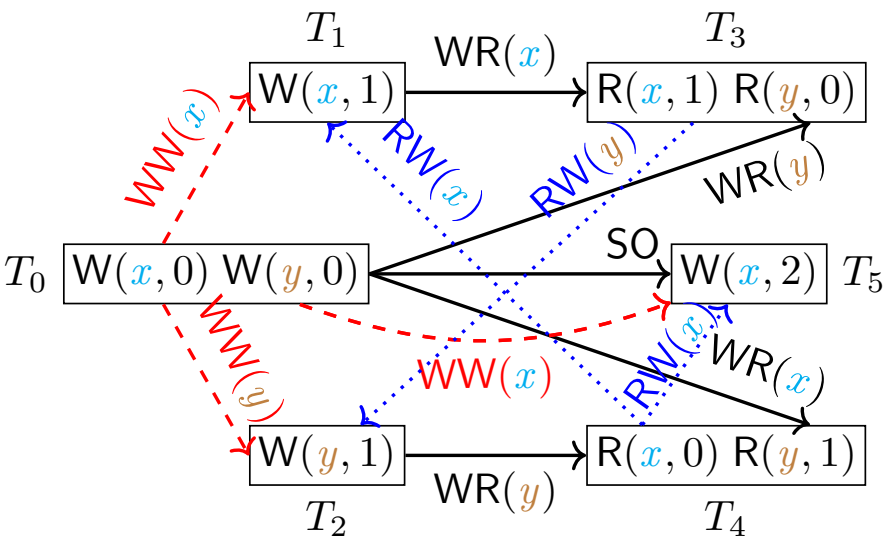
$$\langle either = \{T_1 \xrightarrow{\mathsf{WW}(x)} T_5, T_3 \xrightarrow{\mathsf{RW}(x)} T_5\}, or = \{T_5 \xrightarrow{\mathsf{WW}(x)} T_1\}\rangle$$

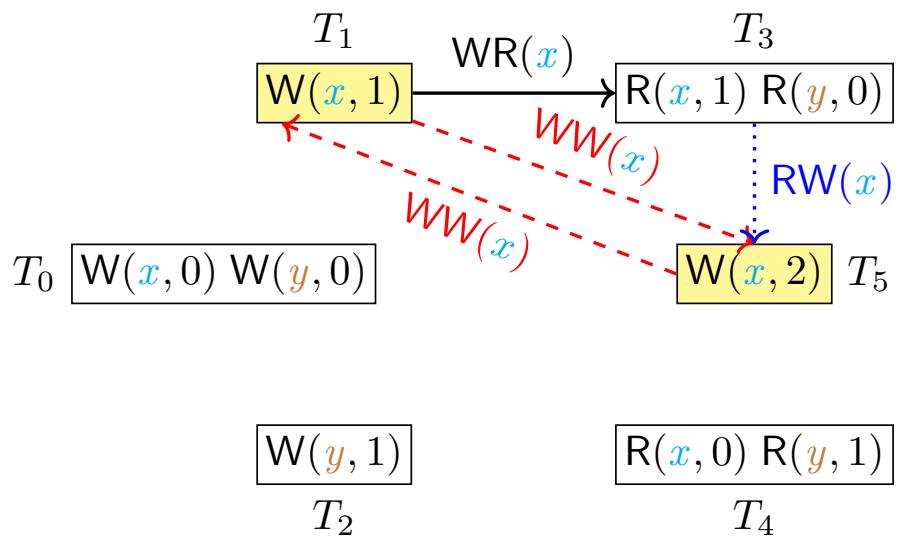


$$(\mathsf{BV}_{1,5} \wedge \mathsf{BV}_{3,5} \wedge \neg\mathsf{BV}_{5,1}) \vee (\mathsf{BV}_{5,1} \wedge \neg\mathsf{BV}_{1,5} \wedge \neg\mathsf{BV}_{3,5})$$

PolySI: An Illustrating Example

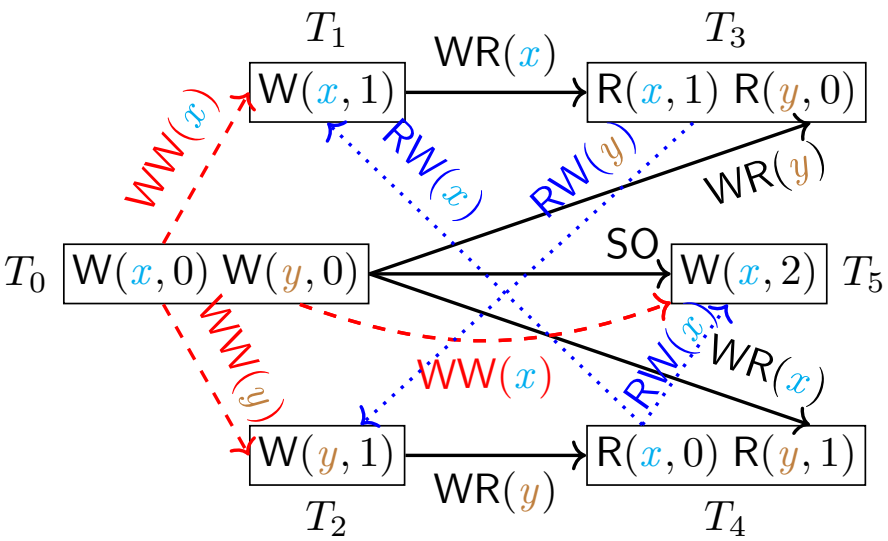
induced graph $((\mathsf{SO}_{\mathcal{G}} \cup \mathsf{WR}_{\mathcal{G}} \cup \mathsf{WW}_{\mathcal{G}}) \; ; \; \mathsf{RW}_{\mathcal{G}}?)$

