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

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Transactions simplify application development, but...

Achieving high performance requires sophisticated concurrency techniques

- Multi-version concurrency control (MVCC), contention-free data structures, etc.

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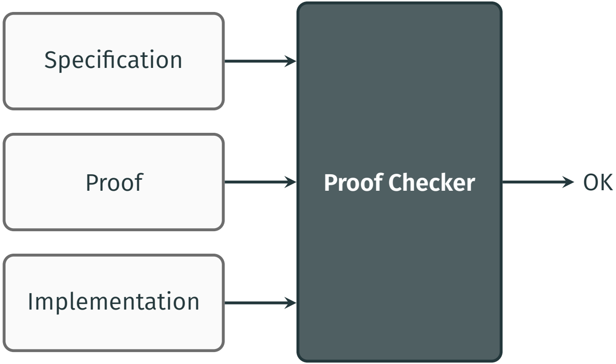
Transaction bugs can lead to severe consequences

- Corrupted databases, data losses, security issues, etc.

Approach: Formal verification



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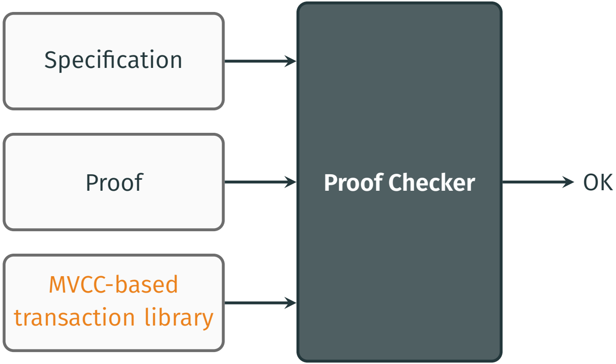

1. improving concurrency with multiple versions
2. ordering transactions with timestamps

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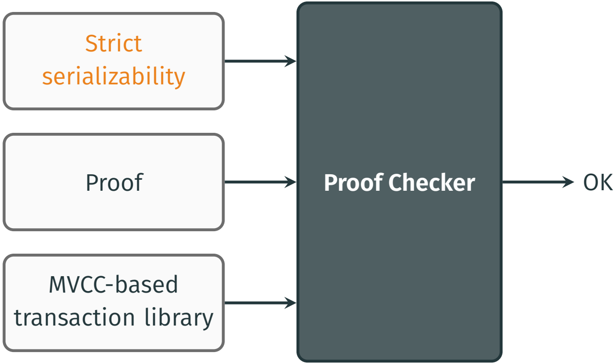

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Benefit of formal verification

Proof establishing strictly serializable execution of transactions

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$\Longrightarrow$ a wide range of bugs are eliminated

- Race conditions
- Out-of-bound accesses
- Off-by-one errors
- Incorrect garbage collection (GC) of versions
- Violation of timestamp monotonicity
- ...

Challenges

1. Requiring a specification for strictly serializable transactions

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2. Proving MVCC transactions execute in some total order despite reordering

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2. Proving MVCC transactions execute in some total order despite reordering
3. Reasoning about garbage collection (GC) and RDTSC-based timestamps

Contributions of this work

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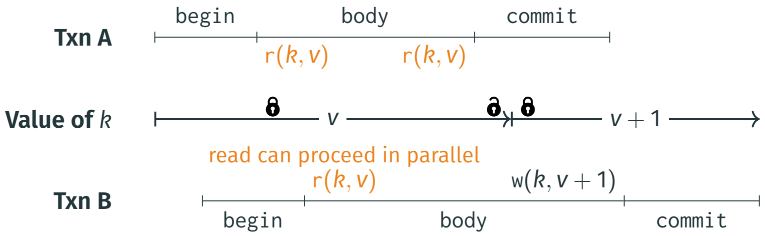
- High-performance Go implementation including GC and `RDTSC`-based timestamps
- Succinct and application-friendly specification
- Proof adopting prophecy variables [LICS ’88] for MVCC transaction linearization

