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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Figure: Distributed key-value stores.

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

Transactional semantics

existential consistency atomic visibility example

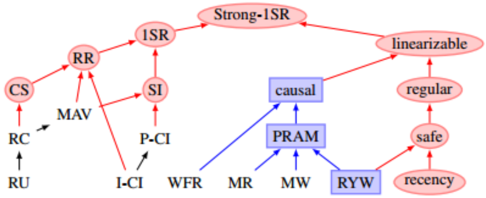

Figure: Transactional consistency models (from [Bailis@VLDB'14]).

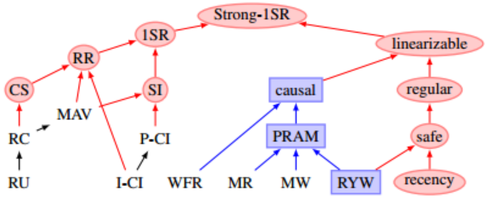

Figure: Transactional consistency models (from [Bailis@VLDB'14]).

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

- Read from the "latest" snapshot as of the time the transaction started
- No write-conflicting concurrent transactions

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
often requires intensive coordinations.

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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1. Unbounded inconsistency
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1. Unbounded inconsistency
   - 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 for motivating "bounded inconsistency" and "runtime-tuable":

Title	Authors	Publisher	Sales	Inventory	Ratings	Reviews	$\cdots$

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

- sales and ratings from *separate snapshots*

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

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

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  - achieves RVSI
  - allows each transaction to tune its consistency level at runtime

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- CHAMELEON prototype: distributed transactional key-value store
  - achieves RVSI
  - allows each transaction to tune its consistency level at runtime
  - deployed on Aliyun [5]
  - explore the impacts of RVSI on the transaction abort rates

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

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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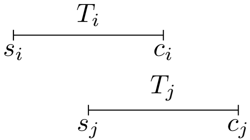
Two transactions are *concurrent* if

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



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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$$\forall r_i(x_{j \neq i}), w_{k \neq j}(x_k), c_k \in h :$$
$$(c_j \in h \land c_j \prec_h s_i) \land (s_i \prec_h c_k \lor c_k \prec_h c_j).$$

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 [6] $\supset$ RVSI$(k_1, k_2, k_3) \supset$ SI
- RVSI$(\infty, \infty, \infty) =$ RC   RVSI$(1, 0, *) =$ SI

[6] RC: Read Committed isolation.

> *Each transaction reads data from the "latest" snapshot as of the time the transaction started.*
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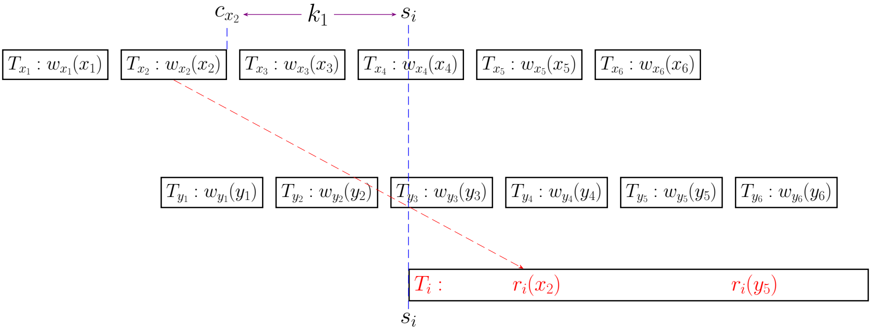
k_2-FV (Forward View): "concurrent" data versions forward level $\leq k_2$