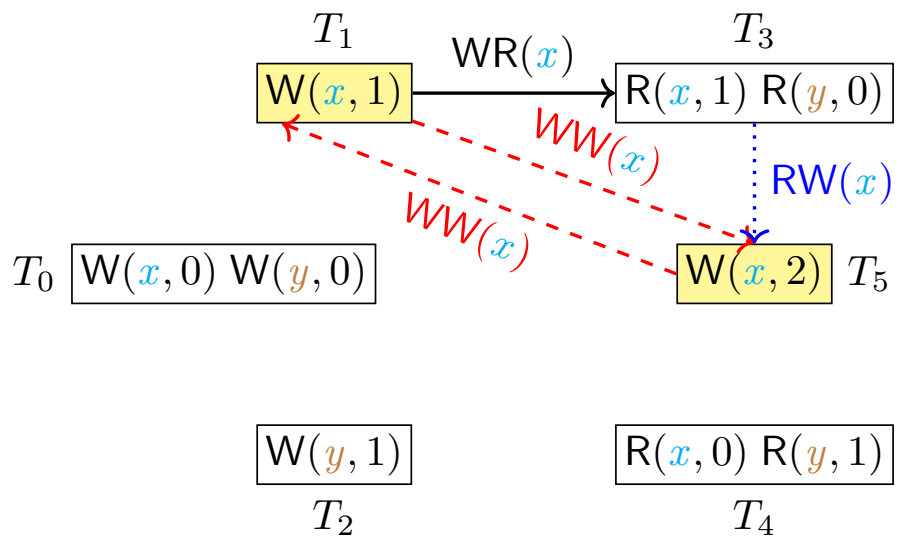




PolySI: An Illustrating Example

induced graph $((\mathsf{SO}_{\mathcal{G}} \cup \mathsf{WR}_{\mathcal{G}} \cup \mathsf{WW}_{\mathcal{G}}) \; ; \; \mathsf{RW}_{\mathcal{G}}?)$

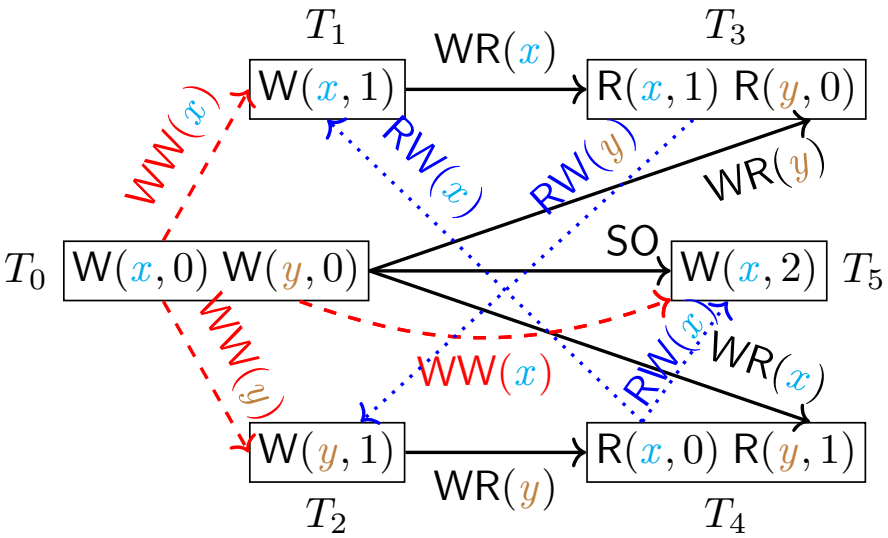


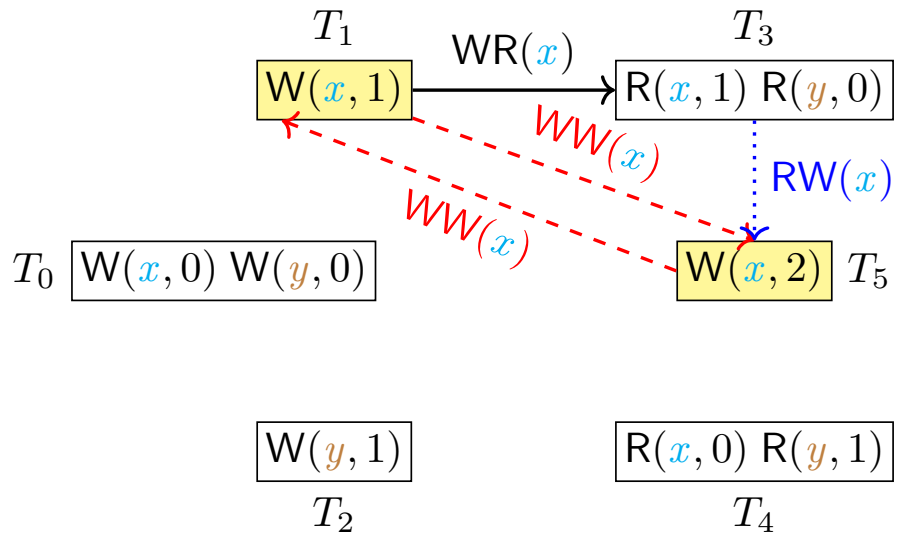


$$T_1 \xrightarrow{\mathsf{WR}} T_3 \xrightarrow{\mathsf{RW}} T_2 : \; \mathsf{BV}^{I}_{1,2} = \mathsf{BV}_{1,3} \wedge \mathsf{BV}_{3,2} \quad (I \text{ for the induced graph})$$

