Verifying vMVCC, a high-performance database using multi-version concurrency control

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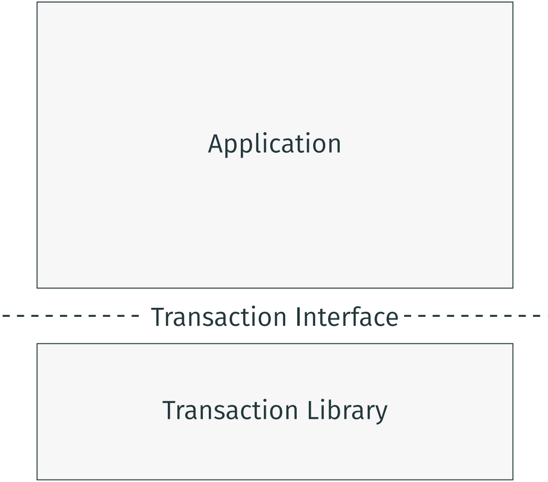
Transactional programming model



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---------- Transaction Interface ----------

Transaction Library

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```go
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c := xfer(txn, src, dst, amt)
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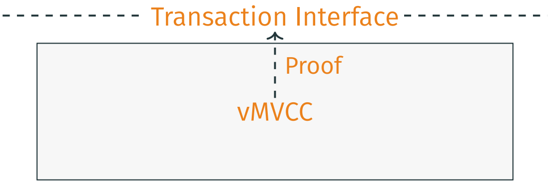
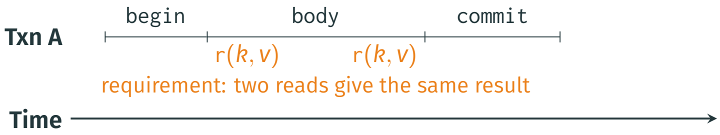


Transactions using locks



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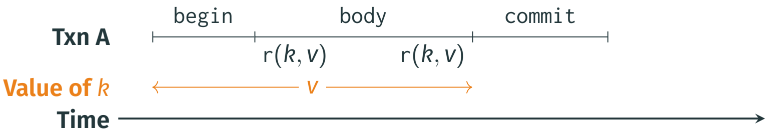

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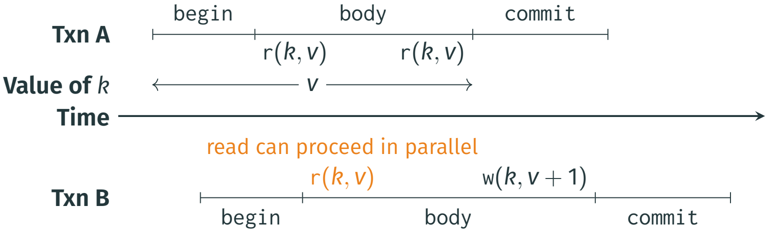

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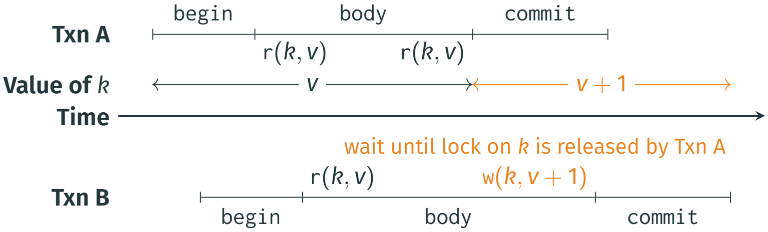
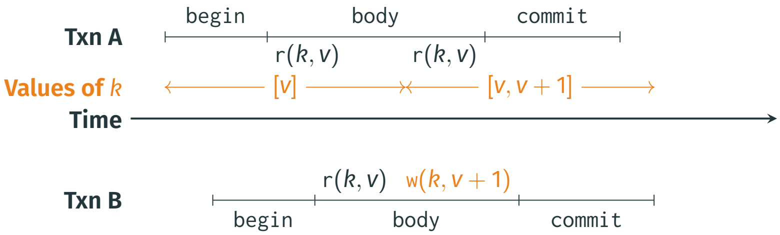