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

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

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

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


c_{x_2}
k_1
s_i
$T_{x_1} : w_{x_1}(x_1)$
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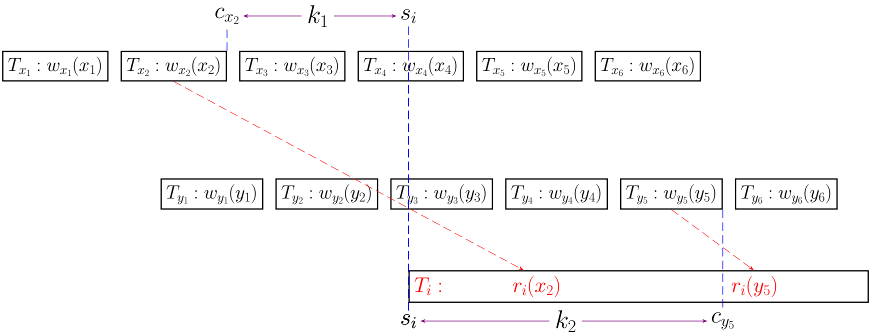

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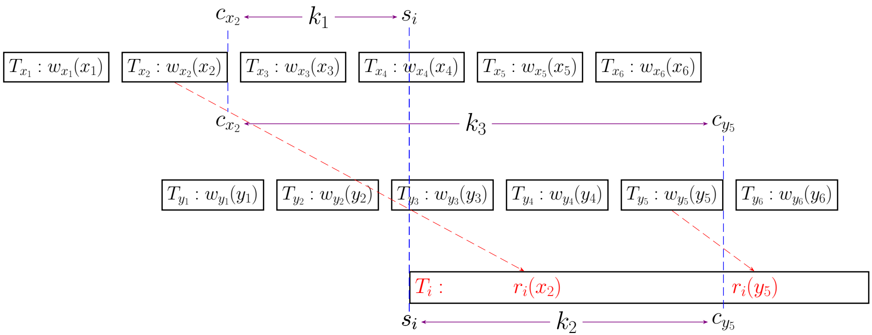
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s_i k_2 c_{y_5}

$(k_1\text{-BV})$

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

$(k_2\text{-FV})$

$$\forall r_i(x_j), w_k(x_k), c_k \in h : \left(c_j \in h \wedge \bigwedge_{k=1}^{m} (s_i \prec_h c_k \prec_h c_j) \right) \Rightarrow m \leq k_2$$

$(k_3\text{-SV})$

$$\forall r_i(x_j), r_i(y_l), w_k(x_k), c_k \in h : \left(\bigwedge_{k=1}^{m} (c_j \prec_h c_k \prec_h c_l) \right) \Rightarrow m \leq k_3.$$

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

$$\text{RVSI}(\infty, \infty, \infty) = \text{RC} \qquad \text{RVSI}(1, 0, *) = \text{SI}$$

RVSI: Relaxed Version Snapshot Isolation

Chameleon Protocol

Chameleon:

A prototype **partitioned replicated**

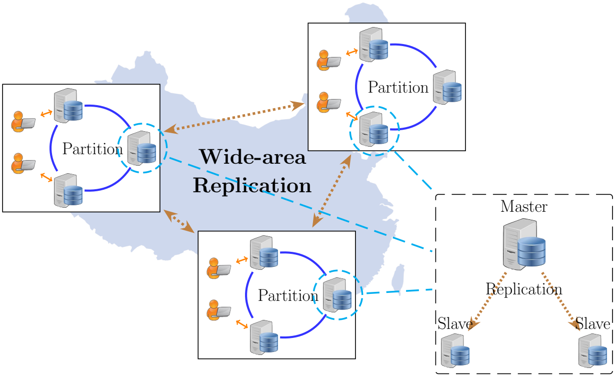
distributed transactional **key-value** store

Chameleon Prototype

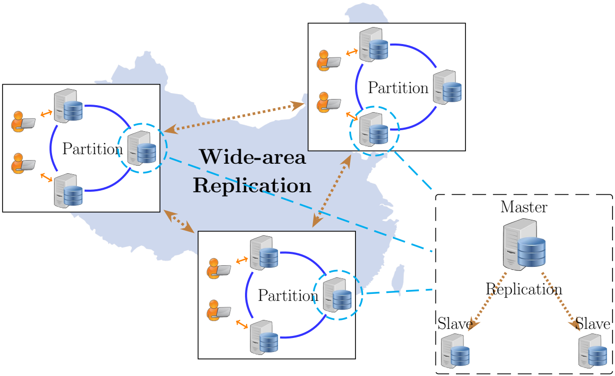
Classic **key-value** data model

Key: (row key, column key)