PolySI: An Illustrating Example

induced graph $((\mathsf{SO}_{\mathcal{G}} \cup \mathsf{WR}_{\mathcal{G}} \cup \mathsf{WW}_{\mathcal{G}}) \; ; \; \mathsf{RW}_{\mathcal{G}}?)$





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

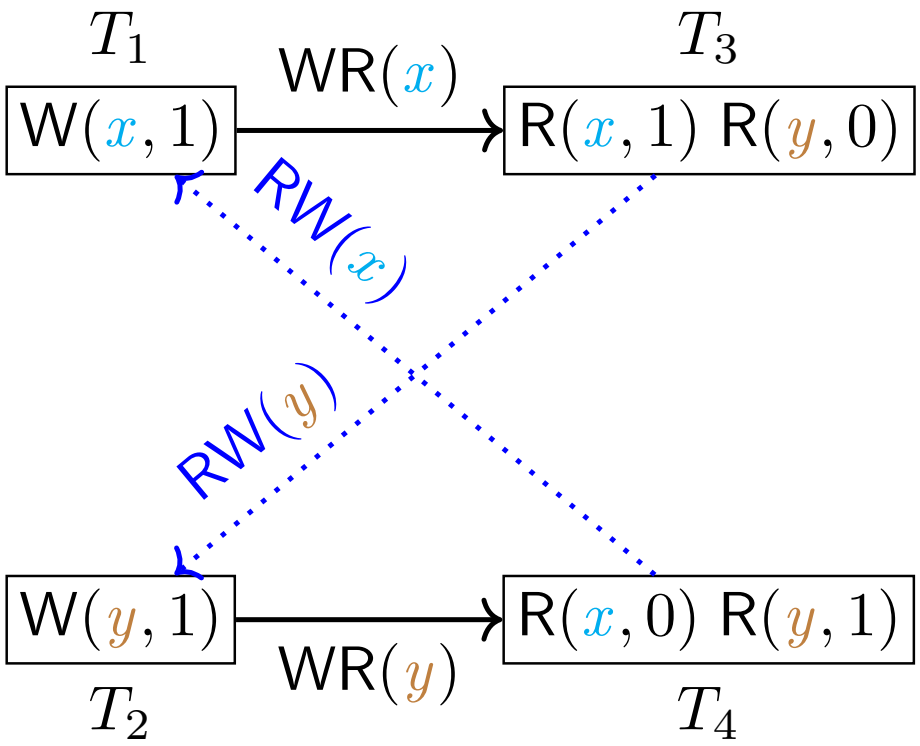
$$T_1 \xrightarrow{\mathsf{WR}} T_3 \xrightarrow{\mathsf{RW}} T_5 : \; \mathsf{BV}^{I}_{1,5} = \mathsf{BV}_{1,3} \wedge \mathsf{BV}_{3,5} \quad (I \text{ for the induced graph})$$

PolySI: An Illustrating Example

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

Assert that the induced graph I is acyclic.

PolySI: An Illustrating Example



the undesired cycle 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?

Workloads

Table: Workload parameters and their default values.[b]

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

[b] Use a database schema of a *two-column table* storing keys and values.

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

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]

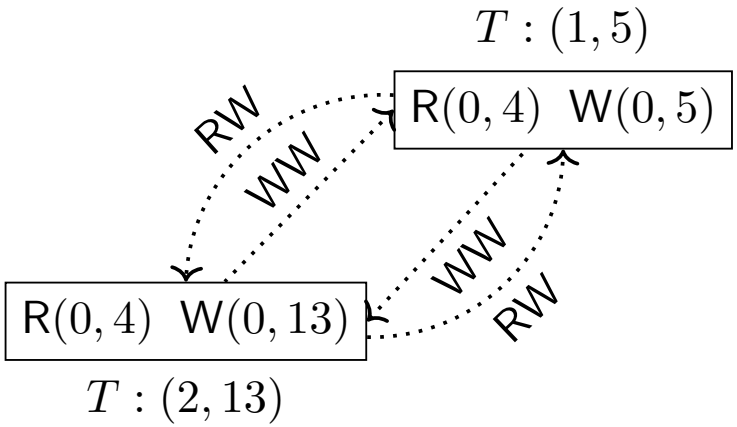
Detecting New SI Violations

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

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

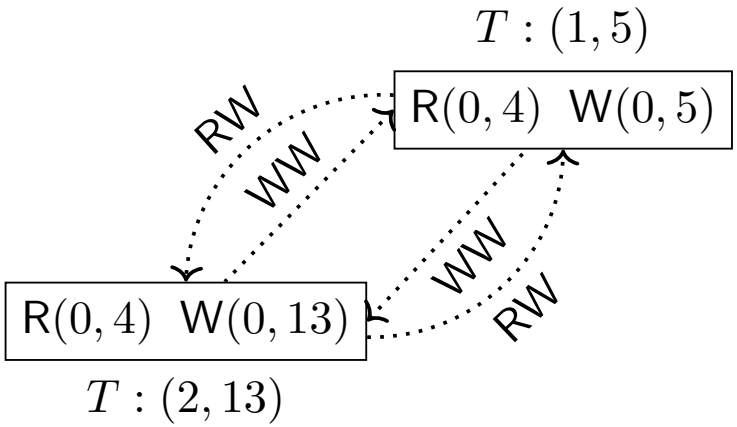
Galera: confirmed the incorrect claim on preventing "lost updates" for transactions issued on different cluster nodes

