Proving Isolation Properties for Software Transactional Memory

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Semantics of transactions

Transactions follow the ACI(D) principle:

- atomicity ("all-or-nothing")
- isolation
- consistency

What does this actually mean?

It should prevent ... [Berenson 1995]

Dirty reads	Reading data that was never committed to shared memory.
Non-repeatable reads	Receiving different values for multiple reads.
Read Skew	Reading data from several memory snapshots.
Lost update	Intermediate updates by other transactions are overwritten.
Dirty writes	T_1 modifies a data item. T_2 then further modifies this data item before T_1 finishes. If T_1 or T_2 then perform a rollback, it is unclear what the restored data value should be.
Write Skew	T_1 and T_2 both read data items x and y. Then, T_1 updates x and commits; T_2 updates y, and commits, possibly violating constraints between x and y.

How to prove that a TM system is correct?

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Our approach

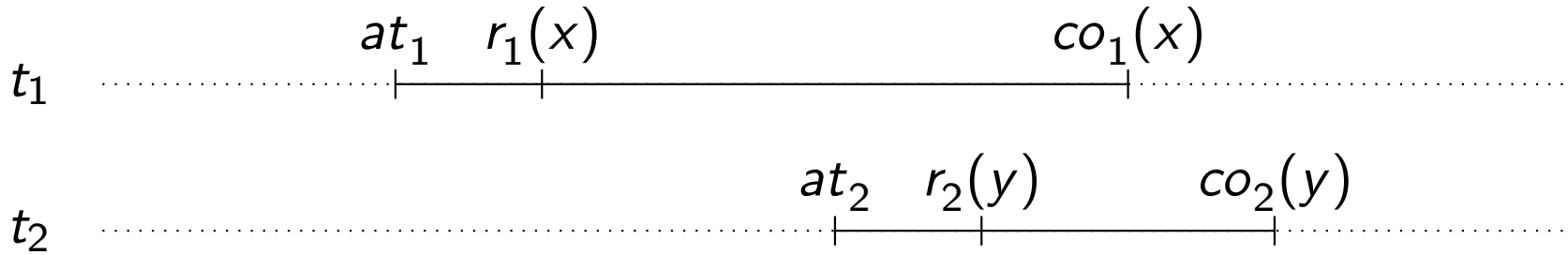
- **Small-step model** of transactions, but without synchronization details
- Operational semantics define the granularity of interleavings
- **Nondeterministic** choice of rules models the scheduling
- Evaluation steps are annotated with **effects** which abstract from the actual operation
- Every effect trace should be **serializable**

Effects

Effects by transaction i in thread t:

at_i^t	start txn
$r_i^t(l)$	read location l
$co_i^t(\bar{l})$	end txn and commit/write locations $\bar{l}$
ab_i^t	abort txn
ϵ_i^t	empty effect, administrative redex in txn
ϵ^t	empty effect
$sp^t(t')$	spawn new thread t'