Chameleon Prototype

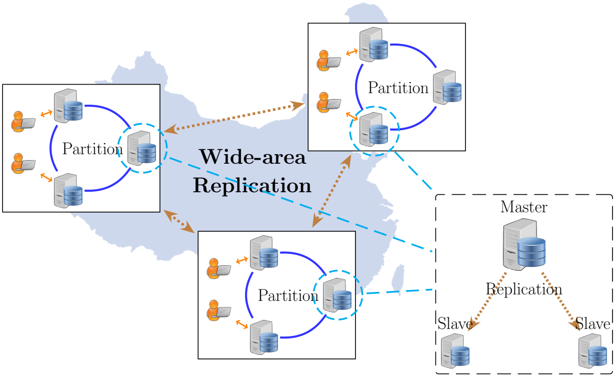


CHAMELEON Prototype



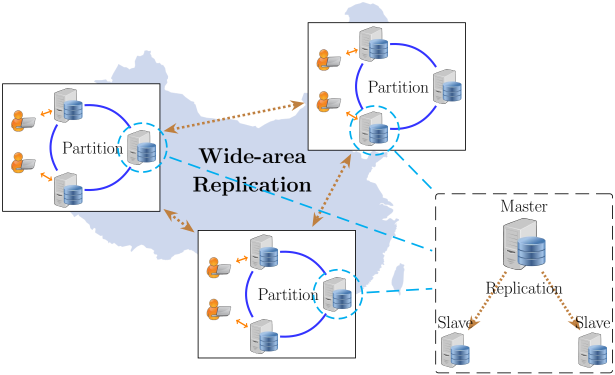
Keys are **partitioned** within a single datacenter.

CHAMELEON Prototype



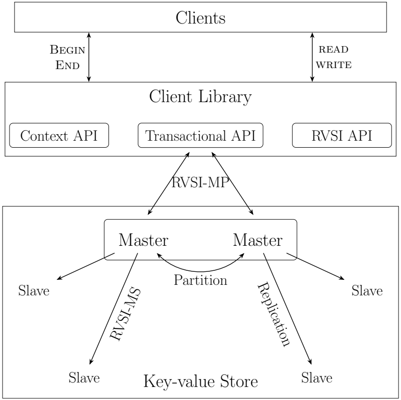
Each key is **replicated** in a master-slave manner across datacenters.

Chameleon Prototype



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

Chameleon Protocol



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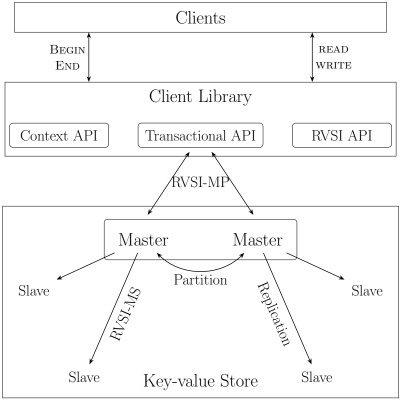
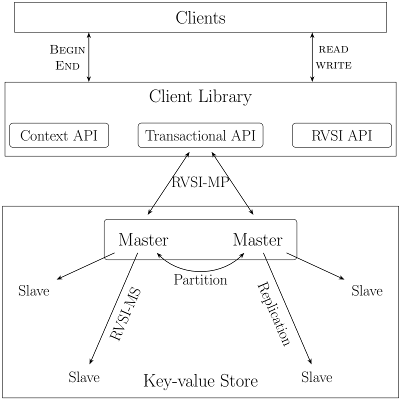