Transactions using multi-version concurrency control (MVCC)

- Keeping past values to improve concurrency



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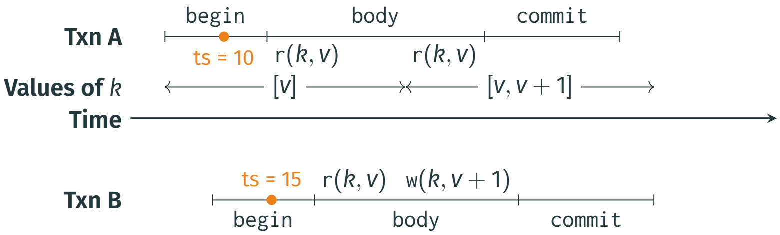
- Ordering transactions with timestamps



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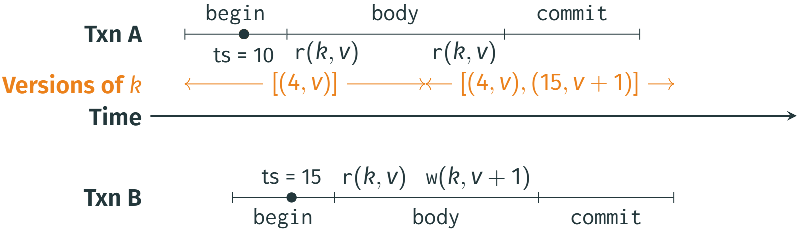

Contribution: Verifying an MVCC-based transaction library implementation

- A practical and high-performance implementation written in Go
  - E.g., concurrent GC of unusable versions and RDTSC-based timestamps

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  - E.g., concurrent GC of unusable versions and `RDTSC`-based timestamps
- Requiring sophisticated reasoning techniques
  - E.g., logical atomicity and prophecy variables

Outline

- Specifying and verifying MVCC transactions
- Low-level optimization: RDTSC-based timestamps
- Evaluation
- Conclusion

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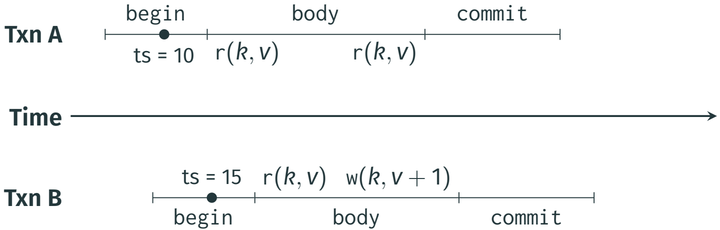
Transactions, intuitively

- Each transaction appears to execute its reads and writes at its linearization point



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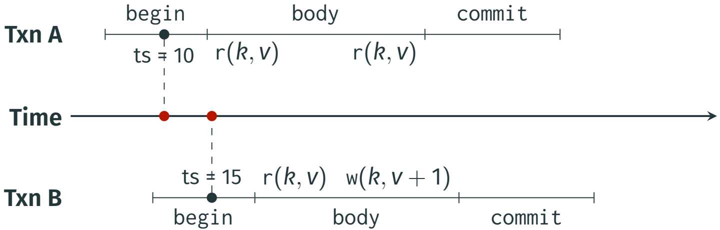

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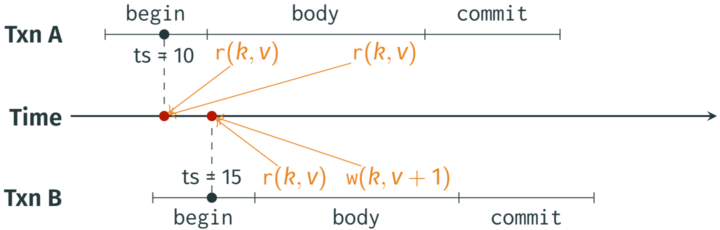
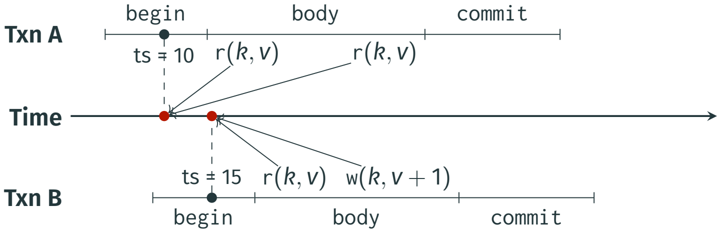


