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

$acct_1 = acct_2 = 60$

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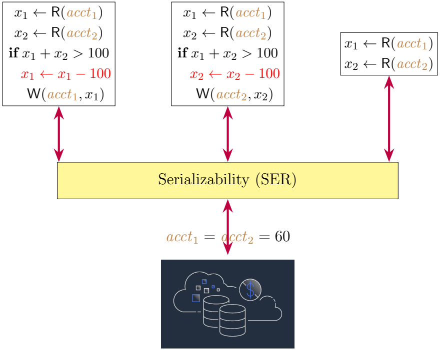
Isolation Level (aka Transactional Consistency Model)

$acct_1 = acct_2 = 60$

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

All transactions appear to execute in some total order.



Serializability (SER)

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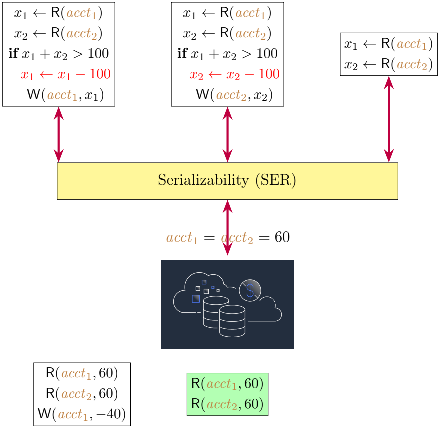

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too expensive, especially for distributed transactions

Snapshot Isolation (SI)

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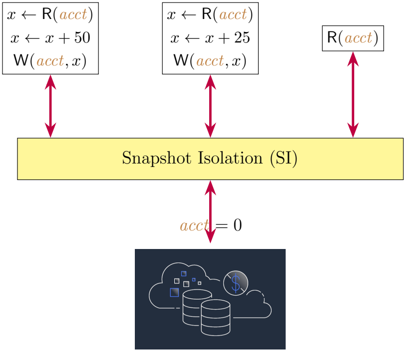
Snapshot Read: Each transaction reads data from a *snapshot* of committed data valid as of the (logical) time the transaction started.



$x \leftarrow \mathsf{R}(acct)$
$x \leftarrow x + 50$
$\mathsf{W}(acct, x)$
$x \leftarrow \mathsf{R}(acct)$
$x \leftarrow x + 25$
$\mathsf{W}(acct, x)$
$\mathsf{R}(acct)$
Snapshot Isolation (SI)
$acct = 0$

Snapshot Isolation (SI)

$x \leftarrow \mathsf{R}(acct)$
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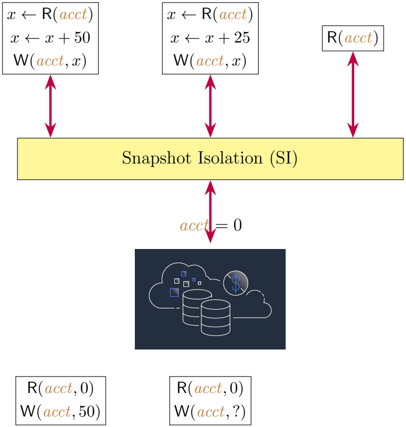
$\mathsf{R}(acct)$

Snapshot Isolation (SI)

$acct = 0$

$\mathsf{R}(acct, 0)$
$\mathsf{W}(acct, 50)$

Snapshot Isolation (SI)



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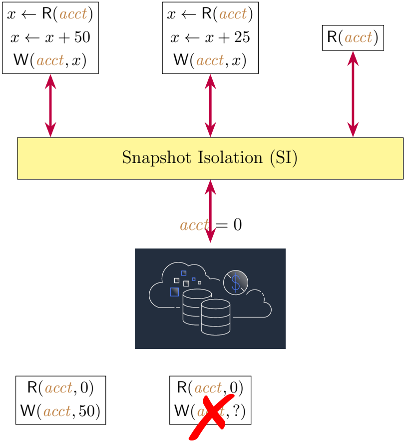

Snapshot Write: Concurrent transactions cannot write to the same key. One of them must be aborted.

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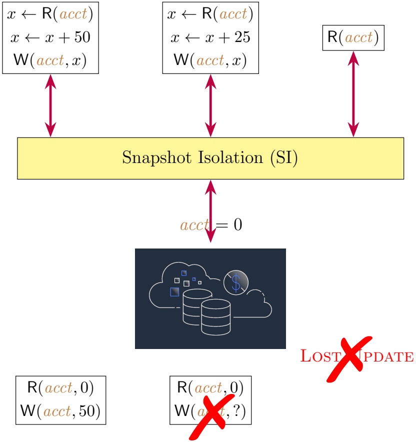

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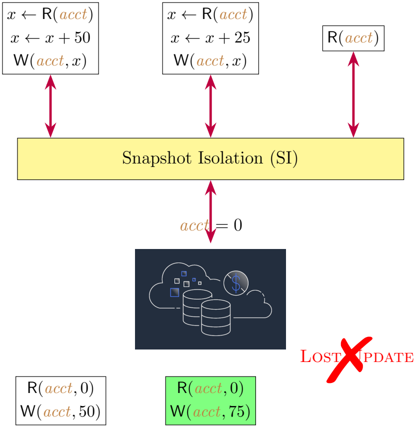

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$\boxed{\mathsf{W}(x, post)}$

Snapshot Isolation (SI)

Snapshot Isolation (SI)

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

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

Snapshot Isolation (SI)

Snapshot Isolation (SI)

W(x, *post*)

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

R(x, *empty*)
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

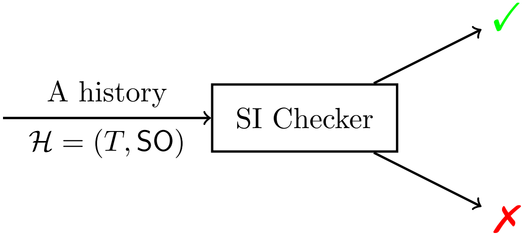
+papers

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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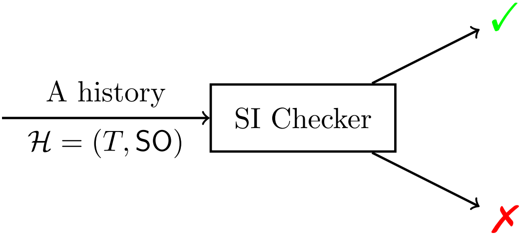
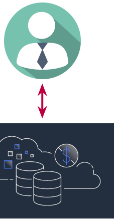


SO : *session order* among the set T of transactions

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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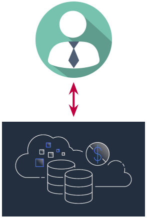

W(x, $post$)	R(x, $post$) W(y, $comment$)	R(x, $empty$) R(y, $comment$)

Lost Update

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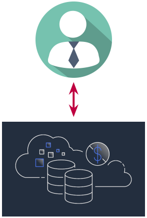

W(x, *post*)	R(x, *post*) W(y, *comment*)	R(x, *empty*) R(y, *comment*)	LOST UPDATE ✗

R($acct_1$, 60) R($acct_2$, 60) W($acct_1$, −40)	R($acct_1$, 60) R($acct_2$, 60) W($acct_2$, −40)	R($acct_1$, −40) R($acct_2$, −40)	WRITE SKEW ✓

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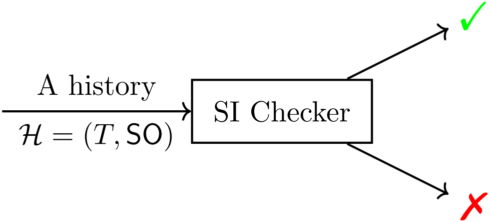
The SI Checking Problem



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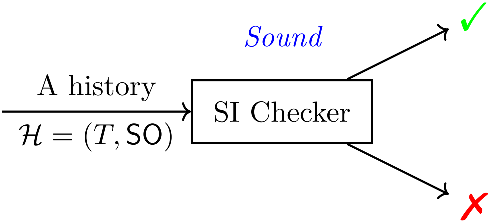
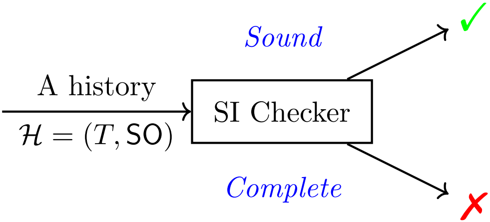


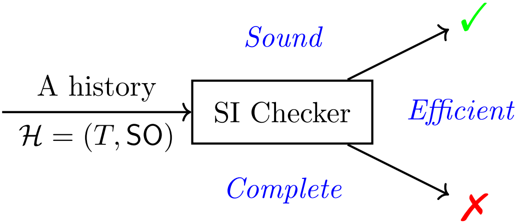
Sound: If the checker says ✗, then the history does *not* satisfy SI.