Transactions using two-phase locking (2PL)

Acquiring a lock before reading/writing a key



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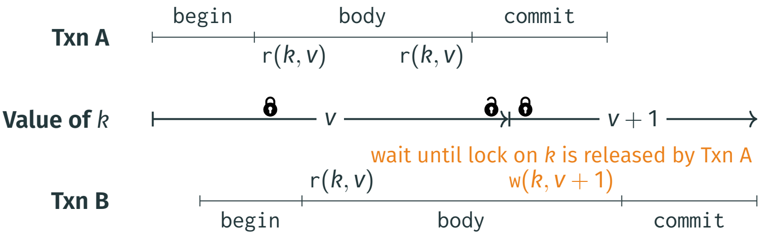
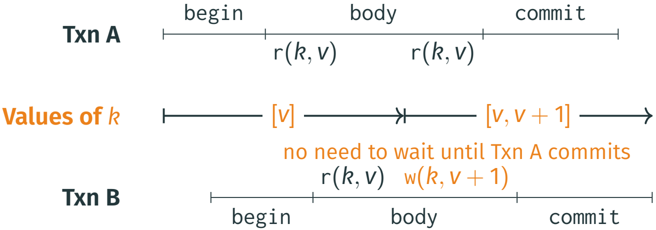


Benefit of MVCC: More concurrency

Keeping past values to improve concurrency



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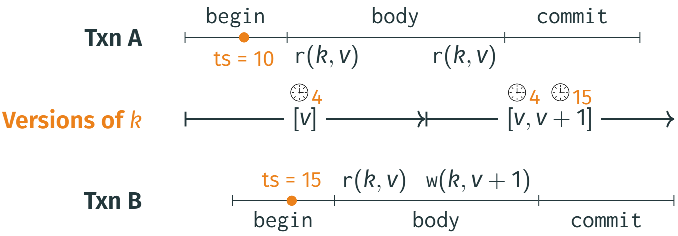
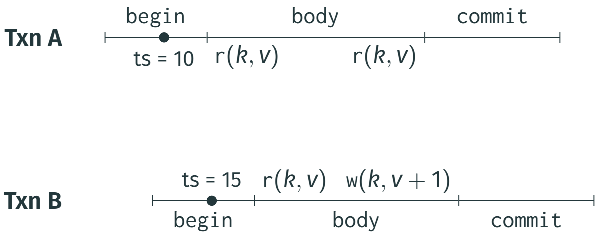
Ordering transactions with timestamps



Specifying strictly serializable transactions

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



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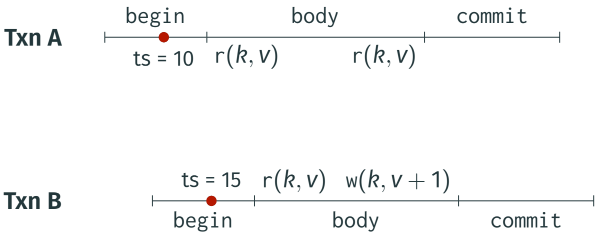

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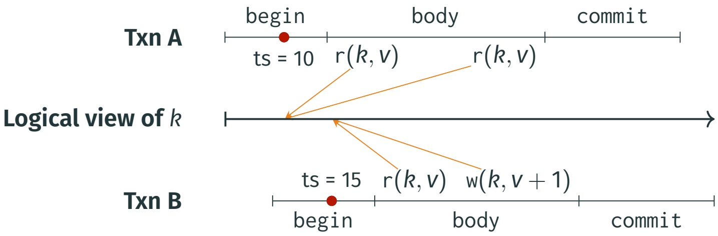

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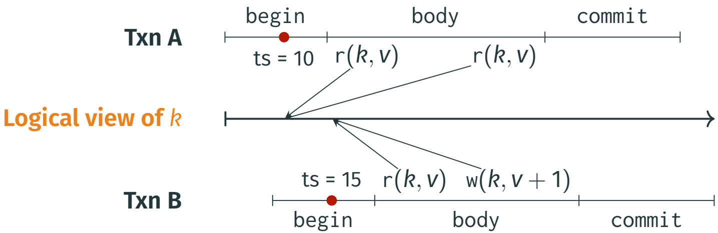