Logical (ghost) state of the database



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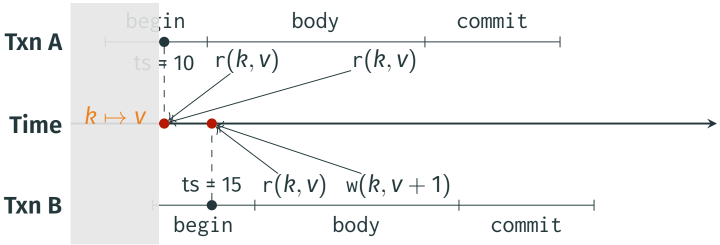
- The current value for each key: $k \mapsto v$



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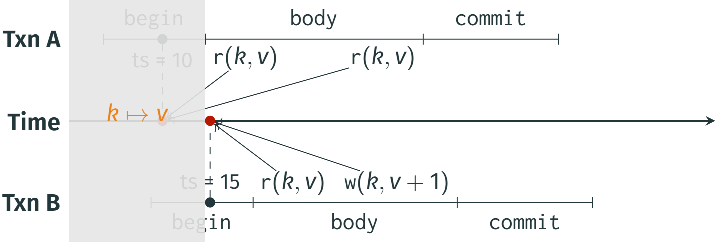

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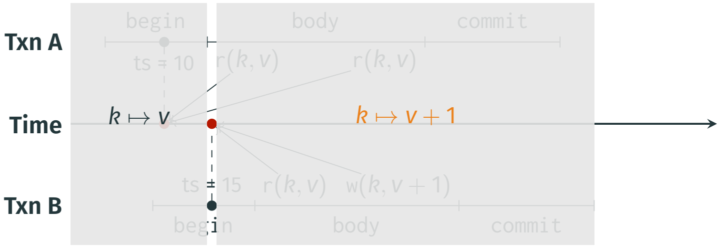
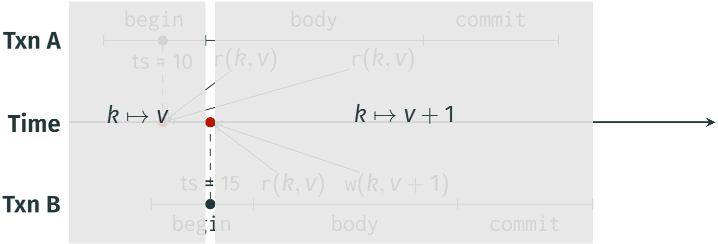
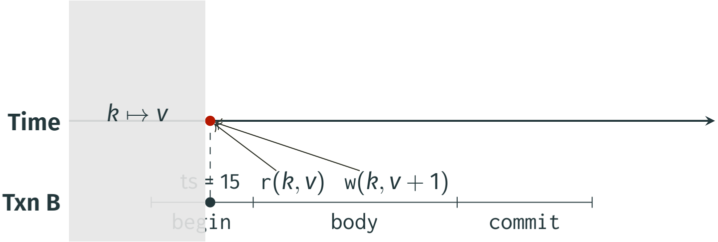


Logical (ghost) state of the database

- The <u>current value</u> for each key: $k \mapsto v$
  - Mismatch in MVCC: multi-version physical layout vs. single-value logical view



Verification challenge: Transaction linearizes before its body runs



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- To update the logical state, we need to know:
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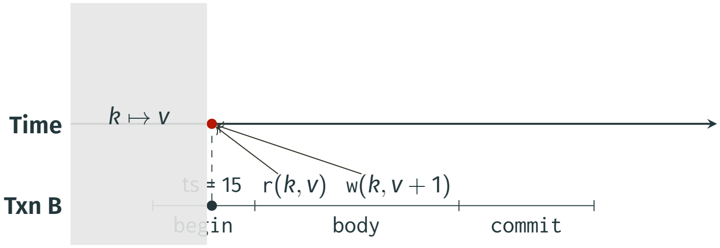