Partitioned replicated transactional key-value store

CHAMELEON Protocol



Client library

Chameleon Protocol

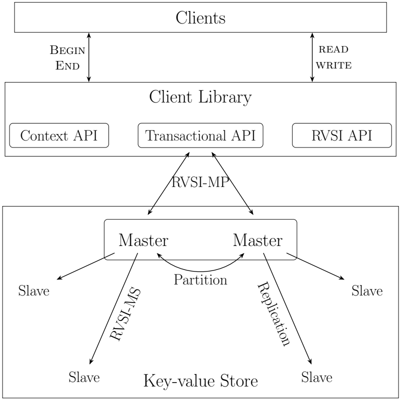
```
// Initialize keys (ck, ck1, and ck2) here
ITx tx = new RVSITx(/** context **/);

tx.begin();

// Read and write
ITsCell tsCell = tx.read(ck);
ITsCell tsCell1 = tx.read(ck1);
tx.write(ck1, new Cell("R1C1"));
ITsCell tsCell2 = tx.read(ck2);

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

CHAMELEON Protocol



RVSI protocol: RVSI-MS + RVSI-MP

RVSI-MS Protocol

RVSI-MS: RVSI protocol for master-slave replication

In terms of *event* generation and handling:

Clients: BEGIN, READ, WRITE, END

Master: START, COMMIT, SEND

Slaves: RECEIVE

RVSI-MS Protocol

TikZ overlay for RVSI-MS

RVSI-MS Protocol

Calculating version constraints:

RVSI-MP Protocol

Distributed transactions spanning multiple masters need to be committed atomically.

RVSI-MP Protocol

Distributed transactions spanning multiple masters need to be committed atomically.

Using the two-phase commit (2PC) protocol.

RVSI-MP Protocol

Assumes a timestamp oracle:

Clients:

Masters:

RVSI-MP Protocol

RVSI version constraints in 2PC protocol:

- k_1-BV:
- k_2-FV:
- k_3-SV:

RVSI-MS Protocol

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

Client-side methods:

procedure $\textsc{begin}()$
    $T.\mathit{sts} \leftarrow$ **rpc-call** $\textsc{start}()$ at master $\mathcal{M}$
procedure $\textsc{read}(x)$
    $x.\mathit{ver} \leftarrow$ **rpc-call** $\textsc{read}(x)$ at any site
procedure $\textsc{write}(x, v)$
    add (x, v) to $T.\mathit{writes}$
procedure $\textsc{end}(T)$
    $T.\mathit{vc} \leftarrow \textsc{add-vc}()$
    $c/a \leftarrow$ **rpc-call** $\textsc{commit}(T.\mathit{writes}, T.\mathit{vc})$ at $\mathcal{M}$