Understanding Violations (Lost Update)

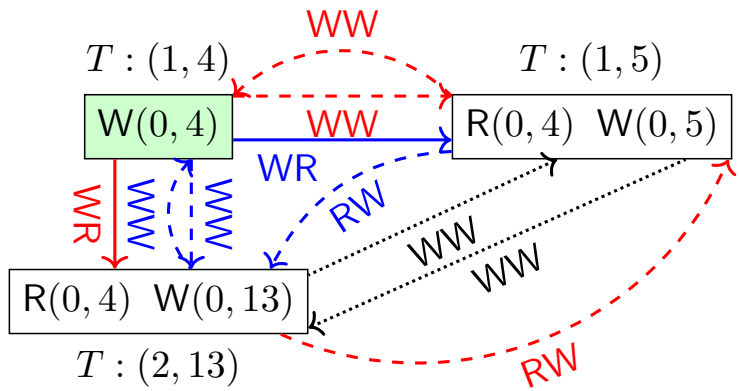


(a) Original output

Understanding Violations (Lost Update)

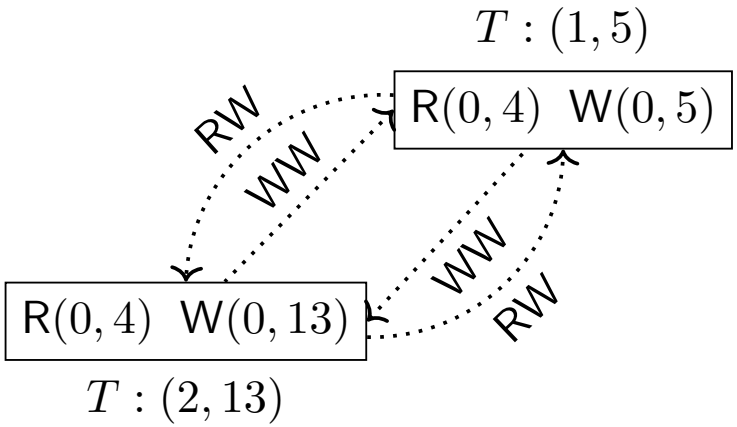


(a) Original output

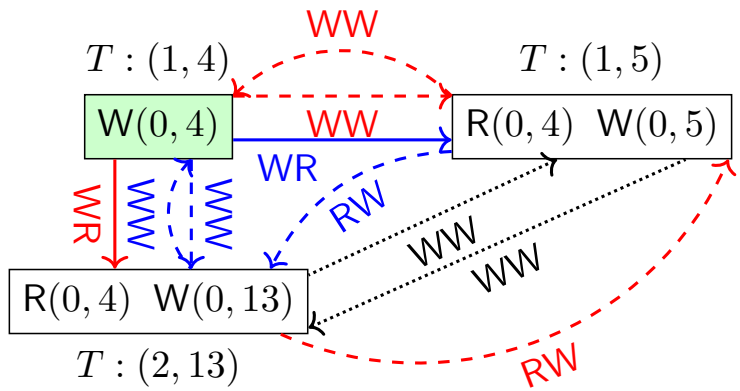


(b) Missing participants

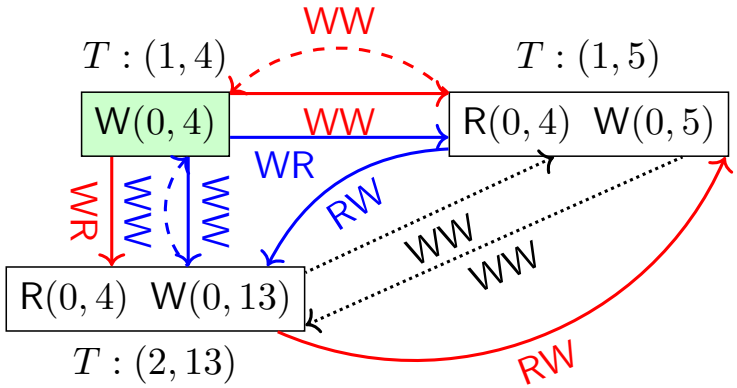
Understanding Violations (Lost Update)