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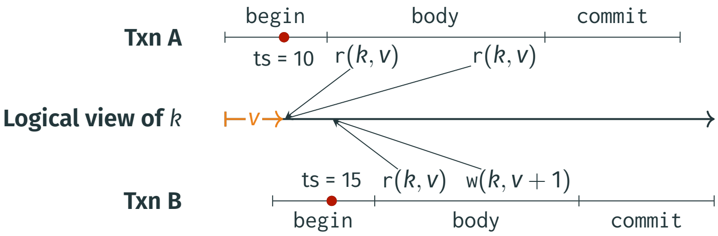

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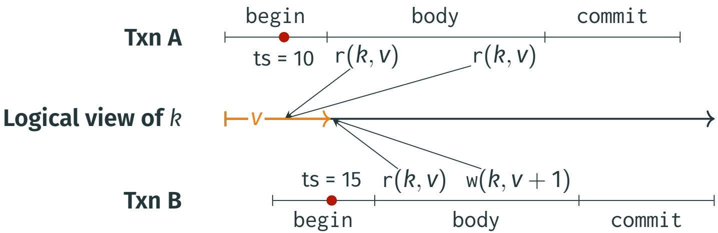

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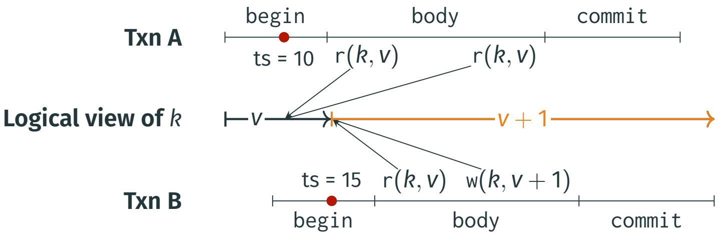
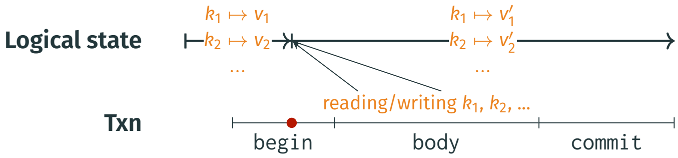


Succinct specification catches a wide range of implementation bugs

Reading and writing the logical state around the linearization point



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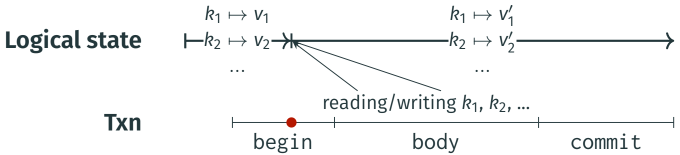

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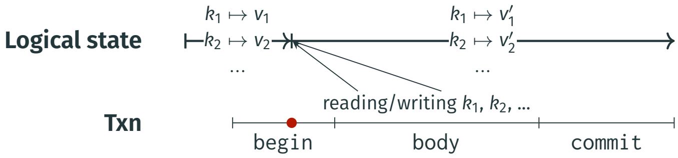
$\implies$ proof ensures correct handling of implementation details