The SI Checking Problem



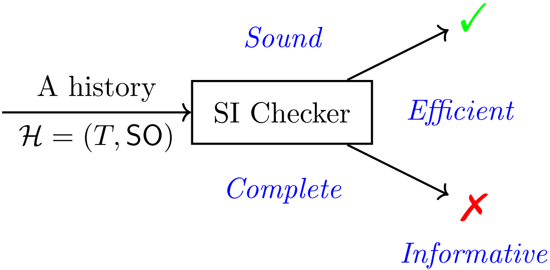
Complete: If the checker says ✓, then the history *satisfies* SI.

The SI Checking Problem



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

The SI Checking Problem

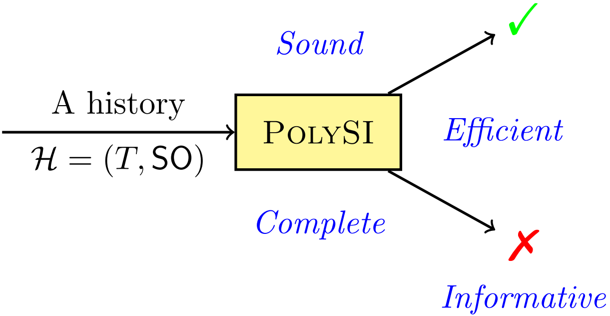


Informative: The checker should provide understandable *counterexamples* if it says ✗.

The SI Checking Problem

related-work

Contribution: the PolySI Checker



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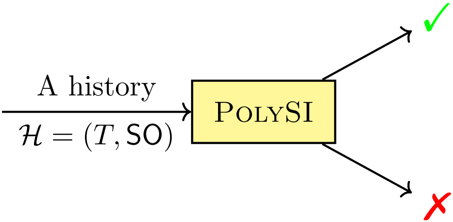

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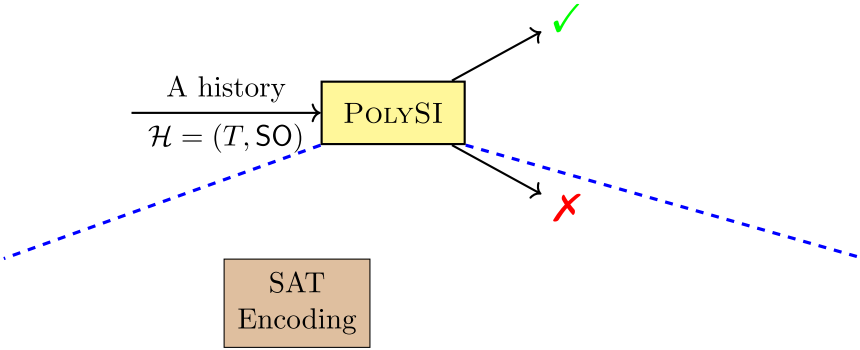
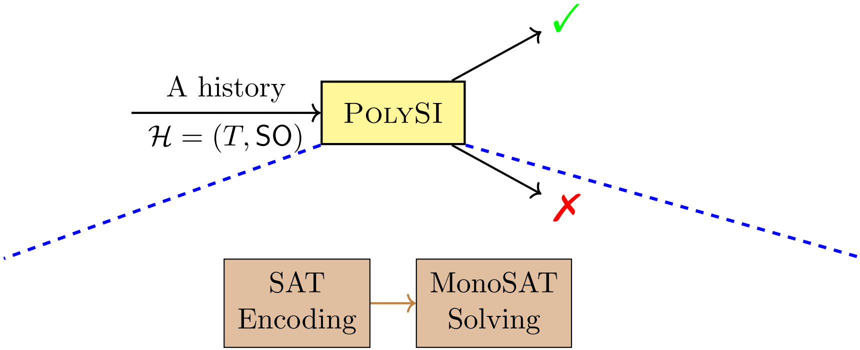


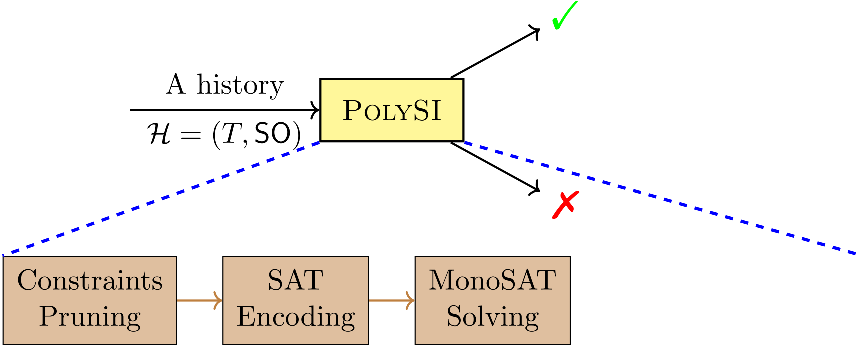
Sound & Complete: polygraph-based characterization of SI

Contribution: the PolySI Checker



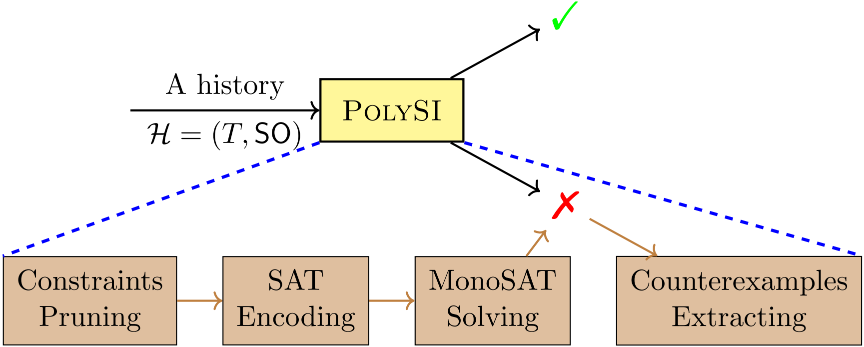
Efficient: utilizing MonoSAT solver optimized for graph problems

Contribution: the PolySI Checker



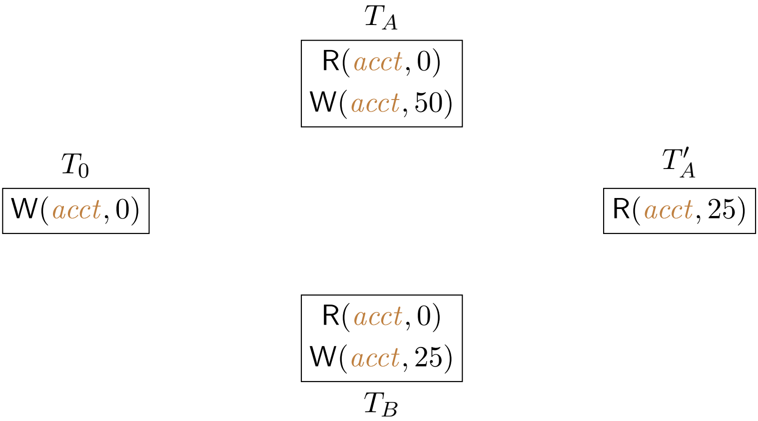
Efficient: domain-specific pruning before encoding

Contribution: the PolySI Checker



Informative: extract counterexamples from the unsatisifiable core

Dependency Graph-based Characterization of SI



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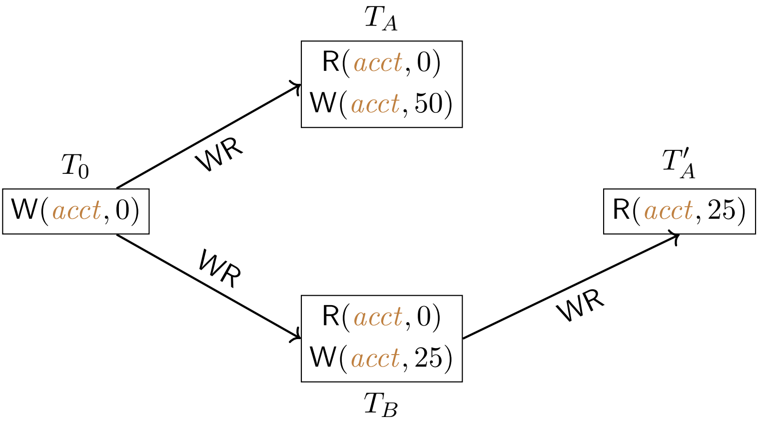