(a) Original output

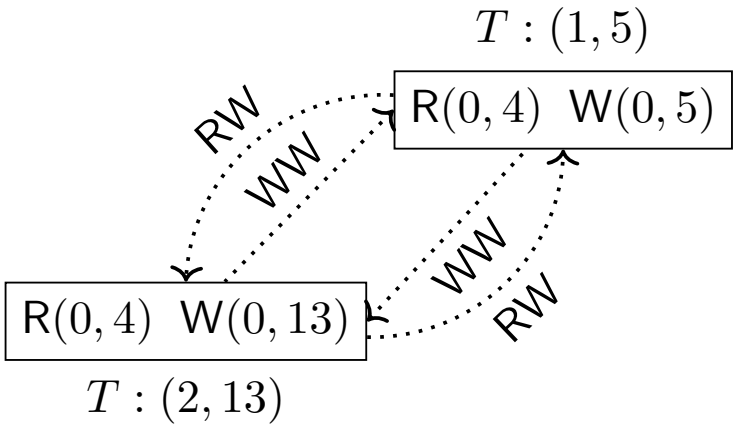


(b) Missing participants

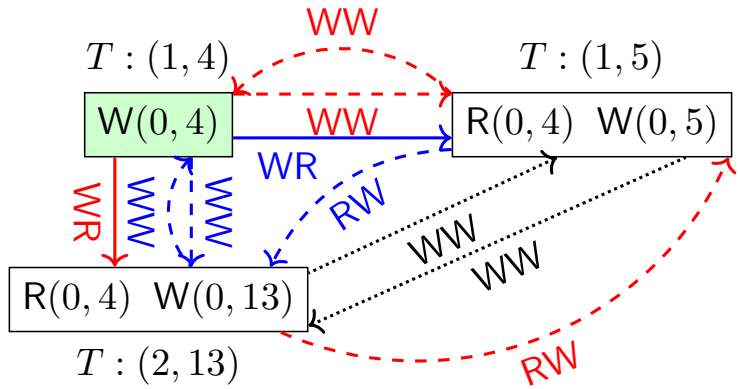


(c) Recovered scenario

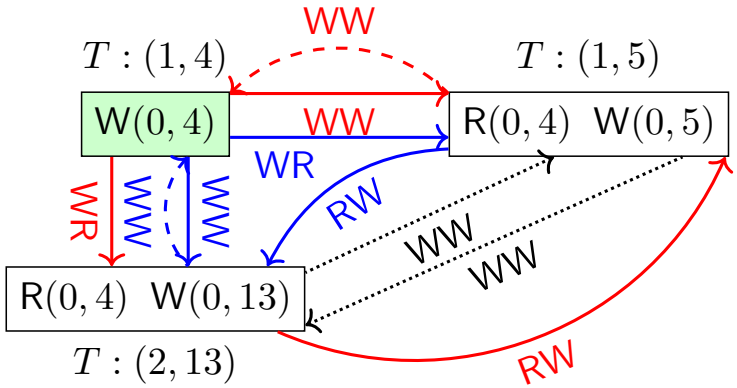
Understanding Violations (Lost Update)



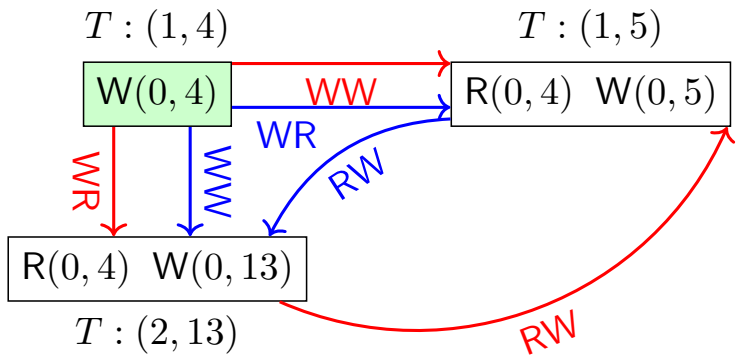
(a) Original output



(b) Missing participants



(c) Recovered scenario



(d) Finalized scenario

Performance Evaluation

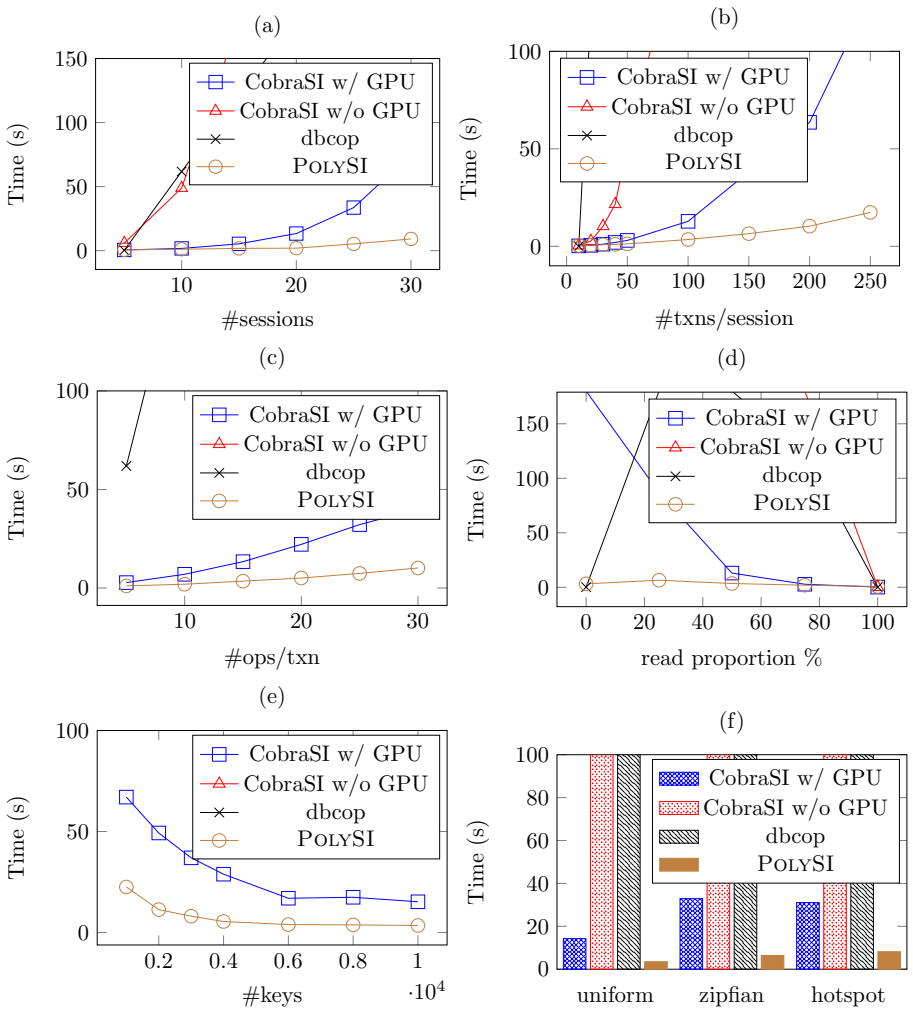
dbcop [Biswas and Enea, 2019]: the state-of-the-art SI checker

