Parameterized and Runtime-tunable Snapshot Isolation in Distributed Transactional Key-value Stores

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RVSI: Relaxed Version Snapshot Isolation

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Distributed key-value stores:

`put(K key, V val)` `get(K key)`

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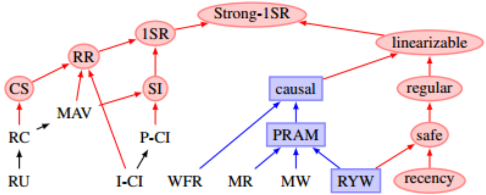

Transactional consistency models (from [Bailis@VLDB'14])

Snapshot isolation (SI [Berenson@SIGMOD'95], [Adya@Thesis'99]):

- Each transaction reads from the "latest" snapshot as of the time it started.
- If multiple concurrent transactions write to the same data item, at most one of them will commit. (WCF: *write-conflict freedom*)

Reading the "latest" in a distributed setting
often requires intensive coordinations.

[1] GSI: Generalized Snapshot Isolation [Elnikety@SRDS'05]
[2] NMSI: Non-Monotonic Snapshot Isolation [Ardekani@SRDS'13]
[3] PL-FCV: Forward Consistent View [Aday@Thesis'99]
[4] PSI: Parallel Snapshot Isolation [Sovran@SOSP'11]

Reading the “latest” in a distributed setting
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Relaxed variants of (distributed) SI:

- GSI [1]: allows to read from “older” snapshots
- NMSI [2]: allows to observe non-monotonically ordered snapshots
- PL-FCV [3]: allows a transaction to observe the updates of transactions that commit after it started
- PSI [4]: causal ordering of transactions across sites

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Two possible drawbacks:

1. Unbounded inconsistency
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   - no specification of the severity of the anomalies w.r.t SI
2. Untunable at runtime
   - determined at the system design phase
   - remain unchanged once the system is deployed

An online bookstore application [1] for motivating "bounded inconsistency" and "runtime-tuable":

Title	Authors	Sales	Inventory	Ratings	Reviews	···

[1] Adapted from [Guo@SIGMOD'04] and [Bernstein@SIGMOD'06].

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Sales Analyst (T_3): Studying sales vs. ratings of a book

- sales and ratings from *separate snapshots*

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The idea of "parameterized and runtime-tunable snapshot isolation".

RVSI: Relaxed Version Snapshot Isolation

- k_1-BV: k_1-version bounded *backward* view
- k_2-FV: k_2-version bounded *forward* view
- k_3-SV: k_3-version bounded *snapshot* view

[1] http://www.aliyun.com/

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CHAMELEON: a prototype distributed transactional key-value store

- Achieves RVSI
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CHAMELEON: a prototype distributed transactional key-value store

- Achieves RVSI
- Allows each transaction to tune its consistency level at runtime
- Deployed on Aliyun [1]
- Evaluates the impacts of RVSI on the transaction abort rates

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RVSI: Relaxed Version Snapshot Isolation

Transaction $T_i: \quad s_i \quad (r_i/w_i)^+ \quad c_i/a_i$

s_i: start operation

r_i/w_i: read/write operation

c_i/a_i: commit/abort operation

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x_i: version i of data item x written by T_i

$r_i(x_j)$: transaction T_i reading x_j

$w_i(x_i)$: transaction T_i writing x_i

History: modelling an execution of a transactional key-value store

- *time-precedes partial order* $\prec_h$ over operations

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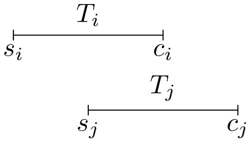
Two transactions are *concurrent* if

$$s_i \prec_h c_j \wedge s_j \prec_h c_i$$



A history h is in *snapshot isolation* iff it satisfies [Adya@Thesis'99]

Snapshot Read: All reads of transaction T_i occur at T_i's start time.

Snapshot Write: No concurrent committed transactions may write the same data item. (WCF: write-conflict freedom)

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$$(c_j \in h \land c_j \prec_h s_i) \land (s_i \prec_h c_k \lor c_k \prec_h c_j).$$

Snapshot Write: No concurrent committed transactions may write the same data item. (WCF: write-conflict freedom)

$$\forall w_i(x_i), w_{j \neq i}(x_j) \in h \implies (c_i \prec_h s_j \lor c_j \prec_h s_i).$$

Principles of RVSI:

- Using parameters (k_1, k_2, k_3) to control the severity of the anomalies w.r.t SI

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- Using parameters (k_1, k_2, k_3) to control the severity of the anomalies w.r.t SI
- RC [1] $\supset$ RVSI$(k_1, k_2, k_3) \supset$ SI
- RVSI$(\infty, \infty, \infty) =$ RC   RVSI$(1, 0, *) =$ SI

[1] RC: Read Committed isolation.

> *Each transaction reads data from the "latest" snapshot as of the time the transaction started.*
>
> *– The "Snapshot Read" property of SI*

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k_1-BV (Backward View): "stale" data versions — staleness $\leq k_1$

k_2-FV (Forward View): "concurrent" data versions — forward level $\leq k_2$

k_3-SV (Snapshot View): "non-snapshot" data versions — distance $\leq k_3$

$(k_1\text{-BV})$

$$\forall r_i(x_j), w_k(x_k), c_k \in h : \left(c_j \in h \wedge \bigwedge_{k=1}^{m} (c_j \prec_h c_k \prec_h s_i) \right) \Rightarrow m < k_1,$$

$(k_2\text{-FV})$

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$$\boxed{h \in \text{RVSI} \iff h \in k_1\text{-BV} \cap k_2\text{-FV} \cap k_3\text{-SV} \cap \text{WCF}}$$

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CHAMELEON:

