# Consistency in Transactional Distributed Databases: Protocols and Testing

Hengfeng Wei (魏恒峰)

hfwei@nju.edu.cn

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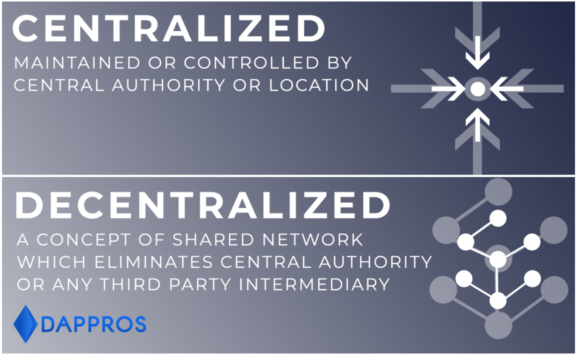
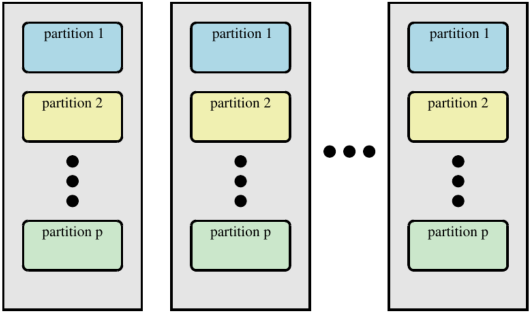
# Background

Centralized Databases *vs.* Distributed Databases



# Data Consistency Problem

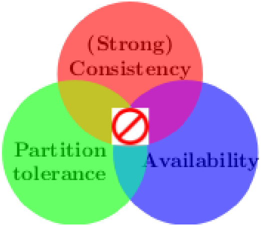
"Data Partition + Data Replication"




Data Consistency Problem

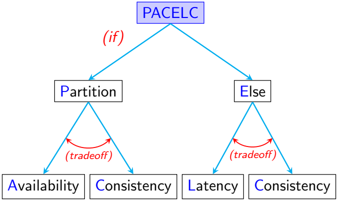
# Data Consistency Problem

(Strong) Consistency, Availability, Latency、Patition tolerance




CAP Theorem

(Brewer@PODC2000)

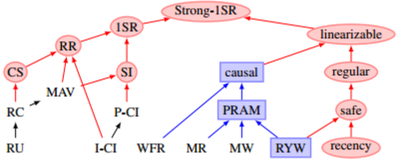



PACELC Tradeoff

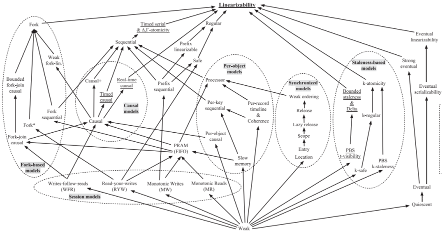
(Abadi@Computer2012)

# Consistency Models

Use consistency models to capture these tradeoffs




(Bailis@VLDB2012)




(Viotti@CSUR2016)

# My Researches

Researches on data consistency around consistency models:

**Computability:** What is possible or impossible?

**Protocol:** How to design fast, scalable, and fault-tolerant protocols?

**Testing:** What is the complexity?

How to design efficient testing algorihthms?

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**Computability:** What is possible or impossible?

**Protocol:** How to design fast, scalable, and fault-tolerant protocols?

**Testing:** What is the complexity?
How to design efficient testing algorihthms?

Classic problems with the ever-changing requirements

# My Researches (I)

Read/Write Register[a] ($\geq$ 2012)

Distributed Non-transactional Key-Value Stores

[a] 读写寄存器，也就是读写变量，虽然最初与计算机系统中的“寄存器”概念相关，但已慢慢解耦。

# My Researches

Hengfeng Wei, Marzio De Biasi, Yu Huang, Jiannong Cao, and Jian Lu. "Verifying Pipelined-RAM consistency over read/write traces of data replicas". In: *IEEE Trans. Parallel Distrib. Syst. (**TPDS'2016**)* 27.5 (May 2016), pp. 1511–1523. DOI: `10.1109/TPDS.2015.2453985`

Hengfeng Wei, Yu Huang, and Jian Lu. "Probabilistically-Atomic 2-Atomicity: enabling almost strong consistency in distributed storage systems". In: *IEEE Trans. Comput. (**TC'2017**)* 66.3 (Mar. 2017), pp. 502–514. DOI: `10.1109/TC.2016.2601322`

Kaile Huang, Yu Huang, and Hengfeng Wei. "Fine-Grained Analysis on Fast Implementations of Distributed Multi-Writer Atomic Registers". In: *Proceedings of the 39th Symposium on Principles of Distributed Computing (**PODC'2020**)*. Association for Computing Machinery, 2020, pp. 200–209. DOI: `10.1145/3382734.3405698`