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

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

Performance Evaluation: Runtime

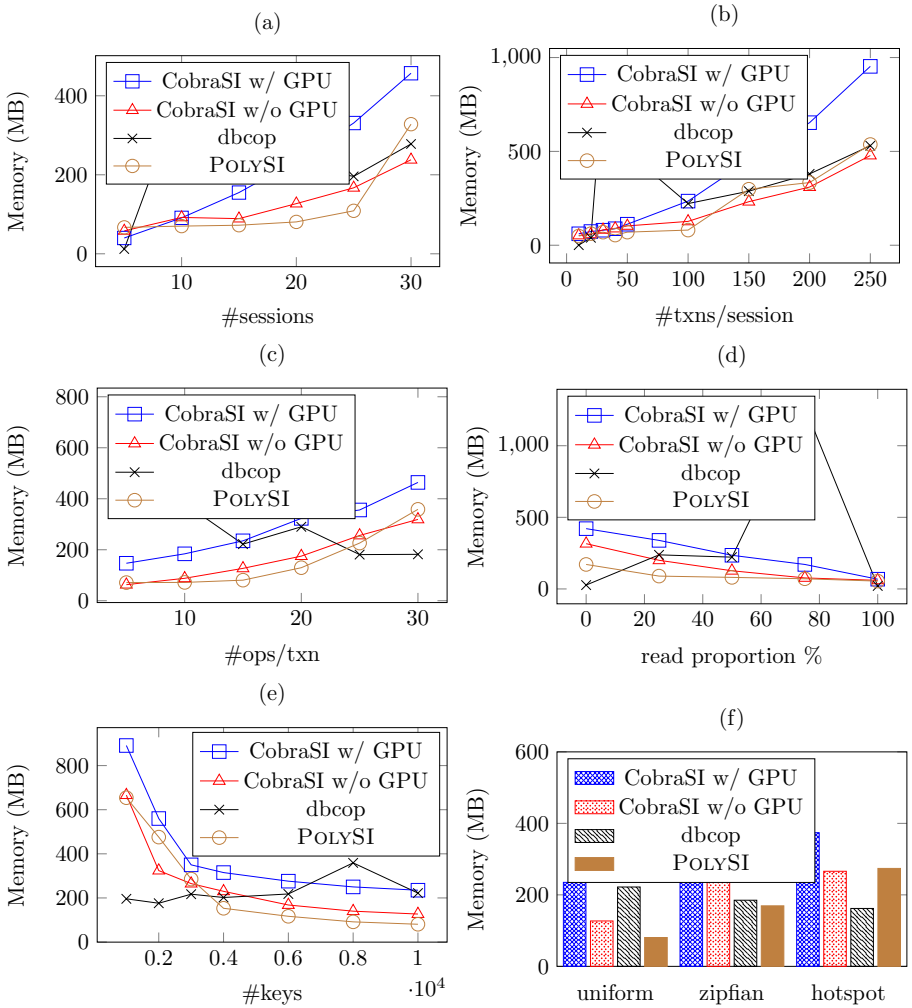
PolySI significantly outperforms the competitors.[c]



[c] All the input histories extracted from PostgreSQL satisfy SI.