A prototype **partitioned replicated**

distributed transactional **key-value** store

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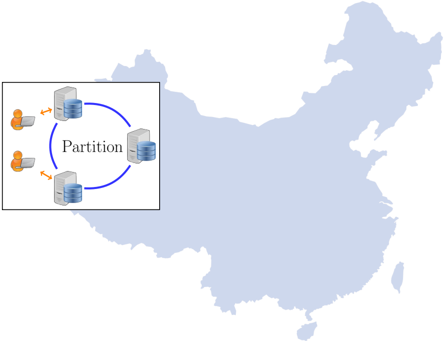
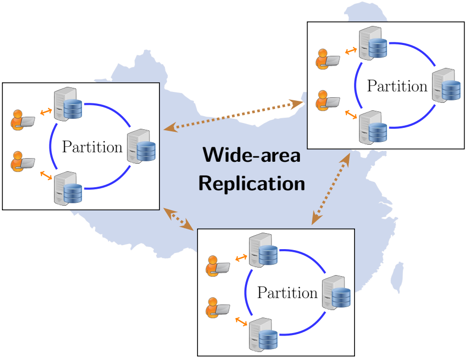
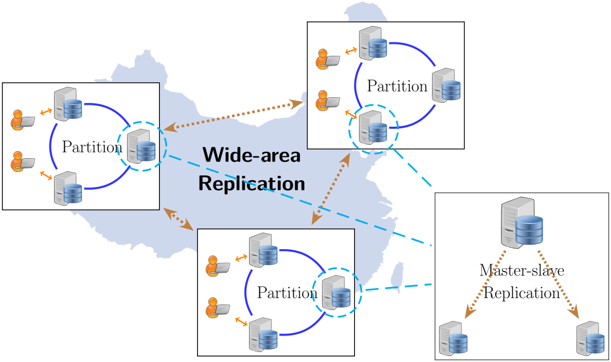
Key: (row key, column key)



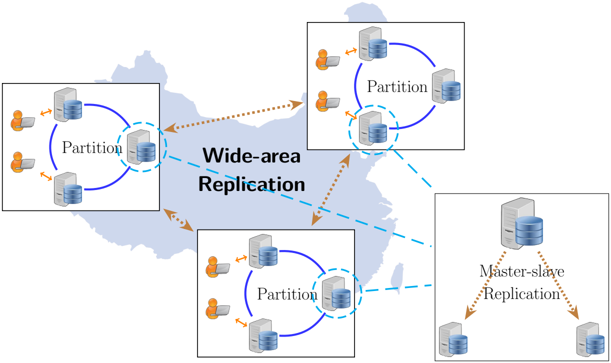
Keys are **partitioned** within a single datacenter.



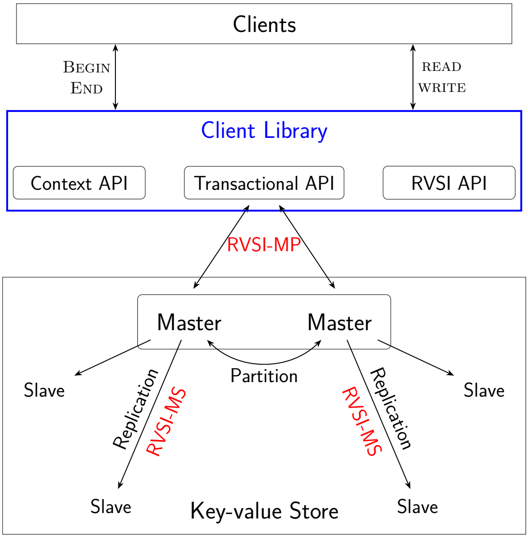
Each key is **replicated** across datacenters



Each key is **replicated** across datacenters in a **master-slave** manner.



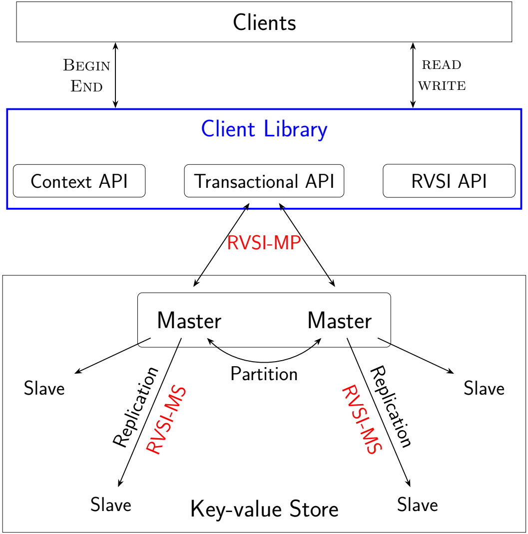
Transactions are first executed and committed on the **masters**, and are then asynchronously propagated to **slaves**.



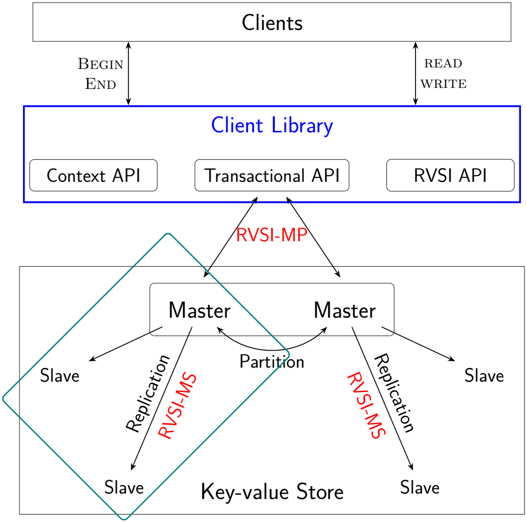
Client library

Code snippet for writing RVSI transactions:

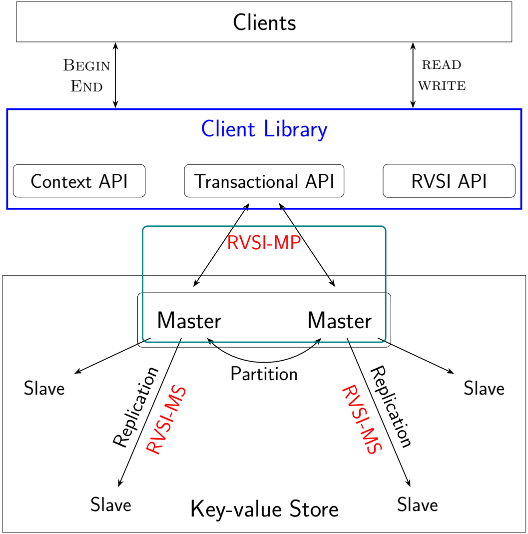
```
// Initialize keys (ck1 and ck2) here
    ...

ITx tx = new RVSITx(/** context **/);

tx.begin();

// Read and write here ...

// Specify RVSI specs. (e.g., SVSpec)
RVSISpec sv = new SVSpec();
sv.addSpec({ck1, ck2}, 2);
tx.collectRVSISpec(sv);

boolean committed = tx.end();
```



RVSI protocol: RVSI-MS + RVSI-MP

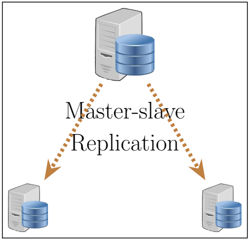


RVSI-MS: RVSI for Master-Slave replication



RVSI-MP: RVSI for Multiple Partitions

RVSI-MS: RVSI protocol for Master-Slave replication



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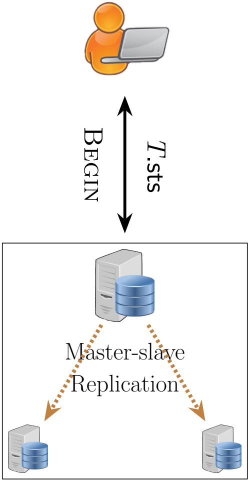

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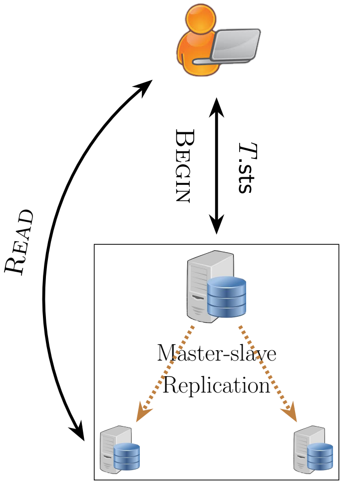

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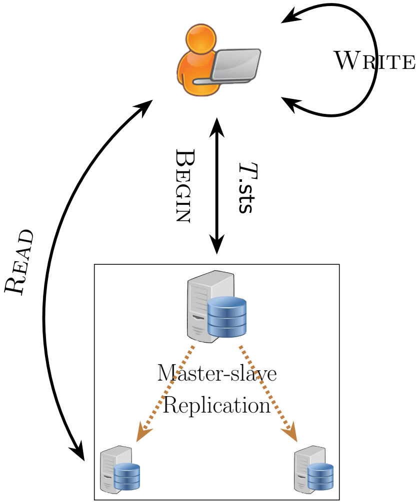

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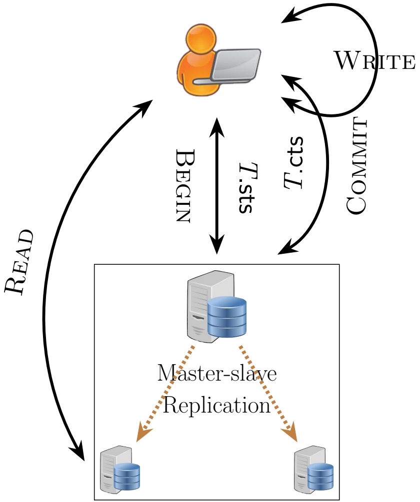

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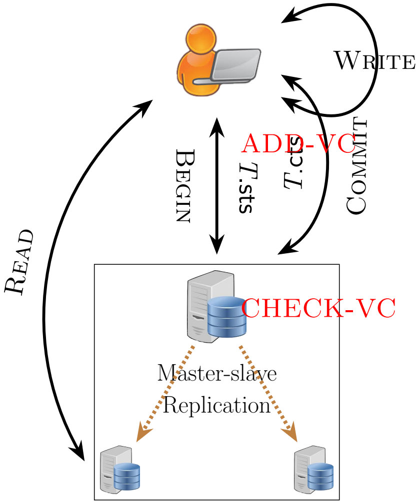

Calculating version constraints for RVSI:

$$\mathcal{O}_x(t) = \#\text{ of versions of } x \text{ before time } t$$

$$r_i(x_j) \in T_i$$

k_1-BV:

$$\mathcal{O}_x(T_i.\mathit{sts}) - \mathcal{O}_x(T_j.\mathit{cts}) < k_1$$

k_2-FV:

$$\mathcal{O}_x(T_j.\mathit{cts}) - \mathcal{O}_x(T_i.\mathit{sts}) \leq k_2$$

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We have two issues to address.

Assumes a timestamp oracle [Peng@OSDI'10]:

Client: asks for the start-timestamp in Begin

Coordinator: asks for the commit-timestamp in Commit

Split the RVSI version constraints according to partitions:

$$r_i(x_j) \in T_i$$

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All version constraints involve only one data item.