# My Researches (II)

Replicated Data Types[b] ($\geq$ 2017)

(a) Google Docs

(b) Apache Wave

(c) Wikipedia

(d) LaTeX Editor

[b] 复制数据类型，是经典数据类型的分布式版本，如列表，集合，队列等。

# My Researches (II)

Hengfeng Wei, Yu Huang, and Jian Lu. "Brief Announcement: Specification and Implementation of Replicated List: The Jupiter Protocol Revisited". In: *Proceedings of the 2018 ACM Symposium on Principles of Distributed Computing*. PODC '18. ACM, 2018, pp. 81–83

Hengfeng Wei, Yu Huang, and Jian Lu. "Specification and Implementation of Replicated List: The Jupiter Protocol Revisited". In: *22nd International Conference on Principles of Distributed Systems, OPODIS 2018*. 2018, 12:1–12:16

Xue Jiang, Hengfeng Wei*, and Yu Huang. "A Generic Specification Framework for Weakly Consistent Replicated Data Types". In: *International Symposium on Reliable Distributed Systems (**SRDS'2020**)*. 2020, pp. 143–154. DOI: 10.1109/SRDS51746.2020.00022

Ye Ji, Hengfeng Wei*, Yu Huang, and Jian Lu. "Specifying and verifying CRDT protocols using TLA$^+$". In: *Journal of Software (**软件学报 JOS'2020**)* 31.5 (2020), pp. 1332–1352. DOI: 10.13328/j.cnki.jos.005956

# My Researches (III)

Distributed Transactions[c] ($\geq$ 2020)

[c] 分布式事务。每个事务由一组操作构成，这些操作要么全成功，要么全不成功。

# My Researches (III)

Manuel Bravo, Alexey Gotsman, Borja de Régil, and Hengfeng Wei. "UniStore: A fault-tolerant marriage of causal and strong consistency". In: *2021 USENIX Annual Technical Conference (**USENIX ATC'2021**)*. USENIX Association, July 2021, pp. 923–937

# Overview of the Work on UNISTORE

**UNISTORE: A fault-tolerant marriage of causal and strong consistency**

Manuel Bravo    Alexey Gotsman    Borja de Régil
*IMDEA Software Institute*

Hengfeng Wei *
*Nanjing University*

ATC'2021 (CCF A)

UNISTORE is the first fault-tolerant and scalable transactional data store that combines causal and strong consistency.

# Overview of the Work on UniStore

*Partial Order-Restrictions Consistency (PoR consistency)*

CC < PoR < SER

CC: CausalConsistency; SER: Serializability

Key Challenges (I): Ensure liveness in presence of faults

Key Challenges (II): Provide rigorous correctness proof

# Overview of the Work on UniStore

**UniStore: A fault-tolerant marriage of causal and strong consistency**

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ATC'2021 (CCF A)

I am fully responsible for the rigorous correctness proof:

- Finished a proof of 20 pages contained in the arXiv version
- Identified several nontrivial bugs in the early versions of the protocol[d]

[d] One of these bugs also exists in the well-known Granola protocol proposed by James Cowling and Barbara Liskov, something that had gone unnoticed for 10 years.

# What is UniStore?

UniStore is a fast, scalable, and fault-tolerant

transactional distributed key-value store

that supports a combination of weak and strong consistency.

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that supports a combination of weak and strong consistency.

Weak consistency: CausalConsistency

Strong consistency: Serializability

# CausalConsistency and Serializability

# Why Uni-?

Weak consistency: low latency, high availability


Strong consistency: easy to preserve critical application invariants

# Why Uni-?

DEPOSIT WITHDRAW QUERY INTEREST


Invariant: $\mathsf{balance} \geq 0$

# Why UNI-?

DEPOSIT WITHDRAW QUERY INTEREST


Invariant: balance $\geq 0$

Causal consistency allows two concurrent WITHDRAW to execute without knowing each other.

# Why Uni-?

DEPOSIT WITHDRAW QUERY INTEREST


Invariant: $\textsf{balance} \geq 0$

Causal consistency allows two concurrent WITHDRAW to execute without knowing each other.

Only WITHDRAW needs to use strong consistency.

# Consistency Model of UniStore

UniStore implements a transactional variant of
Partial Order-Restrictions (PoR) consistency

(Li@OSDI'2012, Li@ACT'2018)

(I) transactional causal consistency by default

(II) to specify conflicting transactions under strong consistency

# Consistency Model of UniStore

**Definition (Session Order)**

A transaction $t_1$ precedes a transaction $t_2$ in the session order, denoted $t_1 \xrightarrow{so} t_2$, if they are executed by the same client and $t_1$ is executed before $t_2$.