WR: "write-read" dependency capturing the "read-from" relation

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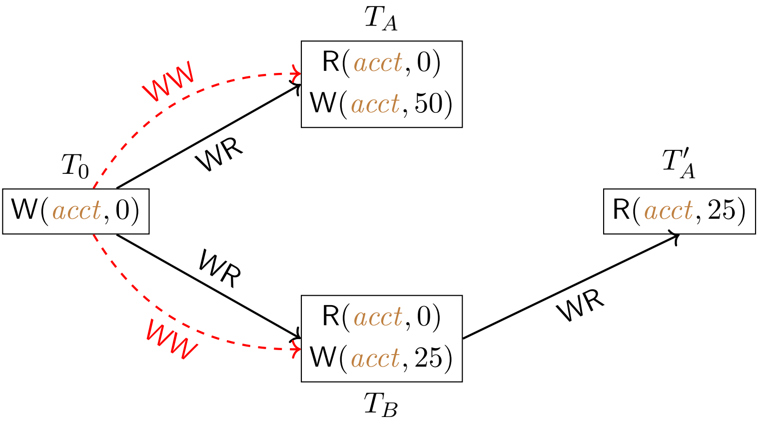
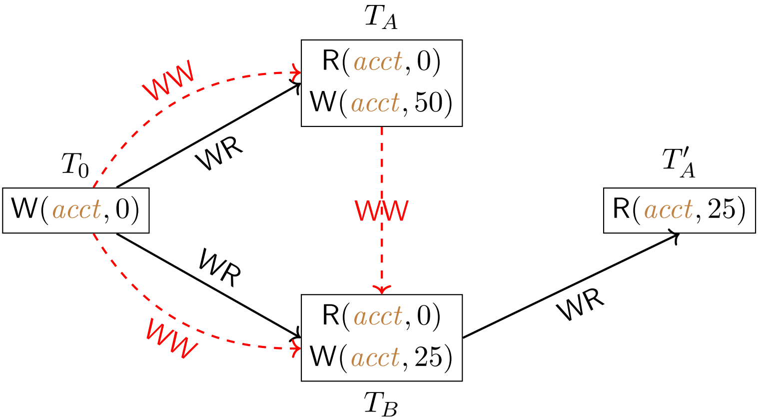


WW: "write-write" dependency capturing the version order

Dependency Graph-based Characterization of SI

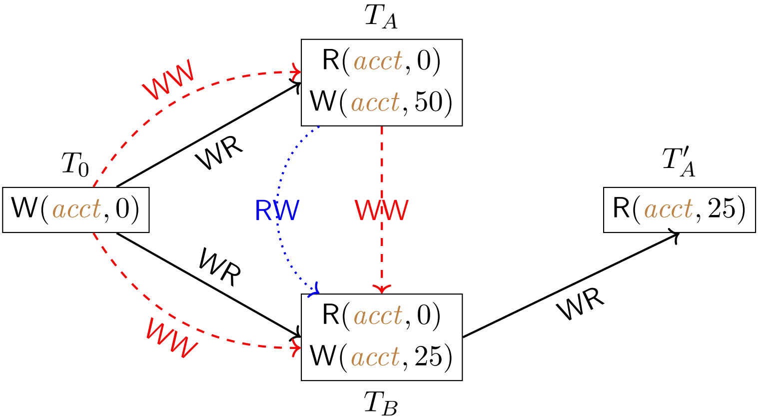
Suppose that $T_A \xrightarrow{\text{WW}} T_B$



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

Dependency Graph-based Characterization of SI

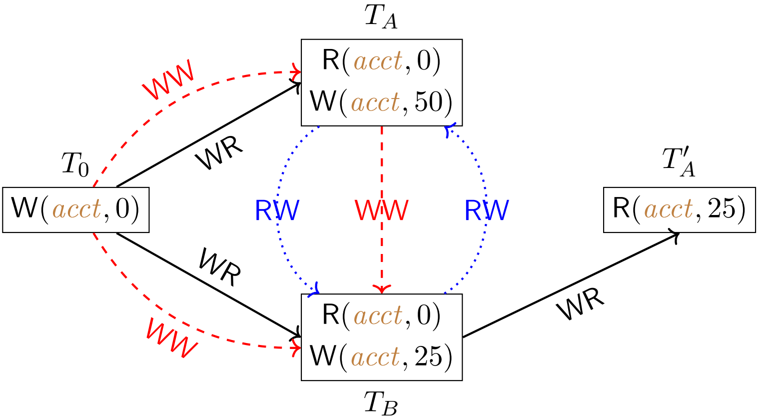
$$T_0 \xrightarrow{\mathsf{WR}} T_A \wedge T_0 \xrightarrow{\mathsf{WW}} T_B \implies T_A \xrightarrow{\mathsf{RW}} T_B$$



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

Dependency Graph-based Characterization of SI

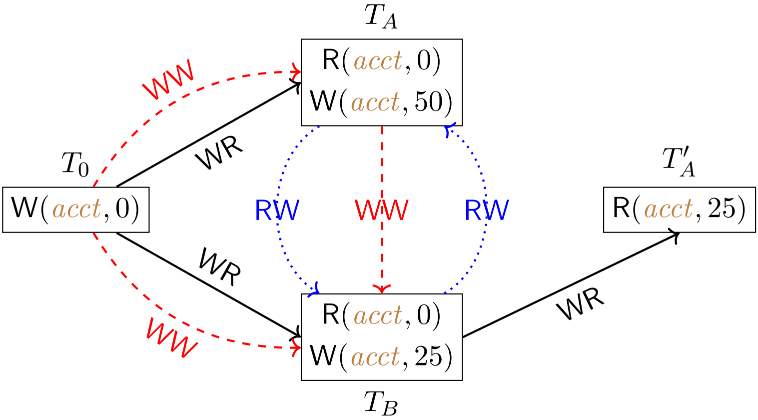
$$T_0 \xrightarrow{\mathsf{WR}} T_B \wedge T_0 \xrightarrow{\mathsf{WW}} T_A \implies T_A \xrightarrow{\mathsf{RW}} T_A$$



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

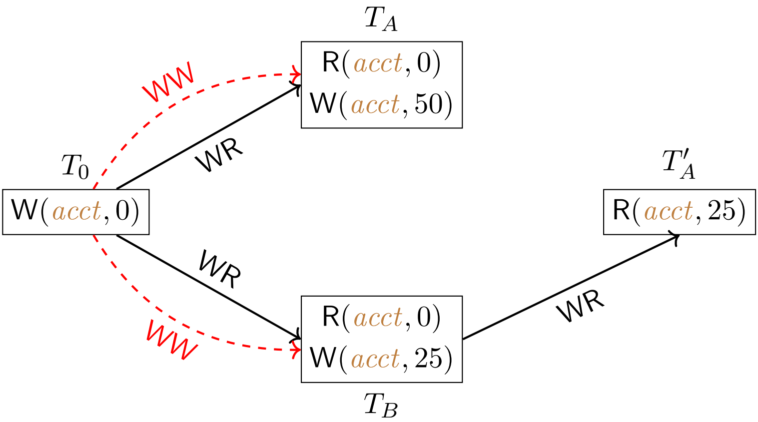
Dependency Graph-based Characterization of SI

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



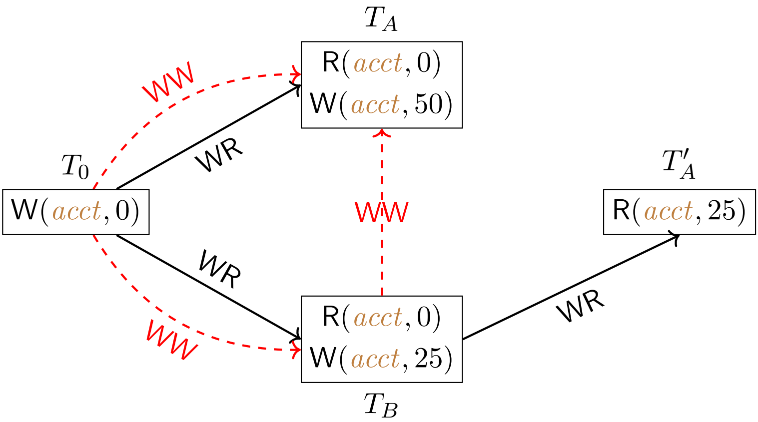
undesired cycle: $T_A \xrightarrow{\text{WW}} T_B \xrightarrow{\text{RW}} T_A$

Dependency Graph-based Characterization of SI



Dependency Graph-based Characterization of SI

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



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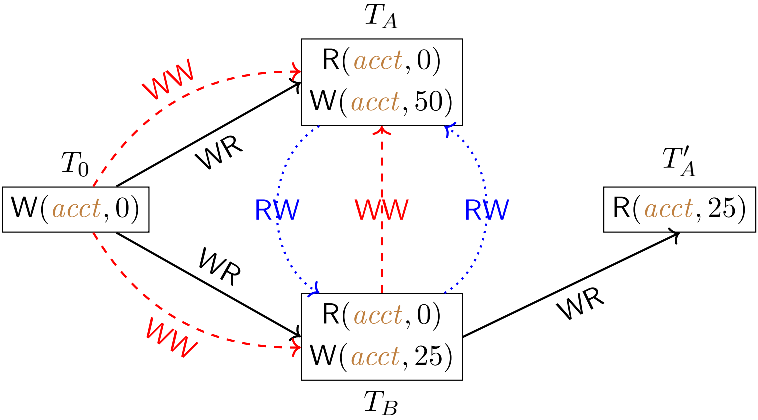