Successful commits



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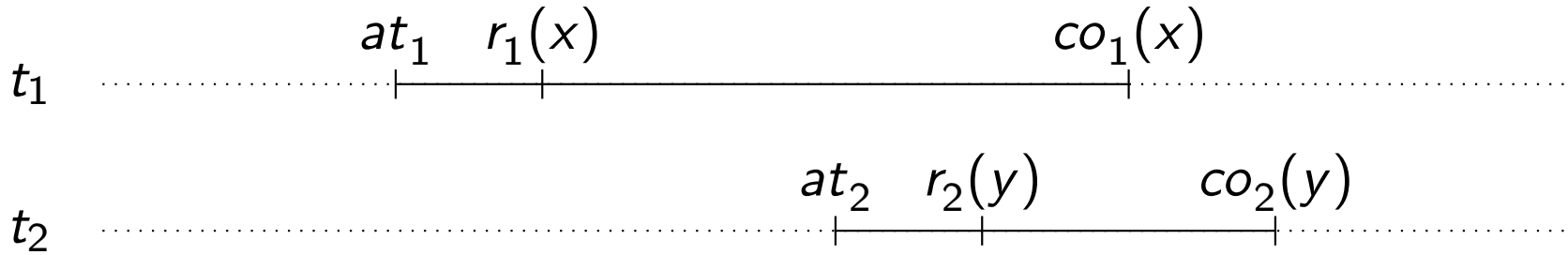
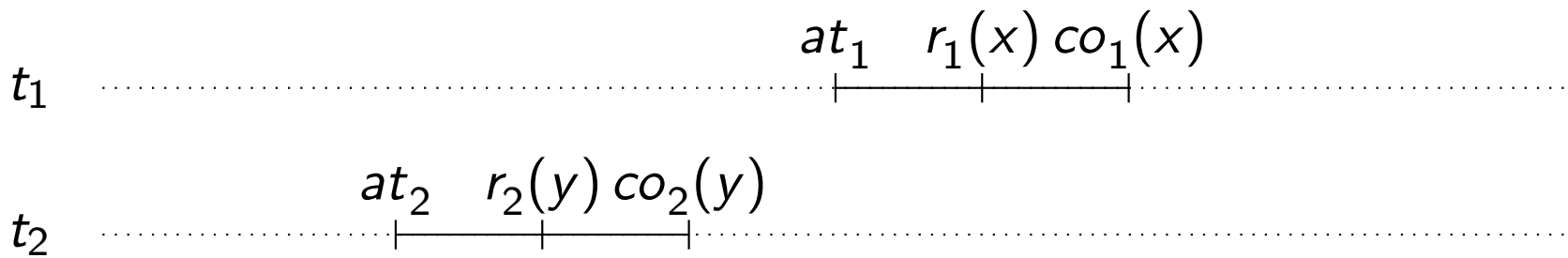
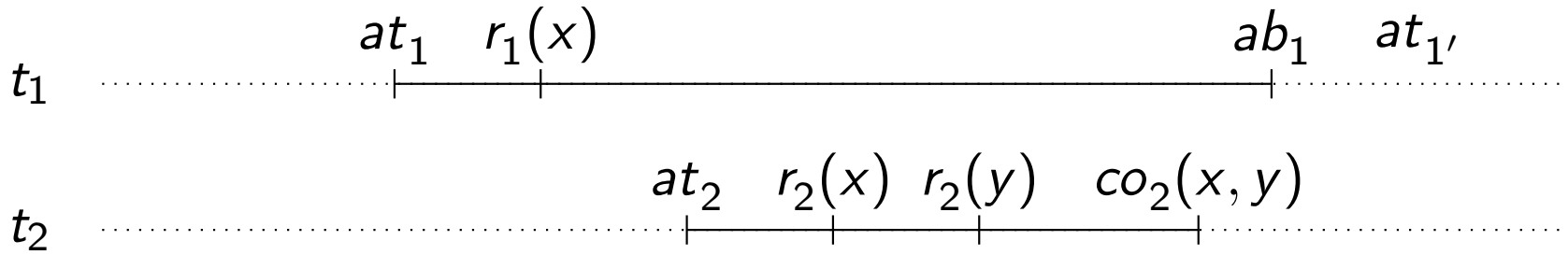


... is equivalent to:



Read conflicts



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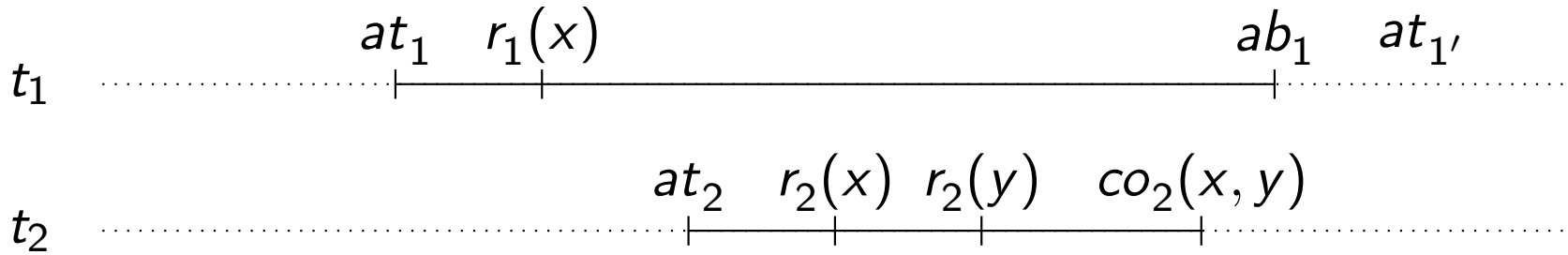