RVSI: Relaxed Version Snapshot Isolation

Impacts of RVSI specification

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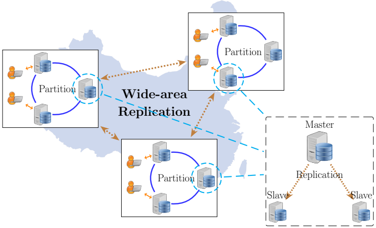
What about performance?

- Not reported in this work
- *Not* sensitive to parameters

CHAMELEON prototype on Aliyun:

- 3 datacenters [1]
- 3 nodes in each datacenter
- Partition & Replication
- Clients in our lab [2]



[1] Located in East China, North China, and South China, respectively.
[2] Located in East China.

Three categories of workload parameters for experiments on Aliyun.

Parameter	**Value**	**Explanation**
#keys	$25 = 5$ (rows) $\times$ 5 (columns)	
#clients	5, 10, 15, 20, 25, 30	
#txs/client	1000	
#ops/tx	$\sim$ Binomial(20, 0.5)	
rwRatio	1:2, 1:1, 4:1	#reads/#writes
zipfExponent	1	parameter for Zipfian distribution
minInterval	0ms	min/max/mean inter-transaction time
maxInterval	10ms	
meanInterval	5ms	
(k_1, k_2, k_3)	(1,0,0) (1,1,0) (1,1,1) (2,0,0) (2,0,1) (2,1,1)	

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Roadmap:

1. Transaction abort rates because of violating the RVSI version constraints are quite *sensitive* to different values of k_1, k_2, or k_3.

[1] https://github.com/hengxin/chameleon-transactional-kvstore

Roadmap:

1. Transaction abort rates because of violating the RVSI version constraints are quite *sensitive* to different values of k_1, k_2, or k_3.
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3. In controlled experiments, the impacts of k_1-BV emerge when the "issueDelay" gets shorter.

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We report the results under the read-frequent (#rwRatio = 4:1) workloads [1].

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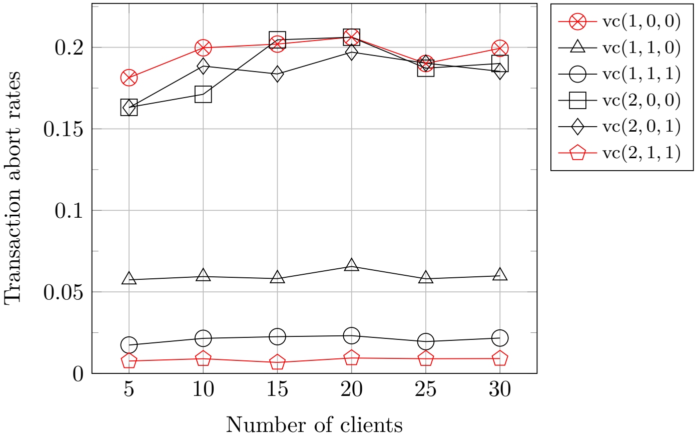
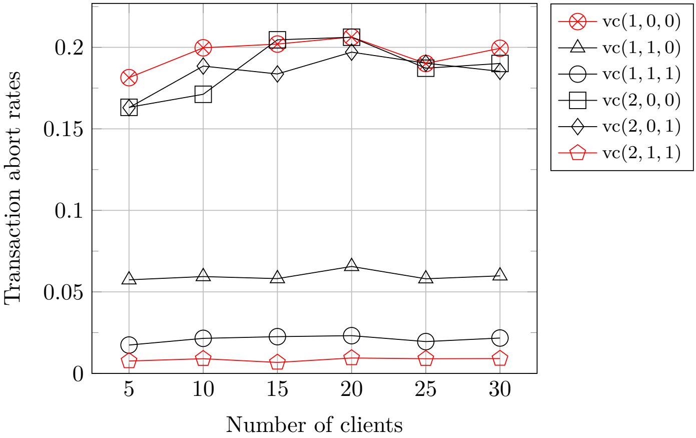
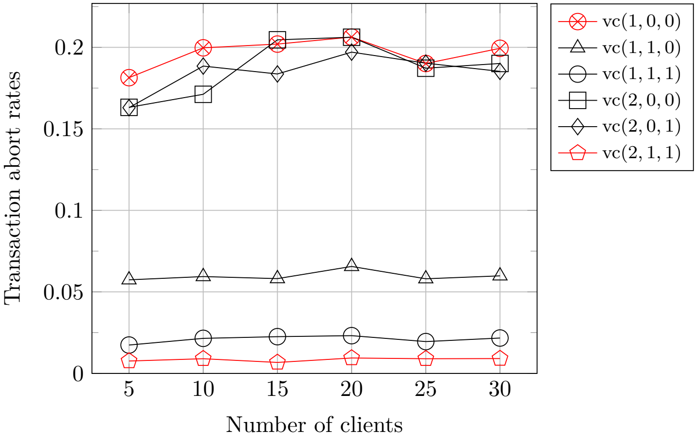


Transaction abort rates
0.2
0.15
0.1
0.05
0
5
10
15
20
25
30
Number of clients
vc(1, 0, 0)
vc(1, 1, 0)
vc(1, 1, 1)
vc(2, 0, 0)
vc(2, 0, 1)
vc(2, 1, 1)