RVSI-MP Protocol

Algorithm 2 RVSI-MP: RVSI Protocol for Partition (for Executing Transaction T).

Client-side methods:

procedure BEGIN()
  return rpc-call GETTS() at $\mathcal{T}$
procedure END()
  $T.vc \leftarrow$ ADD-VC()
  $c/a \leftarrow$ **rpc-call** C-COMMIT($T.writes, T.vc$) at $\mathcal{C}$

Timestamp oracle methods:

$\mathcal{T}.ts$: for start-timestamps and commit-timestamps
procedure GETTS()
  return $++\mathcal{T}.ts$

RVSI: Relaxed Version Snapshot Isolation

Impacts of RVSI specification

on the *transaction abort rates* in various scenarios

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Performance?

- Not done yet in this work
- CHAMELEON prototype is ...

Transactions abort for two reasons:

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- "wcf-aborted": the WCF property violated

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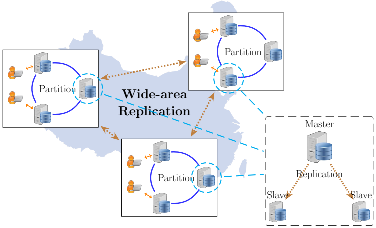
$$h \in \textsf{RVSI} \iff h \in k_1\text{-}\textsf{BV} \cap k_2\text{-}\textsf{FV} \cap k_3\text{-}\textsf{SV} \cap \textsf{WCF}.$$

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

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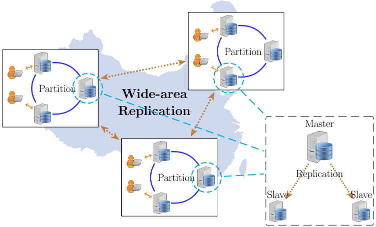

(One-way) delays among nodes [3]:

Within datacenter: $1 \sim 2$ms

Across datacenters: $15 \sim 25$ms

Clients to nodes: $15 \sim 20$ms

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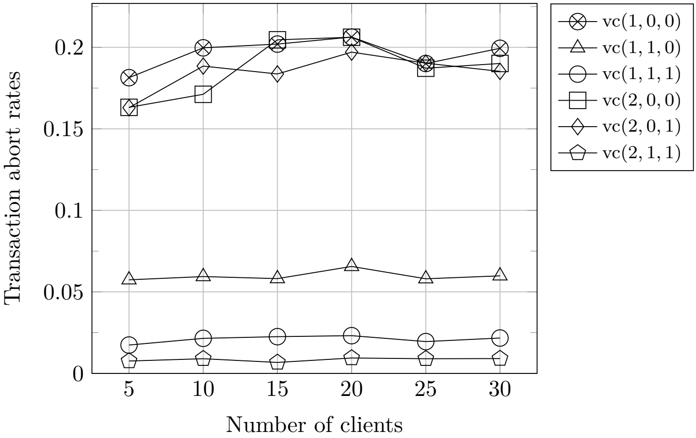
[2] Located in East China.

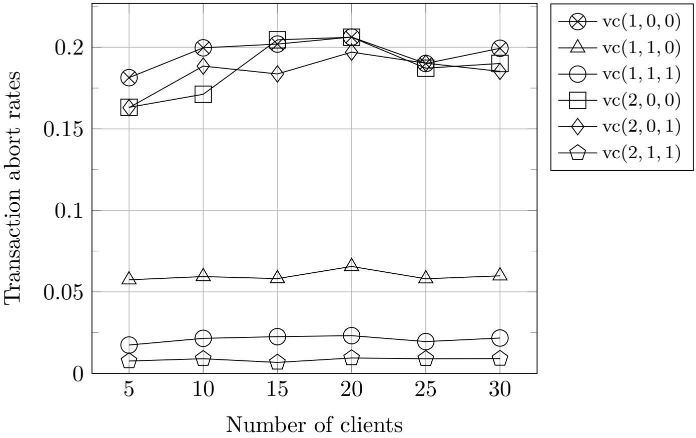
[3] https://github.com/hengxin/aliyun-ping-traces

Table: Three categories of workload parameters for experiments on Aliyun.

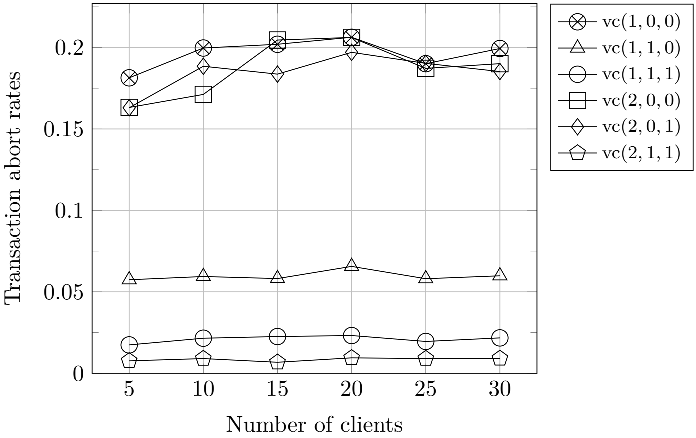
Parameter		**Value**	
Transaction-related	#keys	$25 = 5$ (rows) $\times$ 5 (columns)	
	#clients	5, 10, 15, 20, 25, 30	