Verification challenge: Transaction linearizes before its body runs

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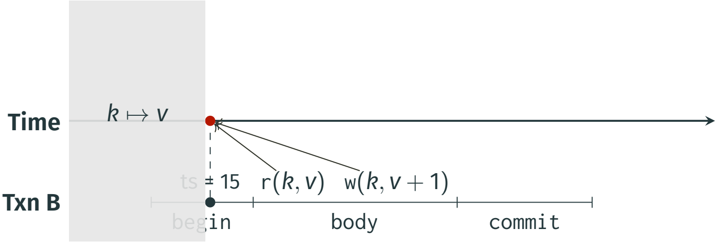

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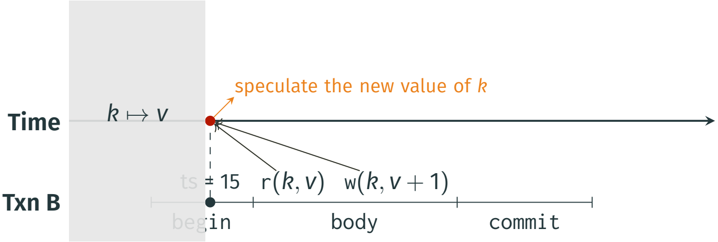
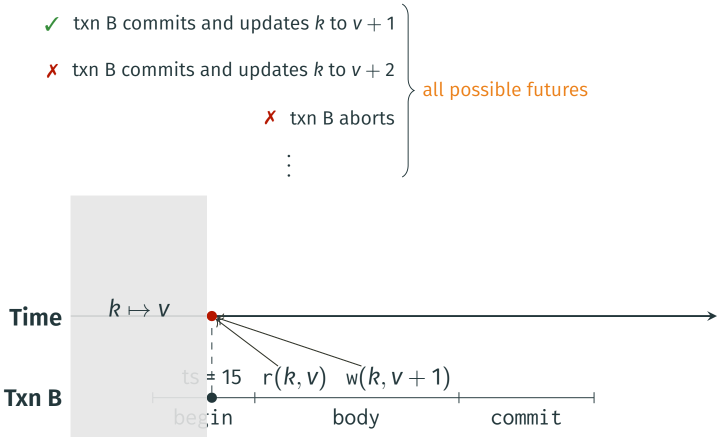
- **Solution**: Prophecy variables



Peeking into the future with prophecy variable



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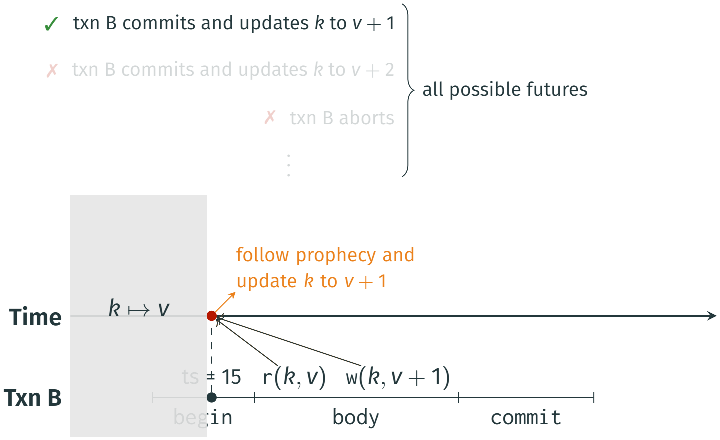
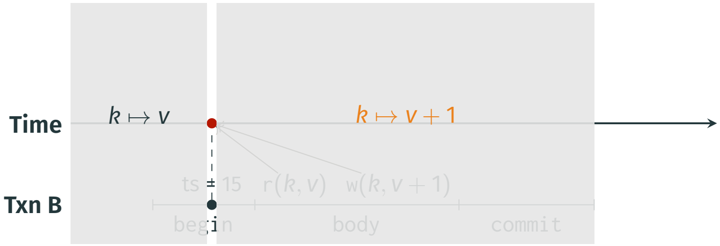