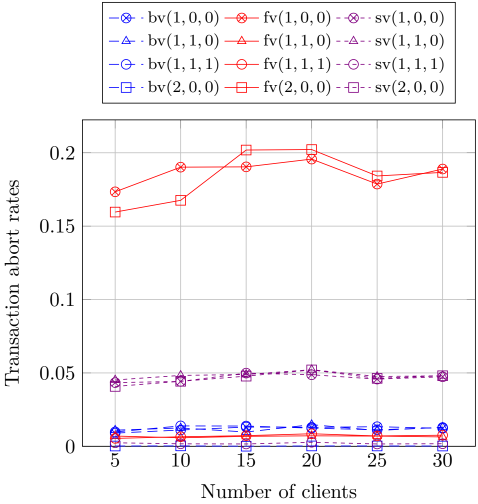


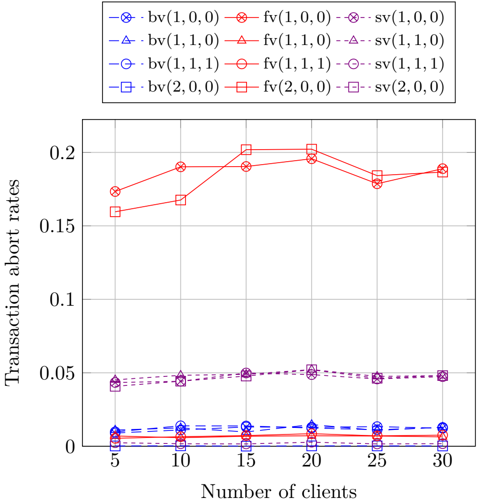
The transaction abort rates due to “vc-aborted”



The transaction abort rates due to "vc-aborted" can be greatly reduced by slightly increasing the values of k_1, k_2, or k_3:

$$vc(1,0,0) = 0.1994 \implies vc(2,1,1) = 0.0091 \quad (\#\text{clients} = 30)$$


bv(1, 0, 0)
fv(1, 0, 0)
sv(1, 0, 0)
bv(1, 1, 0)
fv(1, 1, 0)
sv(1, 1, 0)
bv(1, 1, 1)
fv(1, 1, 1)
sv(1, 1, 1)
bv(2, 0, 0)
fv(2, 0, 0)
sv(2, 0, 0)
Transaction abort rates
0.2
0.15
0.1
0.05
0
5
10
15
20
25
30
Number of clients



Most "vc-aborted" transactions abort because of violating k_2-FV.

$$fv(1,0,0) = 0.1889 \implies fv(2,0,0) = 0.1866 \implies fv(1,1,0) = 0.0064$$

In the Aliyun scenarios, we saw *little* impacts of k_1-BV.

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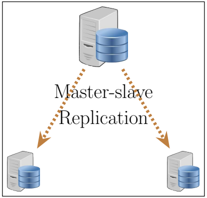
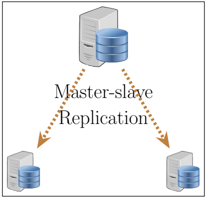
We therefore explore the impacts of k_1-BV in controlled experiments.

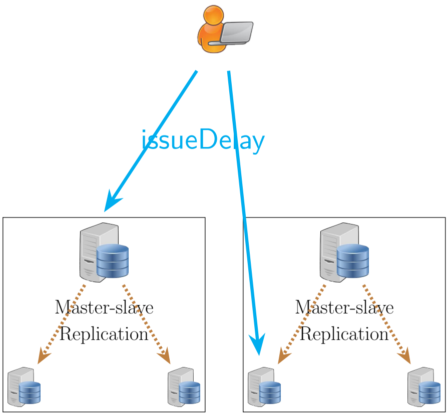
Three types of delays for controlled experiments on local hosts.





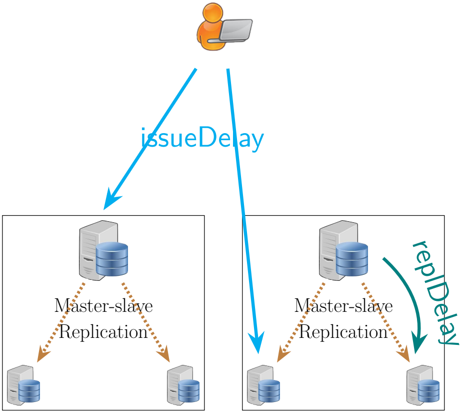
Types	Values (ms)	Explanation

Three types of delays for controlled experiments on local hosts.



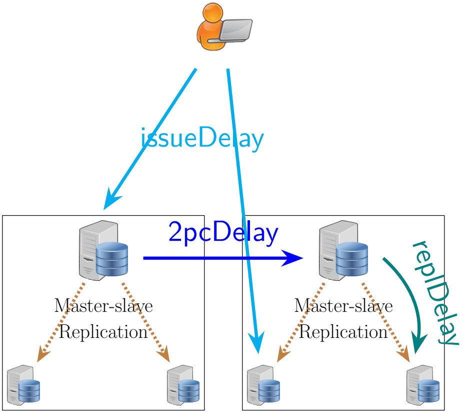
Types	Values (ms)	Explanation
issueDelay	5, 8, 10, 12, 15, 20	delays between clients and replicas

Three types of delays for controlled experiments on local hosts.

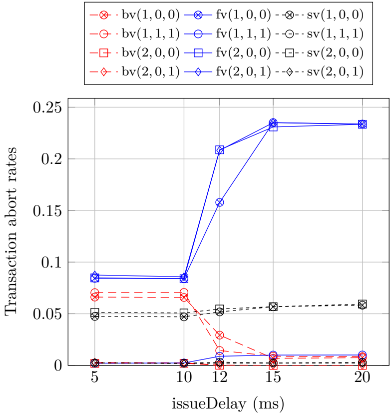


Types	Values (ms)	Explanation
replDelay	5, 10, 15, 20, 30	delays between masters and slaves

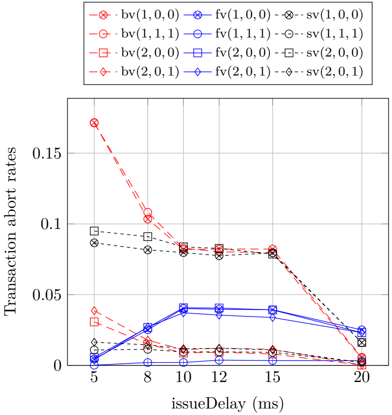
Three types of delays for controlled experiments on local hosts.