	#txs/client	1000	
	#ops/tx	$\sim$ Binomial(20, 0.5)	n
	rwRatio	1:2, 1:1, 4:1	
	zipfExponent	1	
Execution-related	minInterval	0ms	
	maxInterval	10ms	
	meanInterval	5ms	
RVSI-related	(k_1, k_2, k_3)	(1,0,0) (1,1,0) (1,1,1) (2,0,0) (2,0,1) (2,1,1)	

under read-frequent workloads


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)

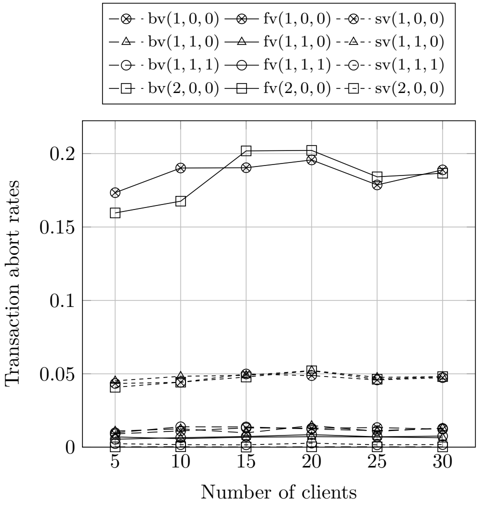


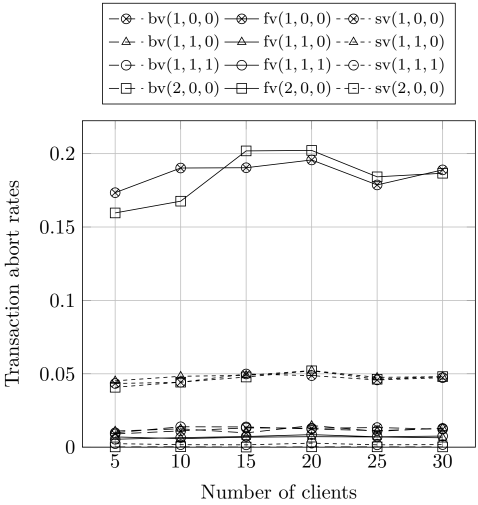
The transaction abort rates due to “vc-aborted”



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.

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

Question: when does k_1 for k_1-BV take effect?

It seems that k_1-BV has *little* impact on the transaction abort rates.

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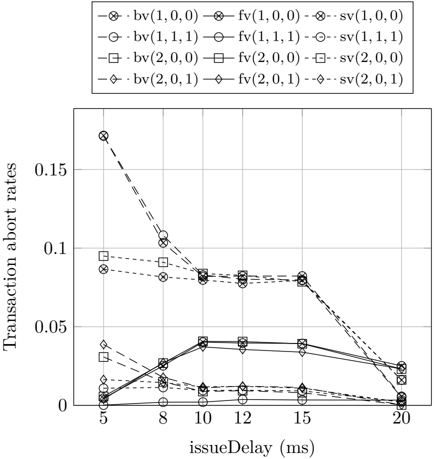
It seems that k_1-BV has *little* impact on the transaction abort rates.

It may be the case in the Aliyun scenarios.

What about other scenarios?

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
replDelay	5, 10, 15, 20, 30	delays between masters and slaves
2pcDelay	10, 20, 30, 40, 50	delays among masters



When the "issueDelay" gets shorter,
the impacts of k_2-FV go weaker,
and the impacts of k_1-BV have begun to emerge.

issueDelay $= 20$ms: $bv(1,0,0) = 0.0057$ $\quad fv(1,0,0) = 0.0251$

issueDelay $= 15$ms: $bv(1,0,0) = 0.08225$ $\quad fv(1,0,0) = 0.0393$

issueDelay $= 5$ms: $bv(1,0,0) = 0.1716$ $\quad fv(1,0,0) = 0.0045$

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issueDelay $= 5$ms: $bv(1,0,0) = 0.1716$ $fv(1,0,0) = 0.0045$

larger issueDelay $\Longrightarrow$ longer transaction

more concurrent transactions

more likely to obtain data versions updated by concurrent transactions

more sensitive to 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)