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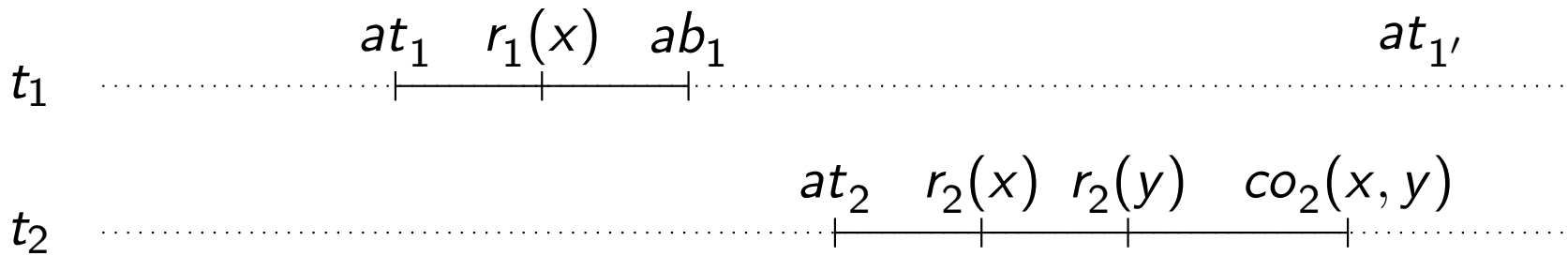

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We can re-order **independent** execution steps.

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- $at_i^t \triangleright_c r_i^t(l)$
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Data Dependency

- $r_i^t(l) \triangleright_d co_j^t(\bar{l})$ if $l \in \bar{l}$
- $co_i^t(\bar{l}) \triangleright_d r_j^t(l)$ if $l \in \bar{l}$
- $co_i^t(\bar{l}) \triangleright_d co_j^{t'}(\bar{l}')$ if $\bar{l} \cap \bar{l}' \neq \emptyset$

Formalization

- Monadic lambda calculus with txn operations
- Syntax of Λ_{STM}:

$$
\begin{array}{lcll}
x & \in & \mathrm{Var} & \quad l \in \mathrm{Ref} \\
v & \in & \mathrm{Val} \quad ::= & \quad l \mid \texttt{tt} \mid \texttt{ff} \mid () \mid \lambda x.e \\
e & \in & \mathrm{Exp} \quad ::= & \quad v \mid x \mid e\ e \mid \texttt{if}\ e\ e\ e \mid \texttt{return}\ e \mid e \gg\!= e \\
 & & \mid & \quad \texttt{spawn}\ e \mid \texttt{atomic}\ e \mid (e, W, R, i, e, \mathcal{H}) \\
 & & \mid & \quad \texttt{newref}\ e \mid \texttt{readref}\ e \mid \texttt{writeref}\ e\ e
\end{array}
$$

Execution traces

Execution steps:

$$\mathcal{H}, \mathcal{P} \stackrel{\alpha}{\Longrightarrow} \mathcal{H}', \mathcal{P}'$$

- Choose a thread from the thread pool nondeterministically.
- Execute one step.

$\Rightarrow$ The trace encodes the scheduler!

Operational Semantics: Transactions (selection)

IO-Atomic

$$\frac{i \text{ fresh}}{\mathcal{H}, \texttt{atomic}\ m \xrightarrow{at_i^t} \mathcal{H}, (m, \langle\rangle, \langle\rangle, i, m, \mathcal{H})}$$

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IO-Commit

$$\frac{check(R, \mathcal{H}) = ok \qquad \mathcal{H}'' = \mathcal{H}[W] \qquad \bar{l} = \mathrm{dom}(W)}{\mathcal{H}, (\texttt{return } v, W, R, i, m', \mathcal{H}') \xrightarrow{co_i^t(\bar{l})} \mathcal{H}'', \texttt{return } v}$$

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IO-Rollback

$$\mathcal{H}, (m, W, R, i, m', \mathcal{H}') \xrightarrow{ab_i^t} \mathcal{H}, \texttt{atomic } m'$$