Dependency Graph-based Characterization of SI

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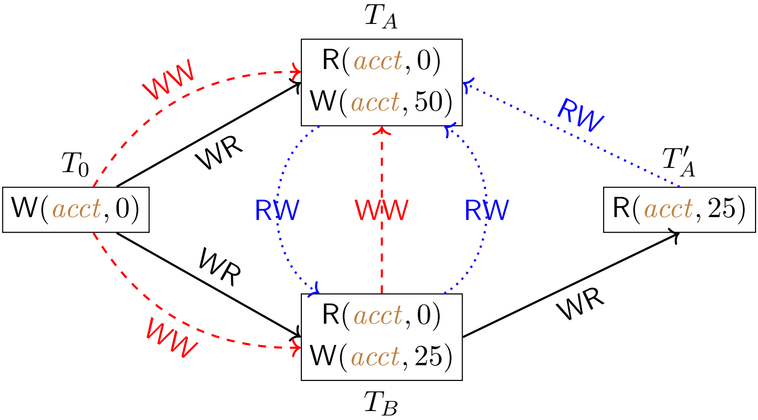
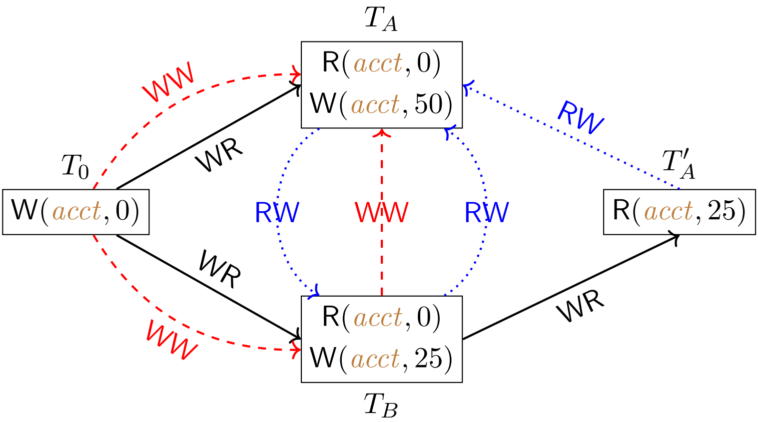


Dependency Graph-based Characterization of SI

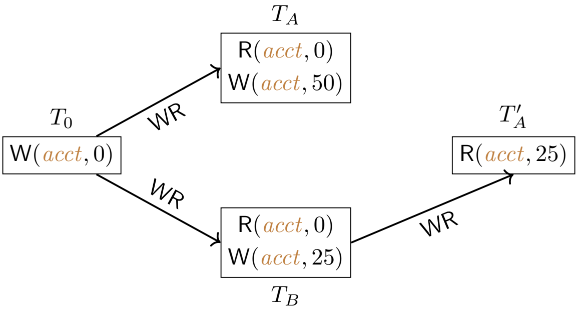
$$\boxed{\textit{Suppose that } T_B \xrightarrow{\text{WW}} T_A}$$



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.

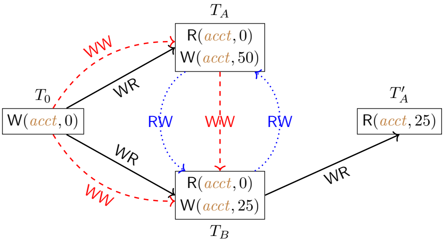
Therefore, it does not satisfy SI.

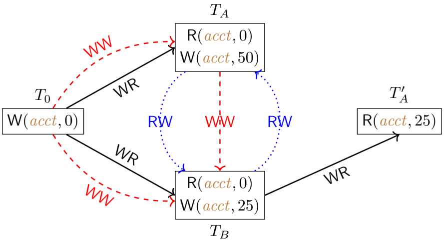
Dependency Graph-based Characterization of SI

Theorem (Theorem 4.1 of [AnalysingSI:JACM2018])

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





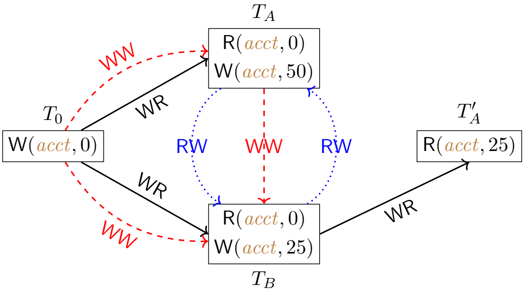
Every possible dependency graph contains an undesired  cycle.

Dependency Graph-based Characterization of SI

Theorem (Theorem 4.1 of [AnalysingSI:JACM2018])

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

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



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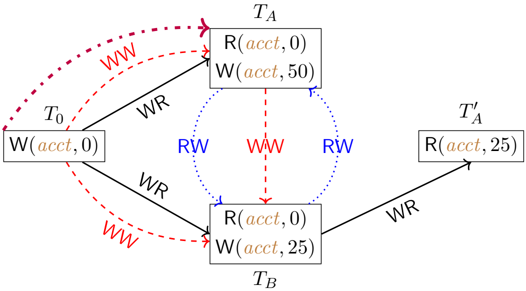

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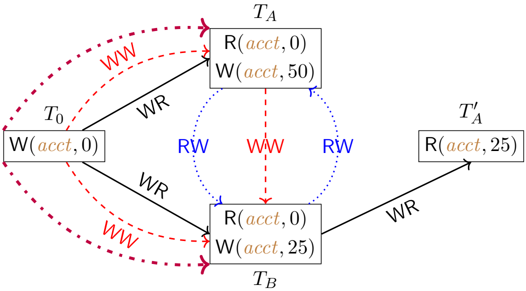

Dependency Graph-based Characterization of SI

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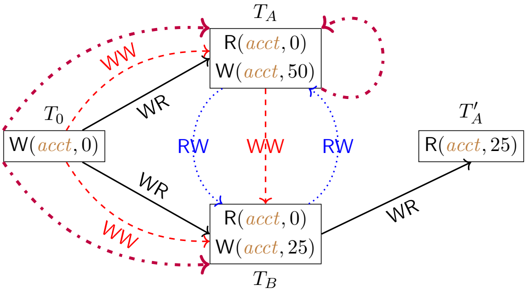

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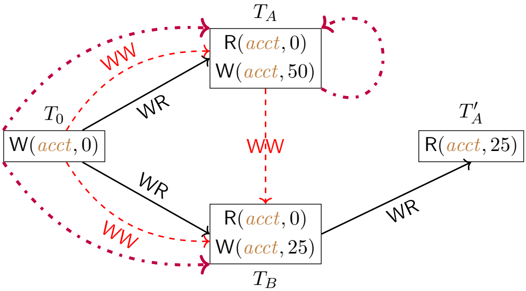
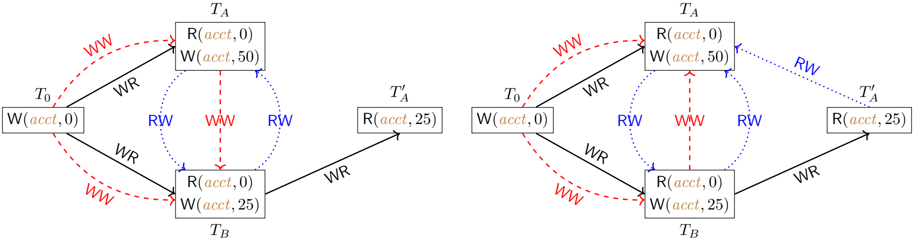


Dependency Graph-based Characterization of SI

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



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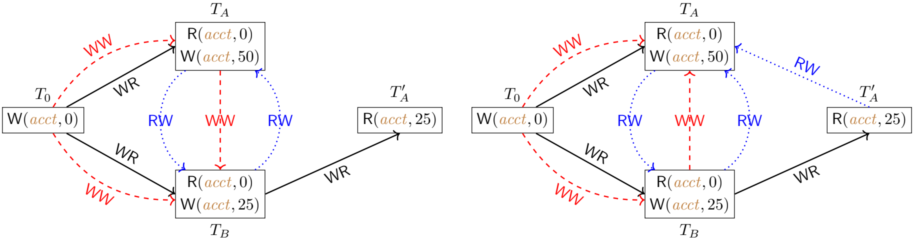
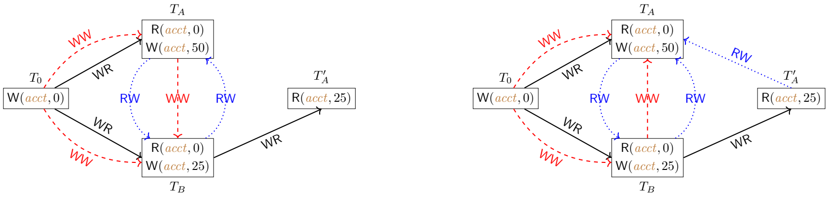


$\mathcal{A}$: encode them into SAT formulas based on (generalized) polygraphs and solve them using SAT solvers.