Peeking into the future with prophecy variable

- ✓ txn B commits and updates k to $v+1$
- ✗ txn B commits and updates k to $v+2$
- ✗ txn B aborts
- ⋮

} all possible futures



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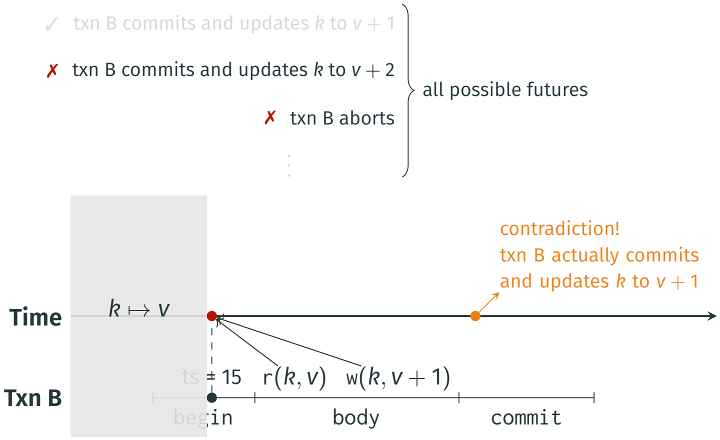
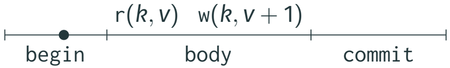


Specifying general transactions with logical atomicity



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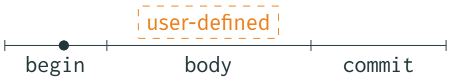

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Specifying general transactions with logical atomicity

∀ body.

sequential spec for
body(txn)

Specifying general transactions with logical atomicity

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⇓

concurrent spec for
db.Run(body)

Specifying general transactions with logical atomicity

$$\forall\, \text{body}.\ \left\{ \qquad\qquad \right\}$$

`body(txn)`

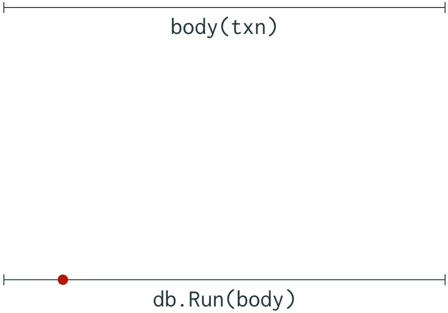
$$\left\{ \qquad\qquad \right\}$$

$$\Downarrow$$

$$\left\langle \qquad\qquad \right\rangle$$

`db.Run(body)`

$$\left\langle \qquad\qquad \right\rangle$$



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`db.Run(body)`

$$\left\langle \qquad \right\rangle$$

take $\overset{t}{\mapsto}$: transaction-local view of database

$k_1 \overset{t}{\mapsto} v_1 * \cdots * k_n \overset{t}{\mapsto} v_n$

`body(txn)`

`db.Run(body)`

Specifying general transactions with logical atomicity

$$\forall \text{ body}.\ \left\{ \mathop{\Huge\ast}_{(k,v)\in m} k \overset{t}{\mapsto} v * P(m) \right\}$$

`body(txn)`

$$\Downarrow$$

`db.Run(body)`

take $P(m)$ describes what's in the starting state

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`body(txn)`

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$$\forall\, \text{body}.\ \left\{ \mathop{\huge\ast}_{(k,v)\in m} k \overset{t}{\mapsto} v * P(m) \right\}$$

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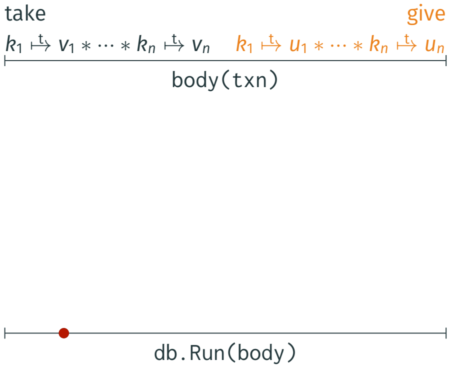