Types	Values (ms)	Explanation
2pcDelay	10, 20, 30, 40, 50	delays among masters



(Under read-frequent workloads.)



(Under write-frequent workloads.)

When the "issueDelay" gets shorter,

the impacts of k_1-BV have begun to emerge.

Generally, RVSI *helps to reduce the transaction abort rates* when applications are willing to tolerate certain anomalies.

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k_2-FV: In the Aliyun scenarios, most transactions have been aborted because of violating k_2-FV.

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- k_2-FV: In the Aliyun scenarios, most transactions have been aborted because of violating k_2-FV.
- k_1-BV: In controlled experiments, the impacts of k_1-BV emerge when the "issueDelay" gets shorter.
- k_3-SV: Complex and challenging (involving multiple data items)

RVSI: Relaxed Version Snapshot Isolation

The idea of "bounded transactional inconsistency" is partially inspired by the work on

- Relaxed Currency and Consistency (C&C) semantics [Guo@SIGMOD'04]
- Relaxed Currency Serializability (RC-SR) [Bernstein@SIGMOD'06]

Two differences:

- Serializability (SR) *vs.* SI
- Currency in real-time *vs.* Versions in order

Bounded transactional inconsistency (others):

Epsilon-SR: inconsistency introduced by concurrent update transactions [Pu@SIGMOD'91] [Ramamritham@TKDE'95]

- uncommitted *vs.* RC (for RVSI)

N-ignorant System: ignorant of $\leq K$ "prior" transactions [Krishnakumar@PODS'91]

- SR *vs.* SI (for RVSI)

Dynamic consistency choices:

Parameterized ESR, N-ignorant, RC-SR, C&C semantics, RVSI

Pileus strong, intermediate, and eventual consistency [Kotla@MSR-TR'2013]

SIEVE a tool automating the choice of consistency levels [Li@ATC'14]
(based on the theory of RedBlue consistency [Li@OSDI'12])

Salt combining ACID and BASE transactions [Xie@OSDI'14]

Multi-level a transaction model supporting four consistency levels [Tripathi@BigData'15]

RVSI: Relaxed Version Snapshot Isolation

The idea of "parameterized and runtime-tunable snapshot isolation".

RVSI: Relaxed Version Snapshot Isolation

k_1-BV: k_1-version bounded backward view

k_2-FV: k_2-version bounded forward view

k_3-SV: k_3-version bounded snapshot view

CHAMELEON: a prototype distributed transactional key-value store

- Achieves RVSI
- Allows each transaction to tune its consistency level at runtime
- Evaluates the impacts of RVSI on the transaction abort rates

Possible future work:

- To evaluate the impacts of k_3-SV on transaction abort rates
- To study the impacts of RVSI from the perspective of developers

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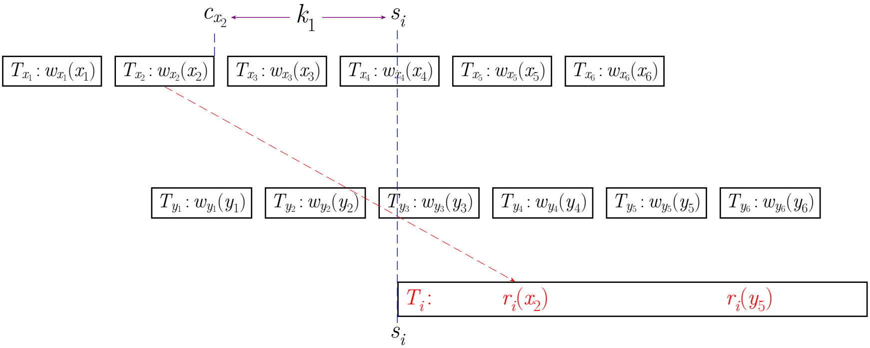
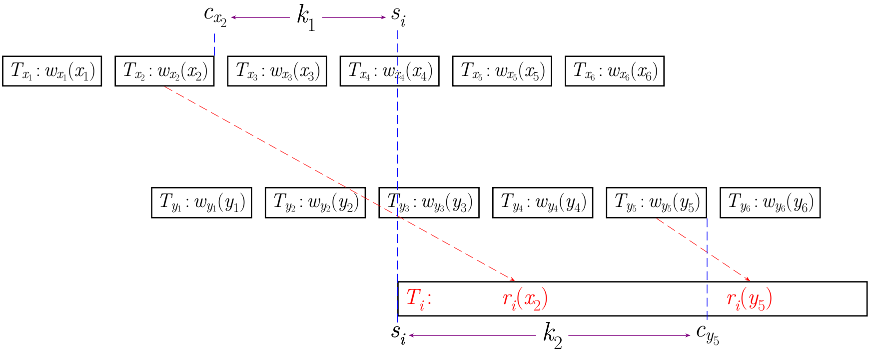
$\boxed{T_{x_1} : w_{x_1}(x_1)}$ $\boxed{T_{x_2} : w_{x_2}(x_2)}$ $\boxed{T_{x_3} : w_{x_3}(x_3)}$ $\boxed{T_{x_4} : w_{x_4}(x_4)}$ $\boxed{T_{x_5} : w_{x_5}(x_5)}$ $\boxed{T_{x_6} : w_{x_6}(x_6)}$