Polygraphs: A Family of Dependency Graphs

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



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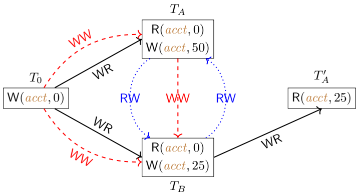

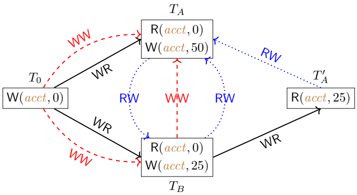

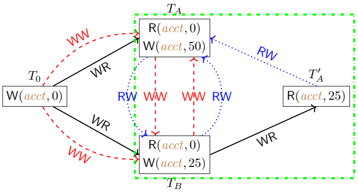

generalized polygraph:

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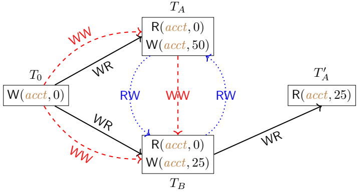
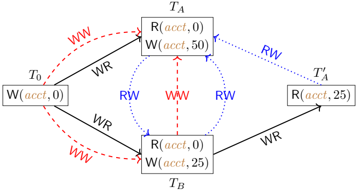
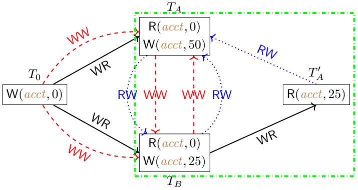


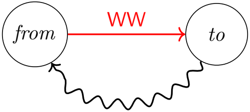


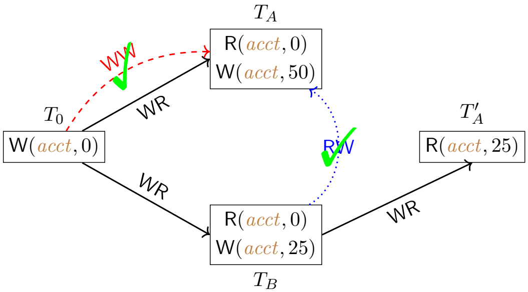


generalized polygraph:

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

PolySI: Pruning before Encoding (the WW case)





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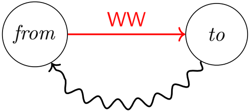
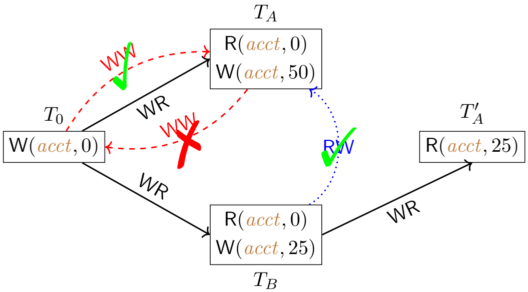
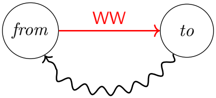
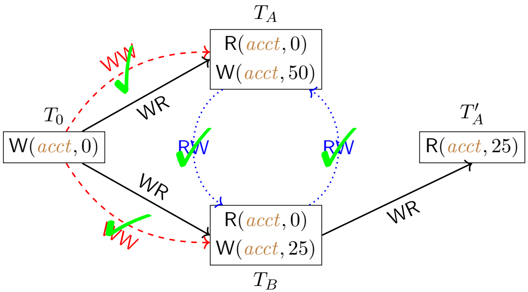




$T_A \xrightarrow{\mathsf{WW}} T_0$ can be pruned due to the $T_A \xrightarrow{\mathsf{WW}} T_0 \xrightarrow{\mathsf{WR}} T_A$ cycle.

PolySI: Pruning before Encoding (the WW case)





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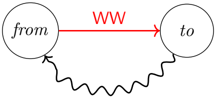
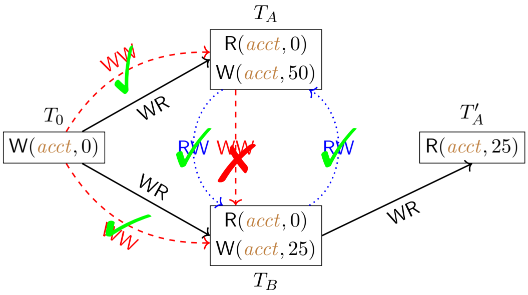
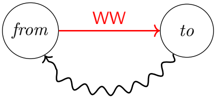
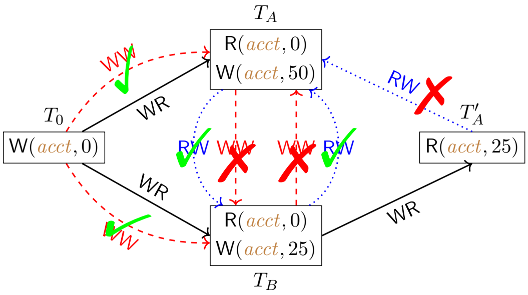




$$T_A \xrightarrow{\text{WW}} T_B \text{ is pruned due to the } T_A \xrightarrow{\text{WW}} T_B \xrightarrow{\text{RW}} T_A \text{ cycle.}$$

PolySI: Pruning before Encoding (the WW case)

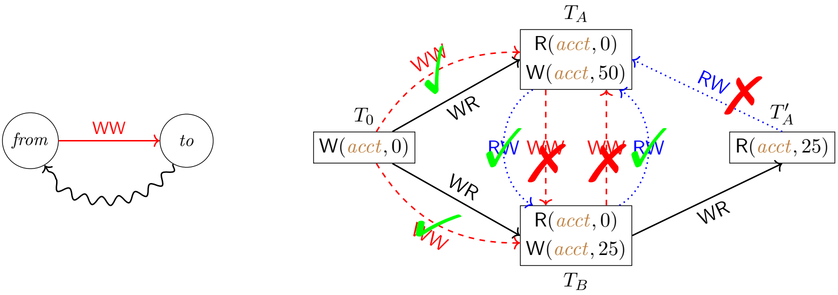




$T_A \xrightarrow{\text{WW}} T_B$ is pruned due to the $T_A \xrightarrow{\text{WW}} T_B \xrightarrow{\text{RW}} T_A$ cycle.

$T_B \xrightarrow{\text{WW}} T_A$ 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)

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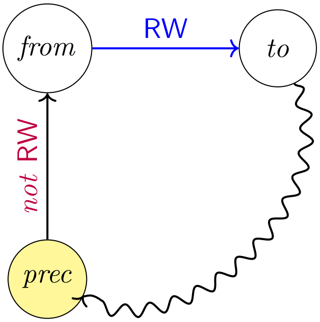
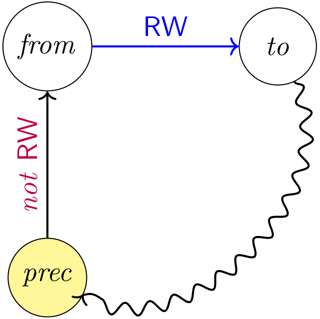


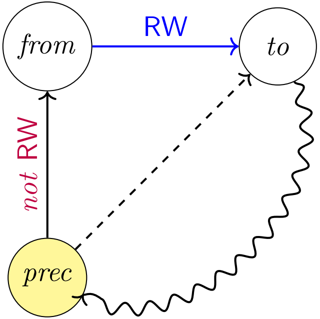
PolySI: Pruning before Encoding (the RW case)



Theorem (Theorem 4.1 of [**AnalysingSI:JACM2018**])

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)



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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”

T_1

$\boxed{\mathsf{W}(x, 1)}$

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

PolySI: An Illustrating Example of "Long Fork"

T_1

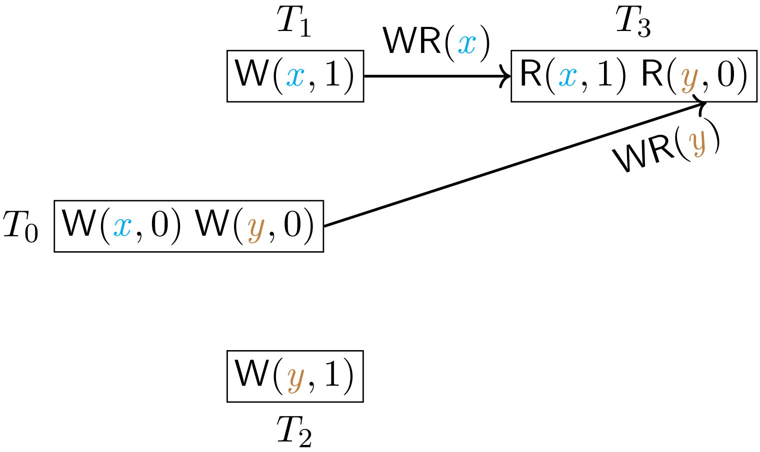
$\boxed{\mathsf{W}(x, 1)}$

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

$\boxed{\mathsf{W}(y, 1)}$

T_2

PolySI: An Illustrating Example of "Long Fork"