Application-friendly specification reduces proof effort

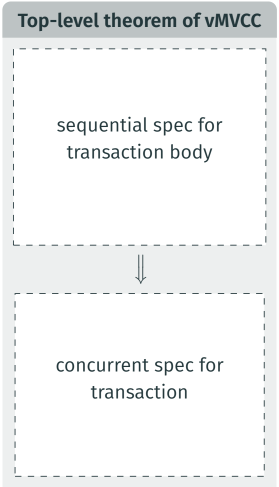
Top-level theorem of vMVCC

sequential spec for transaction body

⇓

concurrent spec for transaction

Application-friendly specification reduces proof effort



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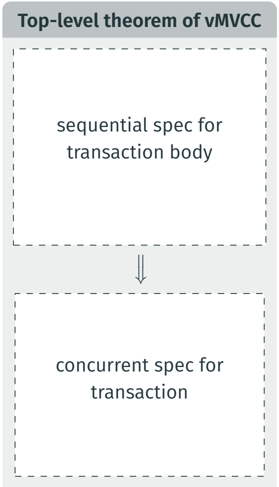
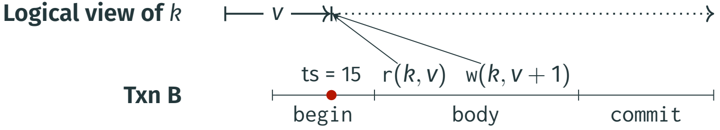


1. Application developer proves the transaction body in an isolated world
2. vMVCC's top-level theorem ensures safety to run the transaction concurrently

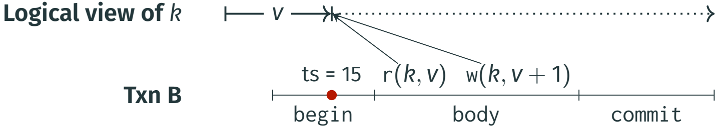
Verification challenge: Transactions linearize before their body runs

Update the logical state requires knowing transaction execution in the future



Addressing the challenge with prophecy variables [LICS '88]

1. Speculate whether a transaction commits/aborts and its updates



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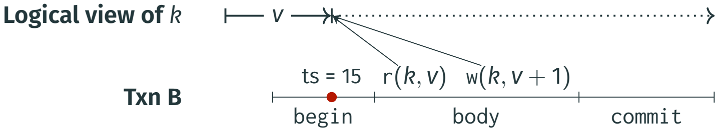

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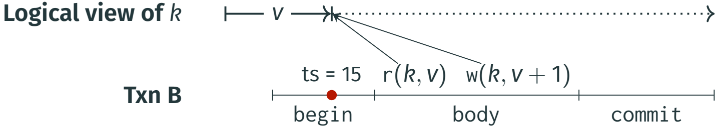
2. Update the logical state accordingly
3. Reconcile speculation with reality on commit/abort



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- ✓ txn B commits and updates k to $v+1$
- ✗ txn B commits and updates k to $v+2$
- ✗ txn B aborts
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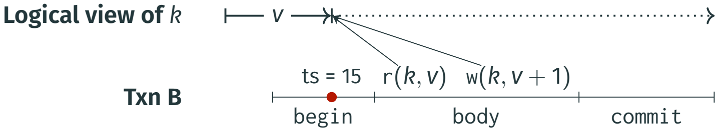
} speculating all possible executions



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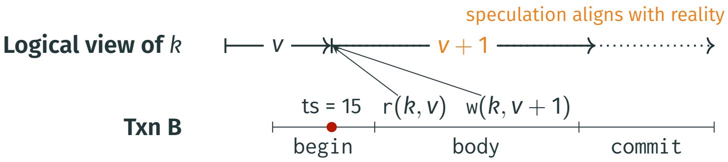

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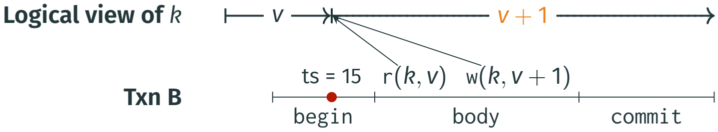

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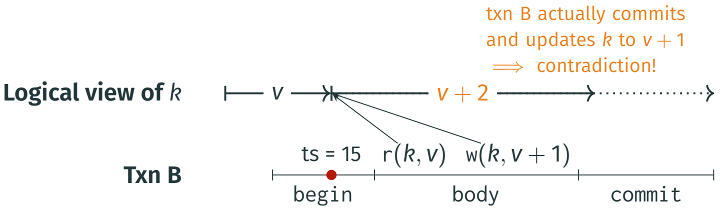

vMVCC: Implementation and proof efforts

Implementation feature and optimization

- Concurrent GC of unusable versions
- Sharding and padding shared data structures
- Timestamp generation with `RDTSC`

Component	Lines of code
Program	827 (Go)

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Proof	∼11K (Coq)

vMVCC: 13×

Prior work: 11–20×
GoTxn, CSPEC, CertiKOS, etc.