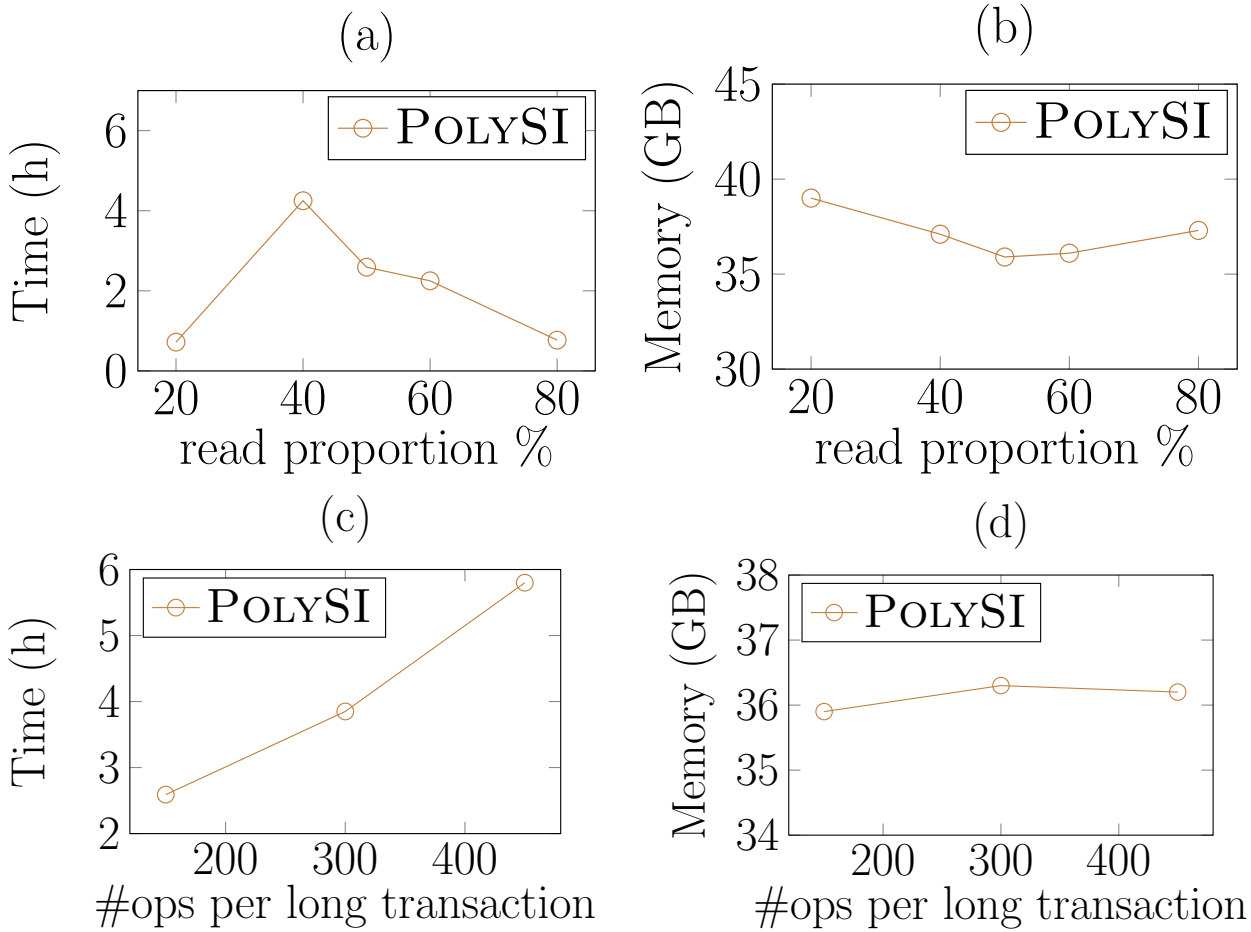
Performance Evaluation: Memory

PolySI consumes less memory.