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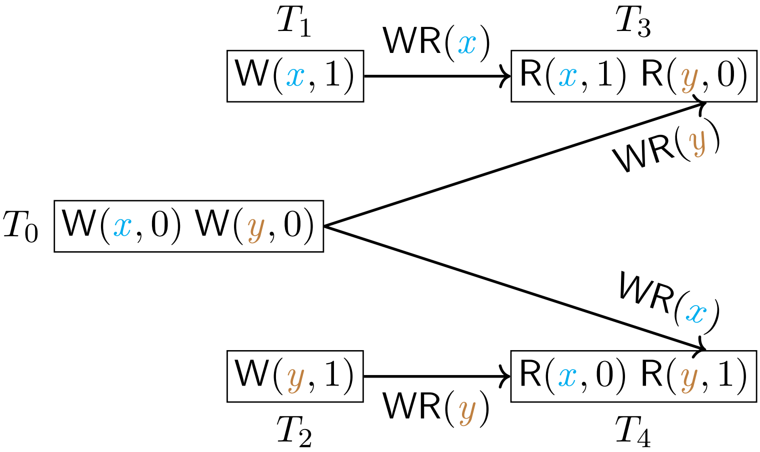

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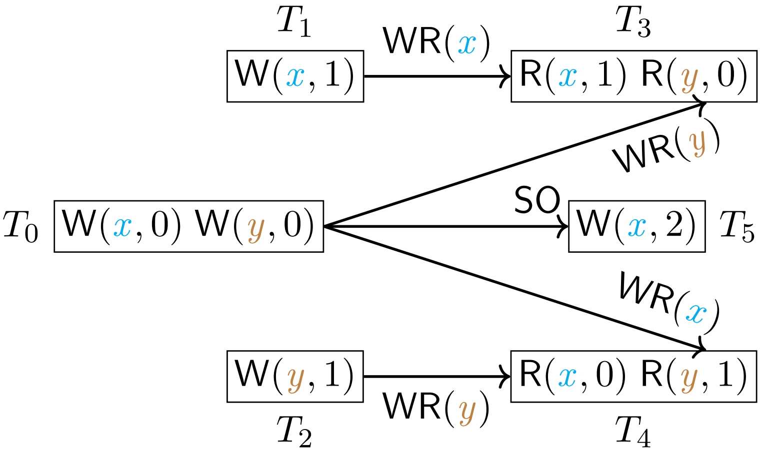
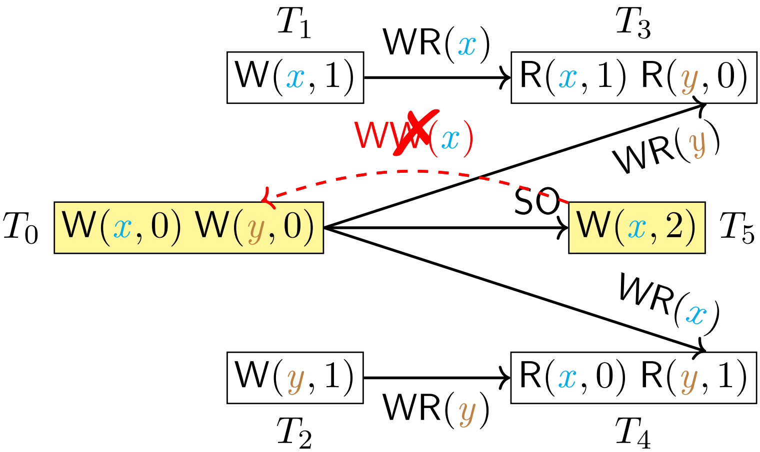
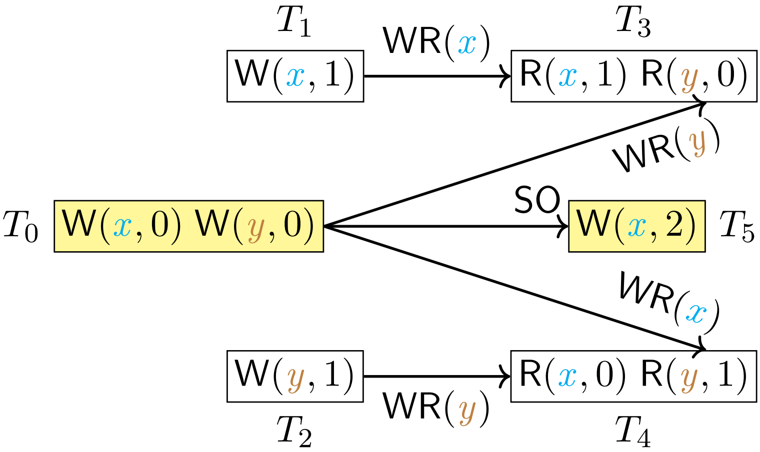


order between T_0, T_1, and T_5 (on x) and between T_0 and T_2 (on y)

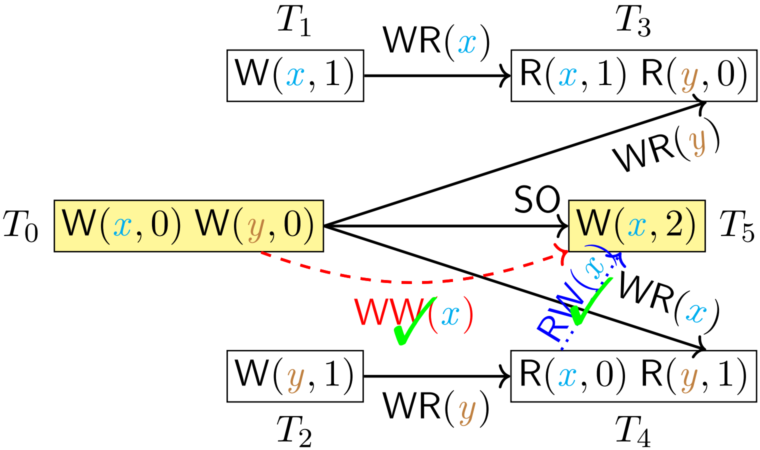


The $T_5 \xrightarrow{\text{WW}(x)} T_0$ case is pruned due to $T_0 \xrightarrow{\text{SO}} T_5 \xrightarrow{\text{WW}(x)} T_0$.

PolySI: An Illustrating Example of "Long Fork"

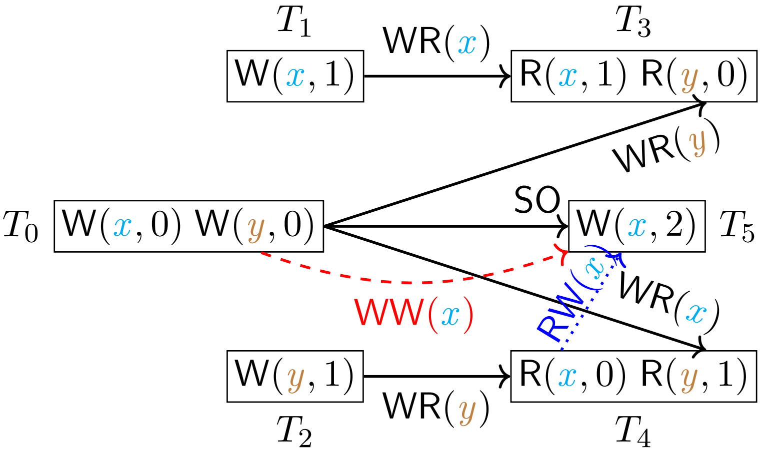


POLYSI: An Illustrating Example of "Long Fork"

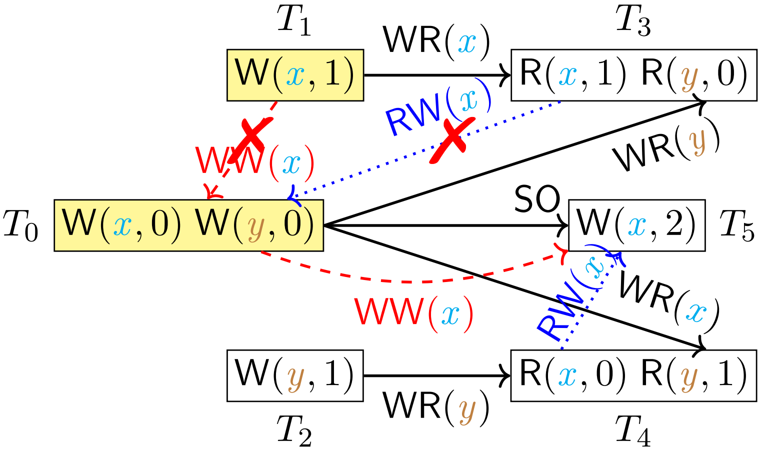


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_5$ case becomes known.