What good is the proof?

Clarify design by writing spec for whole system and internal components

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Caught subtle bugs

- Premature GC of still valid versions
- Violation of strict monotonicity of timestamps
- Off-by-one errors

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
- TPC-C: modelling the operations of a warehouse wholesale supplier

Experimental setup

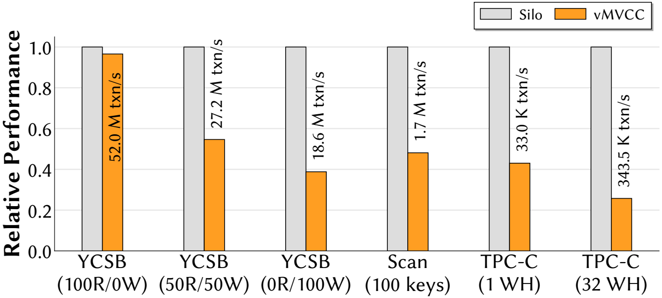
- AWS EC2 instance with 36 vCPUs and 72 GB of main memory

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

- Single-node in-memory transactional key-value store

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

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



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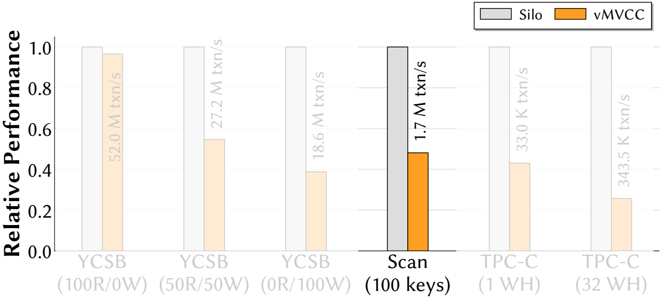

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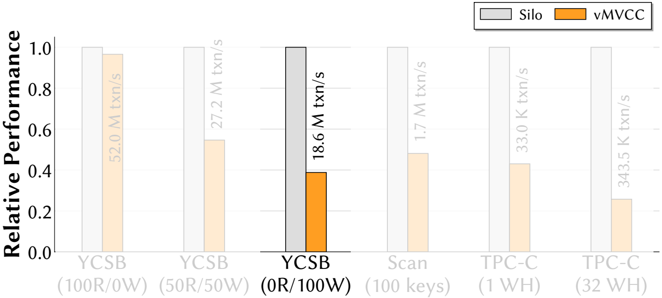

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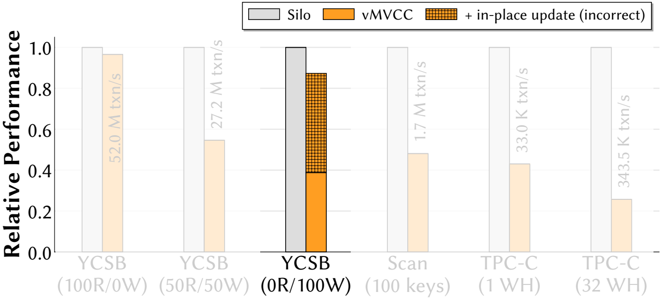

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Reasoning about transactions

- Push/pull model [PLDI ’15]
- C4 [OOPSLA ’22]

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Verified transaction library

- GoTxn [OSDI ’22]

Conclusion

vMVCC is the first MVCC-based transaction library with a machine-checked proof of correctness

- Sophisticated implementation to achieve high performance
- Succinct and application-friendly specification
- Formal proof adopting prophecy variables for MVCC transactions

`https://pdos.csail.mit.edu/projects/vmvcc.html`