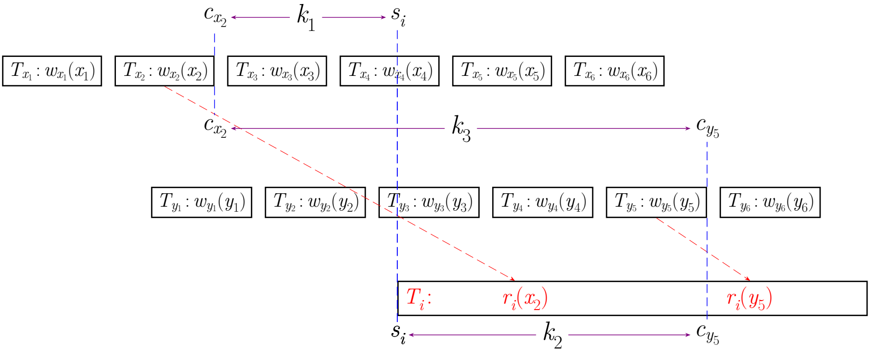
$\boxed{T_{y_1} : w_{y_1}(y_1)}$ $\boxed{T_{y_2} : w_{y_2}(y_2)}$ $\boxed{T_{y_3} : w_{y_3}(y_3)}$ $\boxed{T_{y_4} : w_{y_4}(y_4)}$ $\boxed{T_{y_5} : w_{y_5}(y_5)}$ $\boxed{T_{y_6} : w_{y_6}(y_6)}$

$\boxed{T_i : \quad r_i(x_2) \quad\quad r_i(y_5)}$



c_{x_2}
k_1
s_i
$T_{x_1} : w_{x_1}(x_1)$
$T_{x_2} : w_{x_2}(x_2)$
$T_{x_3} : w_{x_3}(x_3)$
$T_{x_4} : w_{x_4}(x_4)$
$T_{x_5} : w_{x_5}(x_5)$
$T_{x_6} : w_{x_6}(x_6)$
$T_{y_1} : w_{y_1}(y_1)$
$T_{y_2} : w_{y_2}(y_2)$
$T_{y_3} : w_{y_3}(y_3)$
$T_{y_4} : w_{y_4}(y_4)$
$T_{y_5} : w_{y_5}(y_5)$
$T_{y_6} : w_{y_6}(y_6)$
T_i:
$r_i(x_2)$
$r_i(y_5)$
s_i


c_{x_2}
k_1
s_i
$T_{x_1} : w_{x_1}(x_1)$
$T_{x_2} : w_{x_2}(x_2)$
$T_{x_3} : w_{x_3}(x_3)$
$T_{x_4} : w_{x_4}(x_4)$
$T_{x_5} : w_{x_5}(x_5)$
$T_{x_6} : w_{x_6}(x_6)$
$T_{y_1} : w_{y_1}(y_1)$
$T_{y_2} : w_{y_2}(y_2)$
$T_{y_3} : w_{y_3}(y_3)$
$T_{y_4} : w_{y_4}(y_4)$
$T_{y_5} : w_{y_5}(y_5)$
$T_{y_6} : w_{y_6}(y_6)$
$T_i :$
$r_i(x_2)$
$r_i(y_5)$
s_i
k_2
c_{y_5}


c_{x_2}
k_1
s_i
$T_{x_1} : w_{x_1}(x_1)$
$T_{x_2} : w_{x_2}(x_2)$
$T_{x_3} : w_{x_3}(x_3)$
$T_{x_4} : w_{x_4}(x_4)$
$T_{x_5} : w_{x_5}(x_5)$
$T_{x_6} : w_{x_6}(x_6)$
c_{x_2}
k_3
c_{y_5}
$T_{y_1} : w_{y_1}(y_1)$
$T_{y_2} : w_{y_2}(y_2)$
$T_{y_3} : w_{y_3}(y_3)$
$T_{y_4} : w_{y_4}(y_4)$
$T_{y_5} : w_{y_5}(y_5)$
$T_{y_6} : w_{y_6}(y_6)$
T_i:
$r_i(x_2)$
$r_i(y_5)$
s_i
k_2
c_{y_5}

Applicability

Algorithm 1 RVSI-MS Protocol for Executing Transaction T (Client).

procedure BEGIN()
    T.*sts* $\leftarrow$ **rpc-call** START() at master $\mathcal{M}$
procedure READ(x)
    x.*ver* $\leftarrow$ **rpc-call** READ(x) at any site
procedure WRITE(x, v)
    add (x, v) to T.*writes*
procedure END(T)
    T.*vc* $\leftarrow$ ADD-VC()
    $c/a \leftarrow$ **rpc-call** COMMIT(T.*writes*, T.*vc*) at $\mathcal{M}$

Algorithm 1 RVSI-MS Protocol for Executing Transaction T (Master).

$\mathcal{M}.ts$: for start-timestamps and commit-timestamps
$\{x.ver = (x.ts, x.ord, x.val)\}$: set of versions of x

procedure START()
    return $++\mathcal{M}.ts$
procedure READ(x)
    return the latest $x.ver$ installed
procedure COMMIT($T.writes$, $T.vc$)
    if CHECK-VC($T.vc$) && write-conflict freedom **then**
        $T.cts \leftarrow ++\mathcal{M}.ts$
        ▷ *apply $T.writes$ locally and propagate it*
        $T.upvers = \emptyset$ ▷ *collect updated versions*
        for $(x, v) \in T.writes$ **do**
            $x.new\text{-}ver \leftarrow (T.cts, ++x.ord, v)$
            add $x.new\text{-}ver$ to $\{x.ver\}$ and $T.upvers$
        broadcast $\langle$PROP, $T.upvers\rangle$ to slaves
        return c denoting "committed"
    return a denoting "aborted"

Algorithm 1 RVSI-MS Protocol for Executing Transaction T (Slave).