PolySI: An Illustrating Example of "Long Fork"

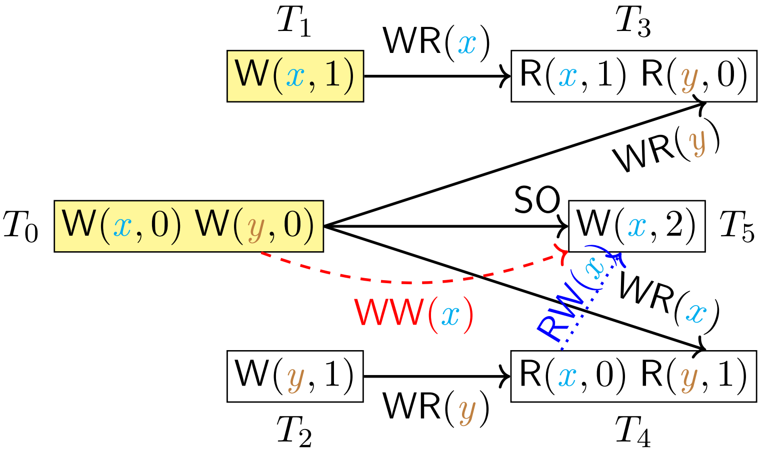


PolySI: An Illustrating Example of "Long Fork"

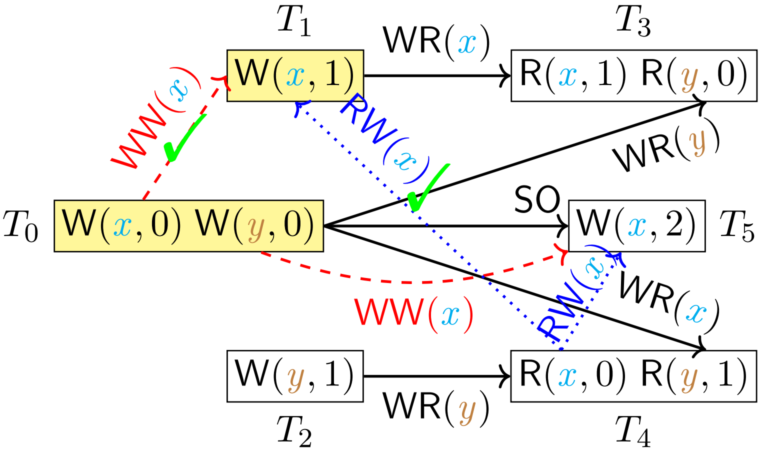


The $T_1 \xrightarrow{\mathsf{WW}(x)} T_0$ case is pruned due to $T_3 \xrightarrow{\mathsf{RW}(x)} T_0 \xrightarrow{\mathsf{WR}(y)} T_3$.

PolySI: An Illustrating Example of "Long Fork"

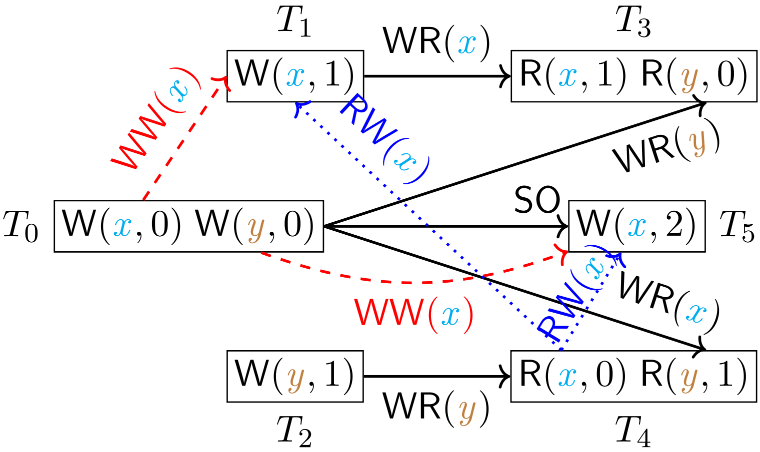


PolySI: An Illustrating Example of "Long Fork"

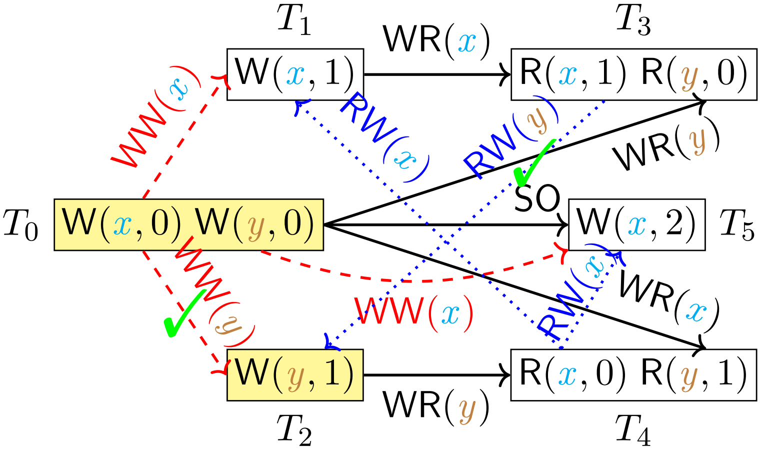


The $T_0 \xrightarrow{\mathsf{WW}(x)} T_1$ case becomes known.

PolySI: An Illustrating Example of "Long Fork"



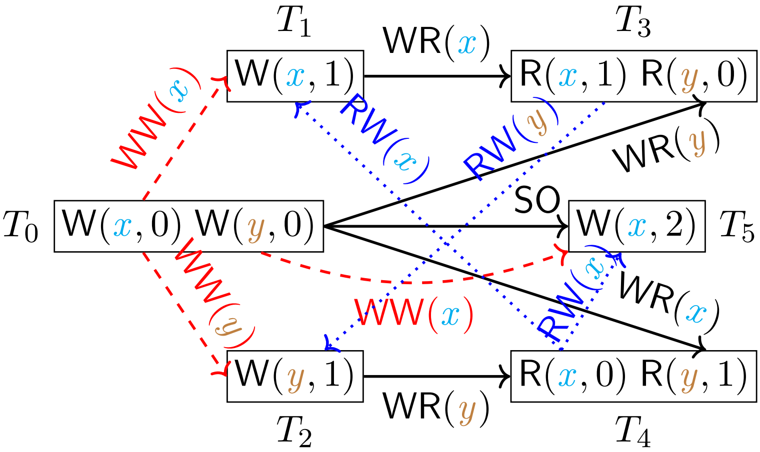
PolySI: An Illustrating Example of "Long Fork"



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"



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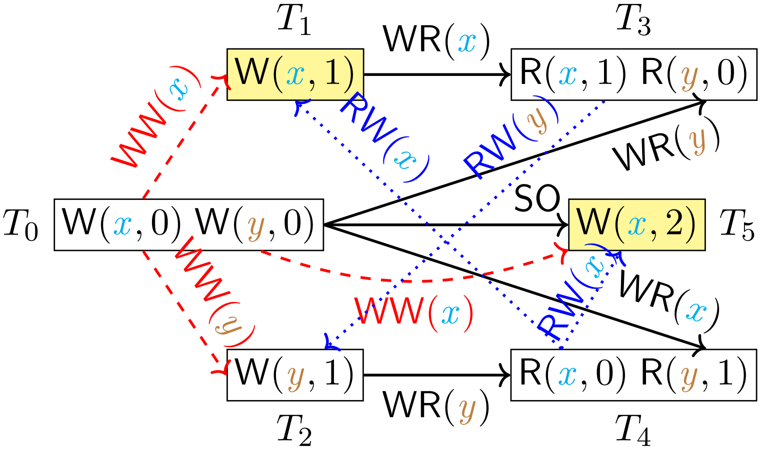
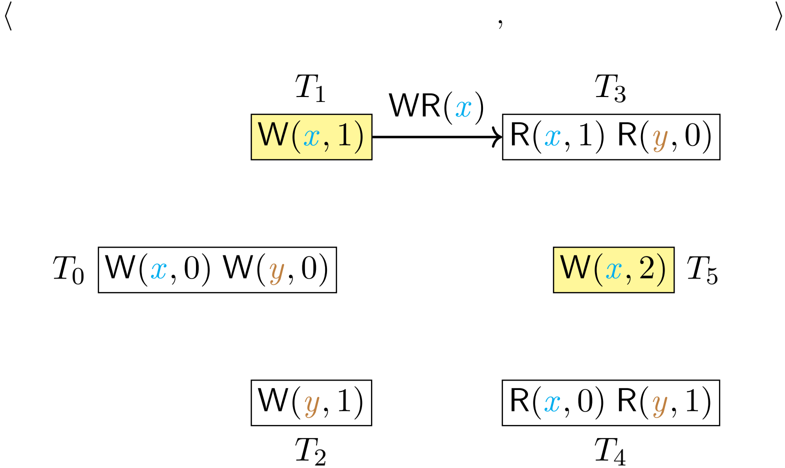


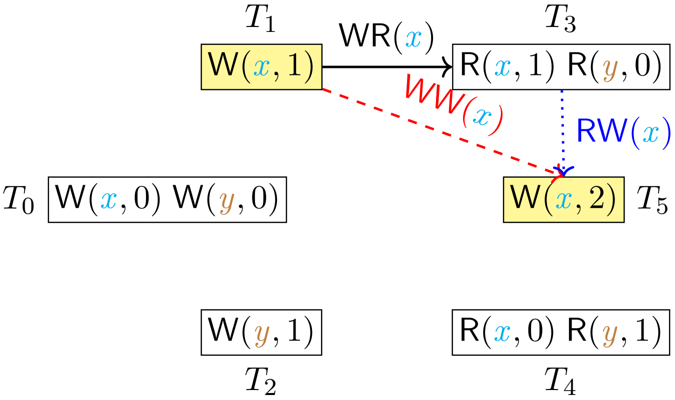
The order between T_1 and T_5 is still uncertain after pruning.