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$$\forall\, \text{body}.\ \left\{ \mathop{\Large *}_{(k,v)\in m} k \overset{t}{\mapsto} v * P(m) \right\}$$

body(txn)

$$\left\{ \mathop{\Large *}_{(k,v)\in m'} k \overset{t}{\mapsto} v * Q(m, m') \right\}$$

$$\Downarrow$$

$$\Big\langle \qquad \Big\rangle$$

db.Run(body)

$$\Big\langle \qquad \Big\rangle$$

take $\quad Q(m, m')$ describes the changes $\quad$ give

$k_1 \overset{t}{\mapsto} v_1 * \cdots * k_n \overset{t}{\mapsto} v_n \qquad k_1 \overset{t}{\mapsto} u_1 * \cdots * k_n \overset{t}{\mapsto} u_n$

body(txn)

db.Run(body)

Specifying general transactions with logical atomicity

$$\forall\, \text{body}.\ \left\{ \mathop{\Huge *}_{(k,v)\in m} k \stackrel{t}{\mapsto} v * P(m) \right\}$$

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$$\left\langle m.\ \mathop{\Huge *}_{(k,v)\in m} k \mapsto v * P(m) \right\rangle$$

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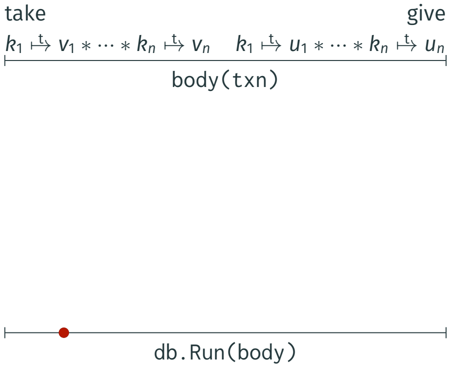

Specifying general transactions with logical atomicity

$$\forall\, \mathrm{body}.\ \left\{ \mathop{\Large\ast}_{(k,v)\in m} k \overset{t}{\mapsto} v \ast P(m) \right\}$$

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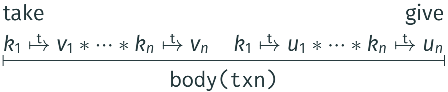

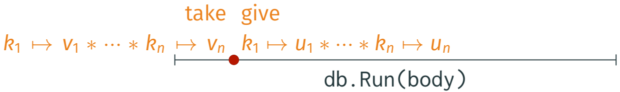

Specifying general transactions with logical atomicity

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`body(txn)`

$$\left\{ \mathop{\Large\ast}_{(k,v)\in m'} k \overset{t}{\mapsto} v \ast Q(m, m') \right\}$$

$$\Downarrow$$

$$\left\langle m.\ \mathop{\Large\ast}_{(k,v)\in m} k \mapsto v \ast P(m) \right\rangle$$

`db.Run(body)`

$$\left\langle \mathop{\Large\ast}_{(k,v)\in m'} k \mapsto v \ast Q(m, m') \right\rangle$$

take give

$k_1 \overset{t}{\mapsto} v_1 \ast \cdots \ast k_n \overset{t}{\mapsto} v_n \quad k_1 \overset{t}{\mapsto} u_1 \ast \cdots \ast k_n \overset{t}{\mapsto} u_n$

`body(txn)`

transactions are allowed to run concurrently!