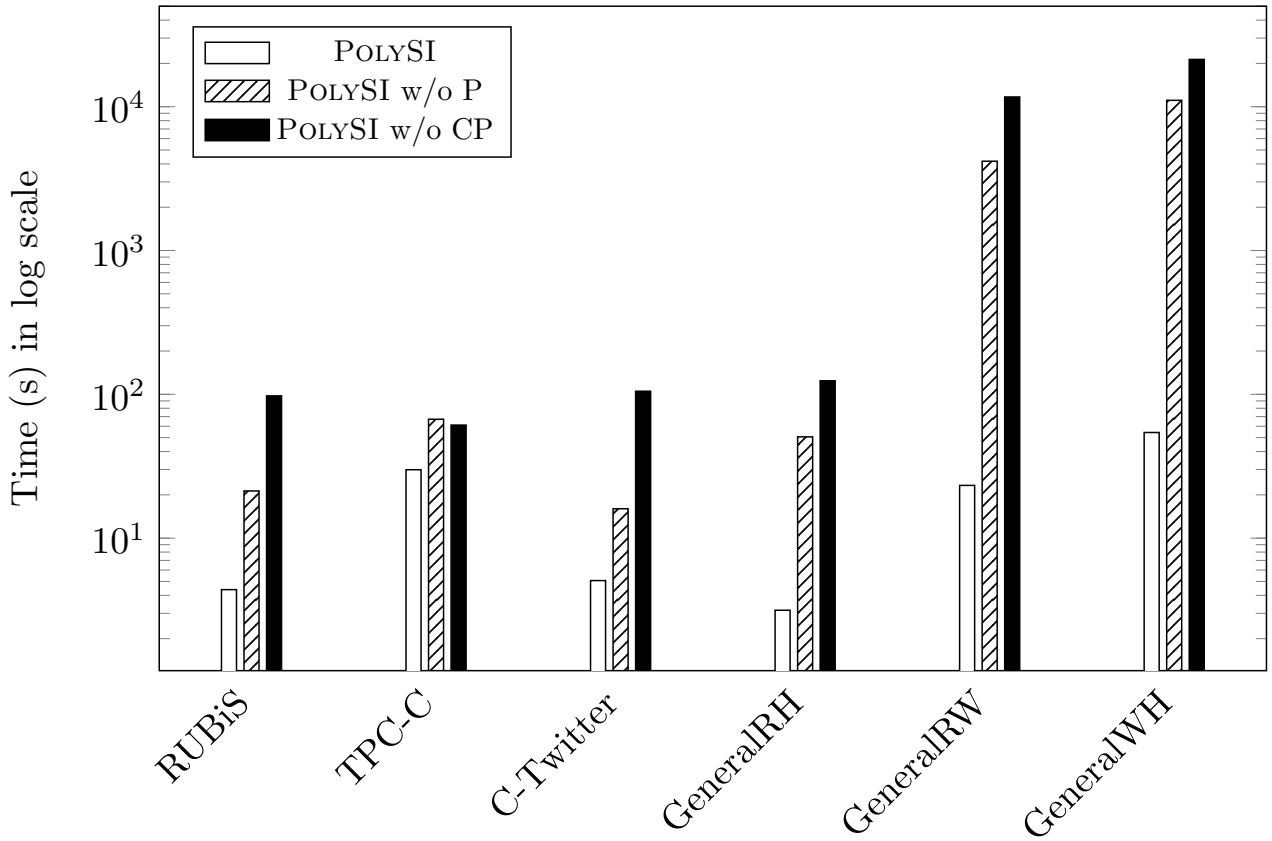
Performance Evaluation: Scalability

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



Performance Evaluation: Differential Analysis

Pruning (P) is crucial to the efficiency of PolySI.[d]



[d] Compacting (C) encoding has been omitted in this presentation.

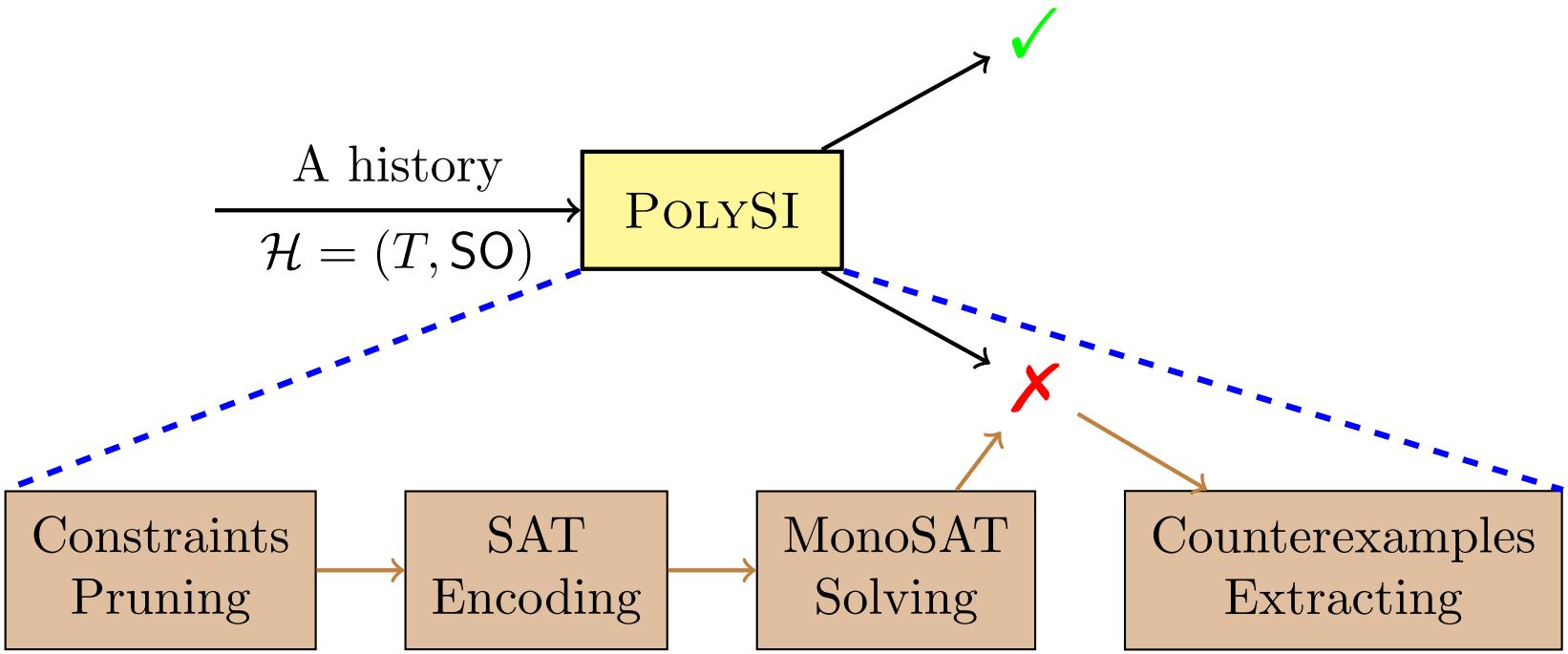
Performance Evaluation: Pruning

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

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].

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Adya, Atul (1999). "Weak Consistency: A Generalized Theory and Optimistic Implementations for Distributed Transactions". PhD thesis. USA.


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Kingsbury, Kyle and Peter Alvaro (Nov. 2020). "Elle: Inferring Isolation Anomalies from Experimental Observations". In: *Proc. VLDB Endow.* 14.3, pp. 268–280. ISSN: 2150-8097.


Tan, Cheng, Changgeng Zhao, Shuai Mu, and Michael Walfish (2020). "COBRA: Making Transactional Key-Value Stores Verifiably Serializable". In: *OSDI'20*. ISBN: 978-1-939133-19-9.