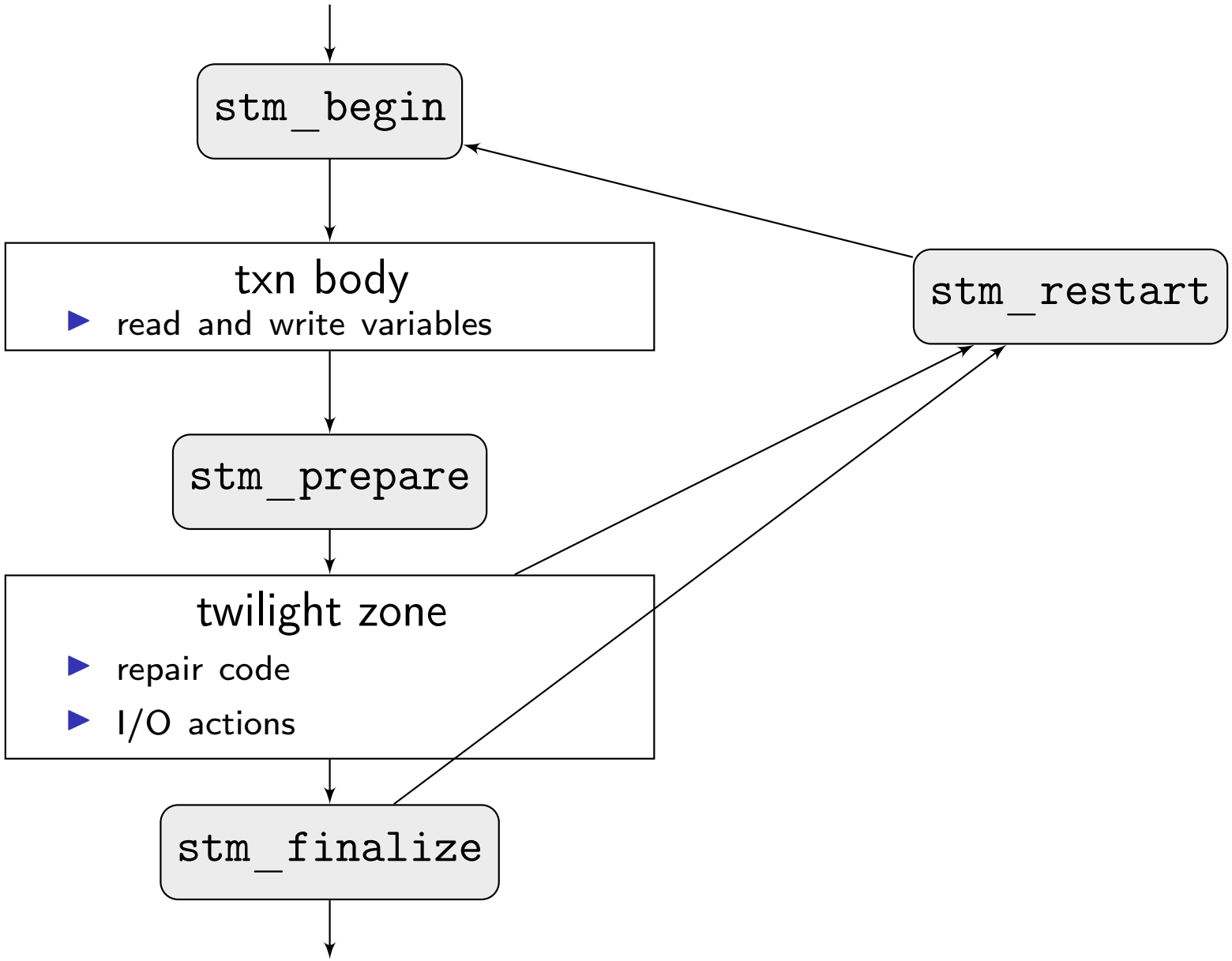
Opacity

- The type system enforces that traces all **well-formed**, but they are **not necessary serial**.
- Can we **re-order execution histories**, i.e. apply another scheduling, such that we get equivalent serial traces?
- We also require correctness for aborted transactions, therefore prove **opacity**.

Extensions

- Simple, yet powerful model
- Easily extensible for other constructs and semantics
  - Semantics of `orElse` and `retry`
  - Snapshot isolation
  - Irrevocable transactions

Twilight STM: Conflict repair and I/O integration



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- extending the STM interface with repair actions, conflict detection, I/O
- application-specific tuning
- implemented and evaluated in C, Java, Haskell

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DecentSTM

- distributed STM without central components, no timestamps
- multi-versioning with GC on versions
- programmer only specifies atomic blocks, shared data, placement of nodes
- JCell: integration in distributed JVM

Summary

- A **formal semantics** of TM that is suitable for proving properties of a TM implementation
  - not high-level because interleavings of transactions are modelled explicitly
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- A proof that the semantics implements **opacity, SI, irrevocability**, ...
- How can we combine txns with different isolation semantics?

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Questions?