`db.Run(body)`

vMVCC: Abstractions and invariants

LOGICAL $(k \mapsto v_4)$ v_4

PHYSICAL

ts	del	val	tslast
1	false	v_1	4
3	false	v_3	

vMVCC: Abstractions and invariants

LOGICAL $(k \mapsto v_4)$ v_4

LINEAR $\bot$ $\bot$ v_1 v_1 v_3

AR

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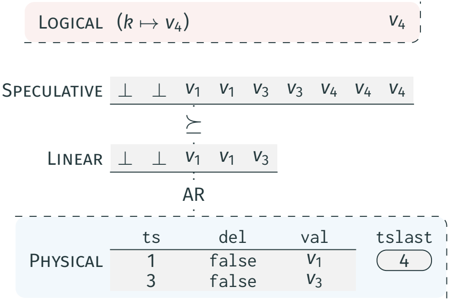

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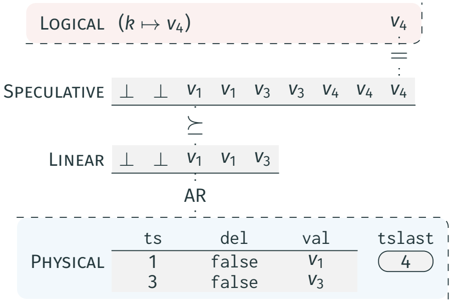

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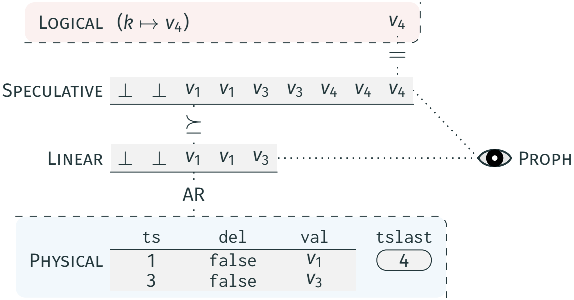

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Generating strictly increasing timestamps

Timestamp schemes

- a global lock on a shared counter

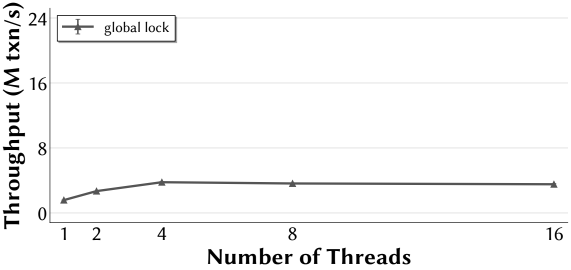


Figure 1: Scalability analysis of different timestamp schemes under the YCSB workload (1 key accessed per transaction, $\theta = 0.2$).

Generating strictly increasing timestamps

Timestamp schemes

- a global lock on a shared counter
- `FAI` on a shared counter

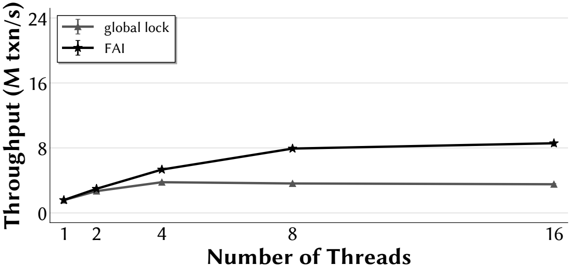
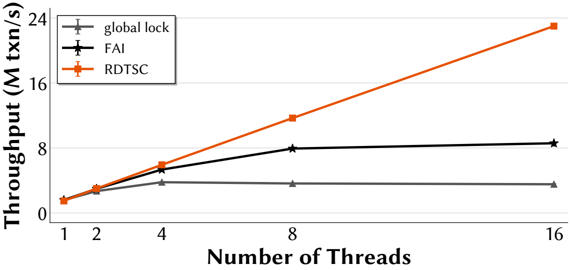


Figure 1: Scalability analysis of different timestamp schemes under the YCSB workload (1 key accessed per transaction, $\theta = 0.2$).