$x.\mathit{ver} = (x.\mathit{ts}, x.\mathit{ord}, x.\mathit{val})$: the latest version of x

procedure $\textsc{Read}(x)$
    return $x.\mathit{ver}$
upon $\textsc{Received}(\langle \text{PROP}, T.\mathit{upvers} \rangle)$
    for $\big(x.\mathit{ver}' = (x.\mathit{ts}', x.\mathit{ord}', x.\mathit{val}')\big) \in T.\mathit{upvers}$ **do**
        if $x.\mathit{ord}' > x.\mathit{ord}$ **then**
            $x.\mathit{ver} \leftarrow x.\mathit{ver}'$

Algorithm 2 RVSI-MP for Executing Transaction T (Client).

```
procedure BEGIN()
    return rpc-call GETTS() at 𝒯
procedure END()
    T.vc ← ADD-VC()
    c/a ← rpc-call C-COMMIT(T.writes, T.vc) at 𝒞
```

Algorithm 2 RVSI-MP for Executing Transaction T (Timestamp Oracle).

$\mathcal{T}$.*ts*: for start-timestamps and commit-timestamps

1: **procedure** $\textsc{getTS}()$

2: **return** $++\mathcal{T}.ts$

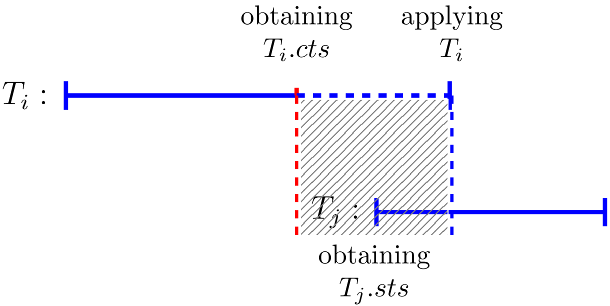
Algorithm 2 RVSI-MP for Executing Transaction T (Coordinator).

procedure C-COMMIT(T.*writes*, T.*vc*)
    split T.*writes* and T.*vc* with the data partitioning strategy
    ▷ *the prepare phase:*
    rpc-call PREPARE(T.*writes*, T.*vc*) at each $\mathcal{M}$
    ▷ *the commit phase:*
    if all PREPARE(T.*writes*, T.*vc*) return *true* **then**
        T.*cts* $\leftarrow$ **rpc-call** GETTS() at $\mathcal{T}$
        rpc-call COMMIT(T.*cts*, T.*writes*) at each $\mathcal{M}$
    else
        rpc-call ABORT() at each $\mathcal{M}$
        return a denoting "aborted"
    if all COMMIT(T.*cts*, T.*writes*) return *true* **then**
        return c denoting "committed"
    else
        return a denoting "aborted"

Algorithm 2 RVSI-MP for Executing Transaction T (Master).

```
procedure PREPARE(T.writes, T.vc)
    return CHECK-VC(T.vc) && write-conflict freedom
procedure COMMIT(T.cts, T.writes)
    ▷ apply T.writes locally and propagate it
procedure ABORT()
    ▷ abort
```

Atomicity of the commit-timestamps:



Delays

(One-way) delays among nodes [1]:

Within datacenter: $1 \sim 2$ms

Across datacenters: $15 \sim 25$ms

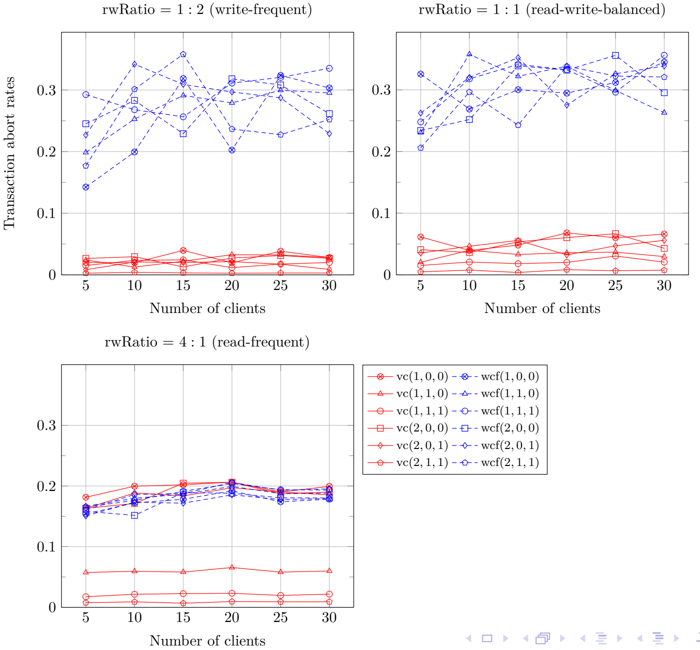
Clients to nodes: $15 \sim 20$ms

[1] `https://github.com/hengxin/aliyun-ping-traces`

Benchmarks

- The TPC-C benchmark is commonly used to benchmark relational databases.
- The YCSB benchmark [Cooper@SoCC'10] for distributed key-value stores does not support transactions.

We design our own workloads.



rwRatio = 1 : 2 (write-frequent)
rwRatio = 1 : 1 (read-write-balanced)
rwRatio = 4 : 1 (read-frequent)
Transaction abort rates
Number of clients
vc(1, 0, 0)
wcf(1, 0, 0)
vc(1, 1, 0)
wcf(1, 1, 0)
vc(1, 1, 1)
wcf(1, 1, 1)
vc(2, 0, 0)
wcf(2, 0, 0)
vc(2, 0, 1)
wcf(2, 0, 1)
vc(2, 1, 1)
wcf(2, 1, 1)