PolySI: An Illustrating Example of "Long Fork"



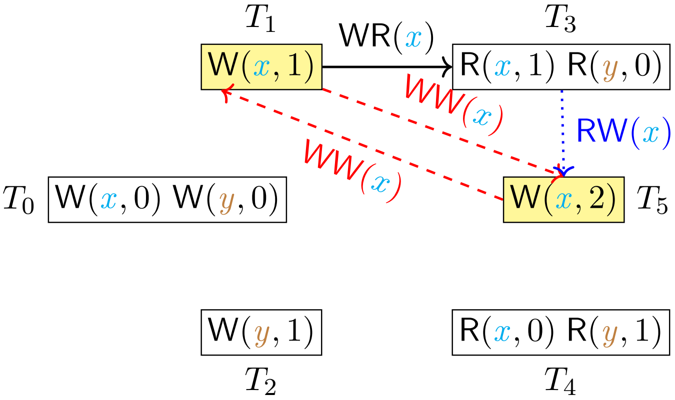
PolySI: An Illustrating Example of "Long Fork"

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



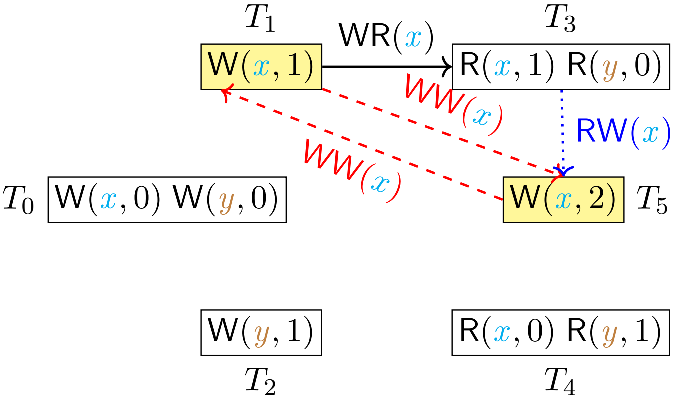
PolySI: An Illustrating Example of "Long Fork"

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



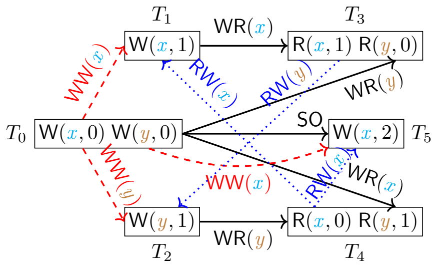
PolySI: An Illustrating Example of "Long Fork"

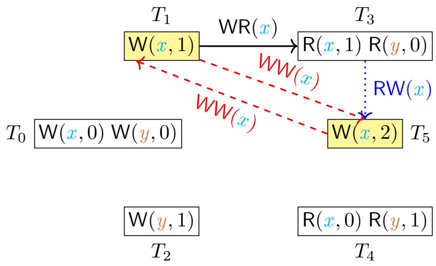
$$\langle \textit{either} = \{T_1 \xrightarrow{\mathsf{WW}(x)} T_5, T_3 \xrightarrow{\mathsf{RW}(x)} T_5\}, \textit{or} = \{T_5 \xrightarrow{\mathsf{WW}(x)} T_1\}\rangle$$



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

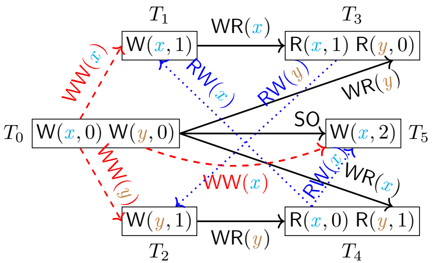
PolySI: An Illustrating Example of "Long Fork"

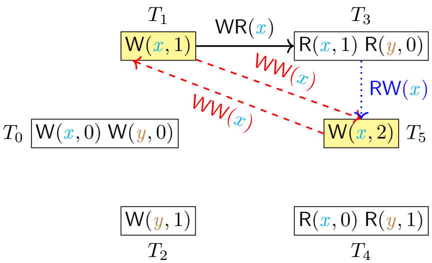




PolySI: An Illustrating Example of "Long Fork"

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





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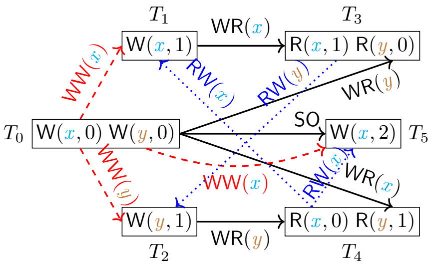

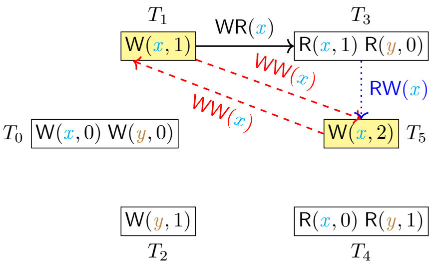

We need to encode the "composition (;)" of dependency edges.

PolySI: An Illustrating Example of "Long Fork"

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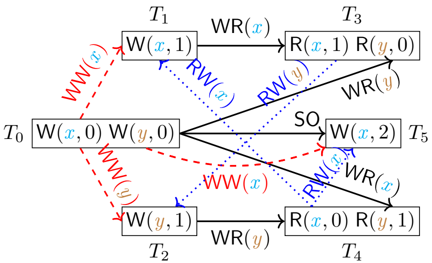

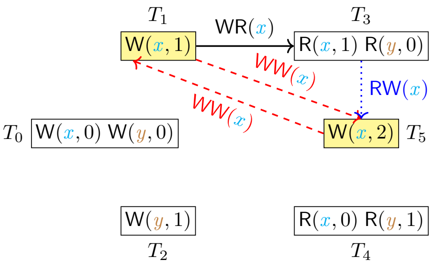

We need to encode the "composition (;)" of dependency edges.

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

PolySI: An Illustrating Example of "Long Fork"

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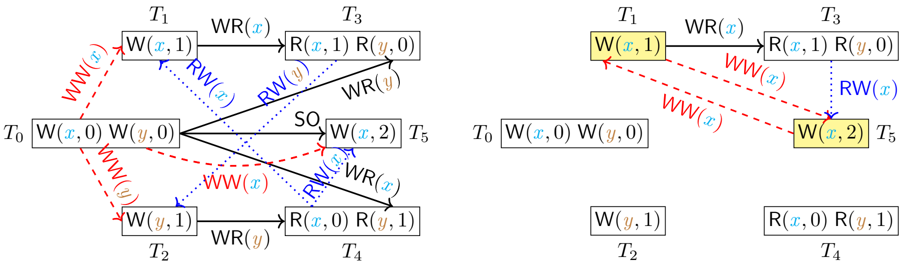


We need to encode the "composition (;)" of dependency edges.

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

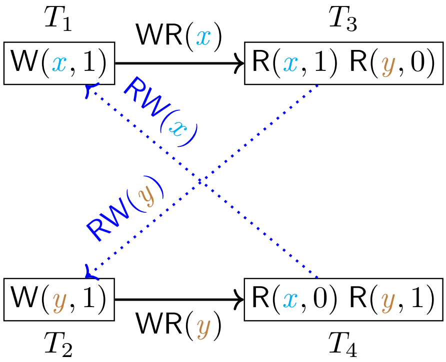
$$T_1 \xrightarrow{\mathsf{WR}} T_3 \xrightarrow{\mathsf{RW}} T_5 :\ \mathsf{BV}^{I}_{1,5} = \mathsf{BV}_{1,3} \wedge \mathsf{BV}_{3,5} \qquad (I \text{ for the induced graph})$$

PolySI: An Illustrating Example of "Long Fork"

Feed the SAT formula into the MonoSAT solver [**MonoSAT:AAAI2015**] 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, Benchmarks, and Setup

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

Workload parameters and their default values.

Finding SI Violations (Reproducing Known 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

[**Complexity:OOPSLA2019**; **CockroachDB-bug**; **YugabyteDB-bug**]

Finding SI Violations (Detecting New Isolations)

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

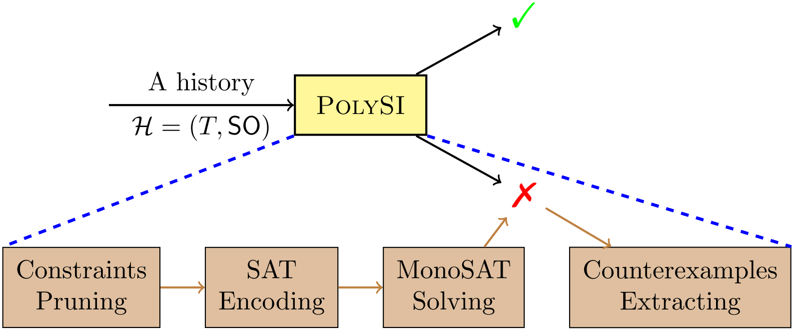
Galera: confirmed the incorrect claim on preventing “lost updates” for transactions issued on different cluster nodes

Understanding Violations

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)