Generating strictly increasing timestamps

Timestamp schemes

- a global lock on a shared counter
- `FAI` on a shared counter
- `RDTSC` on CPU hardware counters



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Generating strictly increasing timestamps with RDTSC

```
func GenTID(sid uint64) uint64 {
    var tid uint64
    tid = RDTSC()



    return tid
}
```

RDTSC()

↓

tid = 101011110

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Transaction site

- Each site is assigned a short unique ID (e.g., 5 bits)

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func GenTID(sid uint64) uint64 {
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(on site 5)

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- Acquiring a per-site mutex before calling `GenTID`

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Proof challenge: unsolicited helping

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- Later credits!

vMVCC: Implementation and proof efforts

Implementation feature and optimization

- Concurrent garbage collection of unusable versions
- Lock sharding and padding
- Timestamp generation with `RDTSC`

Component	Lines of code
Program	∼800 (Go)

vMVCC: Implementation and proof efforts

Implementation feature and optimization

- Concurrent garbage collection of unusable versions
- Lock sharding and padding
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Proof framework

- Translating Go code with Goose and proving in Perennial/Iris/Coq

Component	Lines of code
Program	$\sim$800 (Go)
Proof	$\sim$11K (Coq)

Outline

- Specifying and verifying transactions
- Low-level optimization: `RDTSC`-based timestamps
- Evaluation
- Conclusion

Evaluation: Is the performance of vMVCC competitive to unverified systems?

Database benchmarks

- YCSB: reading or writing (given a certain R/W ratio) a key sampled uniformly

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Silo [SOSP '13]: a state-of-the-art research system

- Single-node in-memory transactional key-value store
- Creating one version every one second $\implies$ less memory and better performance
- Read-only transactions not linearizable $\implies$ weaker consistency level

vMVCC is competitive with Silo, the state-of-the-art unverified system

Observation

- 25%–96% of Silo for YCSB and TPC-C workloads

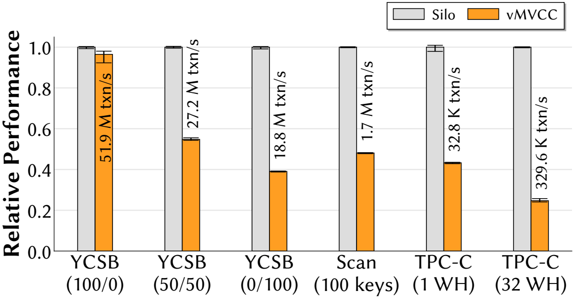

Figure 2: Comparison of Silo and vMVCC. For YCSB, each transaction reads or writes a key sampled from a uniform distribution with a certain R/W ratio. For TPC-C, the number of warehouses is same as the number of worker threads.

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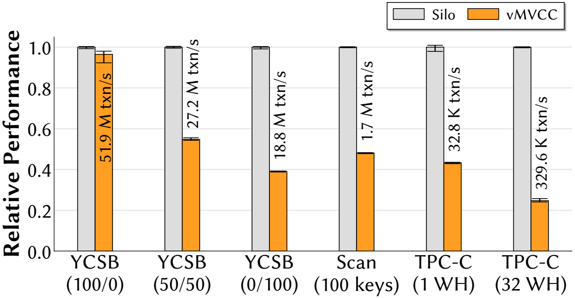
- Lack of a tree-based index



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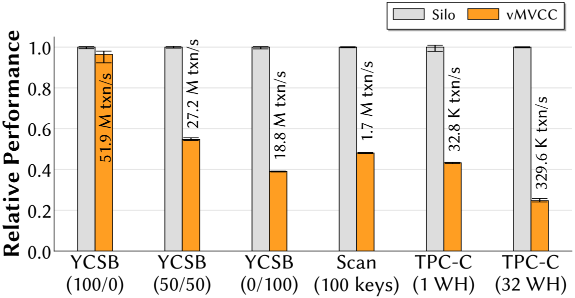
Performance difference

- Lack of a tree-based index
- Higher memory management overhead



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Conclusion

Contribution

- A logically-atomic specification for transactions
- A proof approach using prophecy variable for MVCC transaction linearization
- A verified high-performance transaction library using MVCC and low-level optimizations such as `RDTSC`-based timestamps

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- A logically-atomic specification for transactions
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- A verified high-performance transaction library using MVCC and low-level optimizations such as `RDTSC`-based timestamps

Thank you Iris!

- Specification: logical atomicity and resource algebras
- Proof: invariants, prophecy variables, and later credits