**Definition (Conflict Relation)**

The conflict relation, denoted $\bowtie$, between transactions is a symmetric relation.

$$t_1 \bowtie t_2 \iff t_2 \bowtie t_1.$$

# Consistency Model of UniStore

**Definition (PoR)**

A set of transactions $T \triangleq T_{causal} \uplus T_{strong}$ committed by UniStore satisfies PoR if there exists a causal order $\prec$ on $T$ such that

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Causality: '$\prec$' is a partial order and $so \subseteq \prec$.

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EventualVisibility: A transaction $t \in T$ that is either strong or originates at a correct data center eventually become visible at all correct data centers: from some point on, $t$ precedes in $\prec$ all transactions issued at correct data centers.

## Consistency Model of UniStore

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RETVAL: INTRETVAL $\land$ EXTRETVAL

# Consistency Model of UniStore

Consider a read $r$ from key $k$ in a transaction $t$.

IntRetVal : read from the latest update on $k$ preceding $r$ in $t$

$$\textsc{RetVal} = \textsc{IntRetVal} \land \textsc{ExtRetVal}$$

ExtRetVal : read from the last update on $k$

of the latest transaction (in an order consistent with $\prec$) preceding $t$

# Consistency Model of UniStore

DEPOSIT WITHDRAW QUERY INTEREST


Invariant: $\mathsf{balance} \geq 0$

Declaring that strong transactions
including WITHDRAW on the same account conflict.

# Design Challenges of UniStore

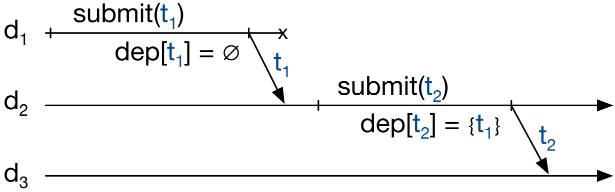
How to satisfy liveness (EventualVisibility) despite failures?


A transaction $t \in T$ that is either strong or originates at a correct data center eventually become visible at all correct data centers.

# Design Challenge of UniStore (I)

Data center $d_1$ crashes

before $t_1$ is replicated to correct data center $d_3$.



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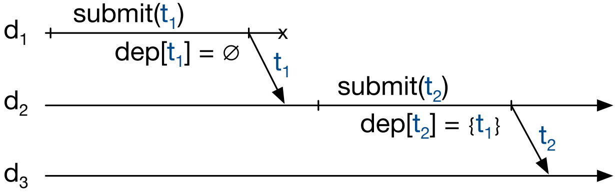


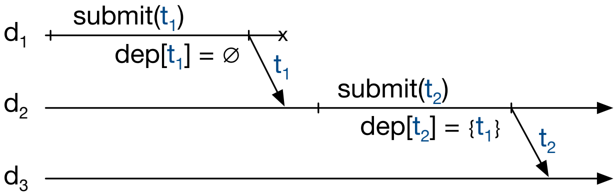

Transaction $t_2$ (at correct data center $d_2$)

may never become visible at correct data center $d_3$.

# Fault-tolerance of UniStore (I)

Data center $d_1$ crashes

before $t_1$ is replicated to correct data center $d_3$.



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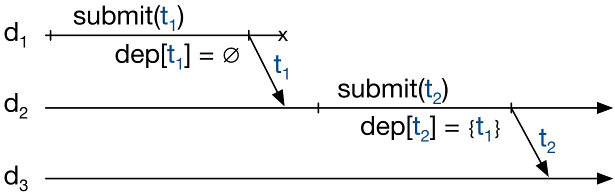


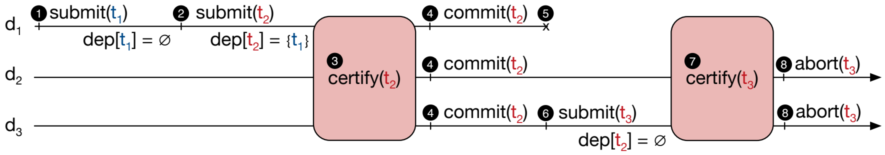

Data center $d_2$ need to forward causal transactions

to other data centers.

# Design Challenge of UniStore (II)

Data center $d_1$ crashes

before $t_1$ is replicated to correct data center $d_3$.



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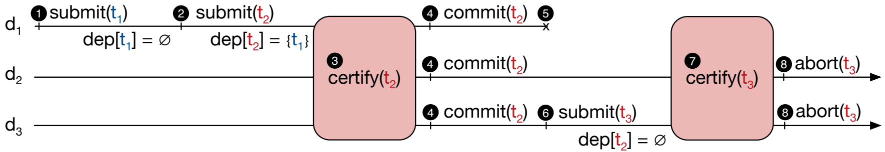
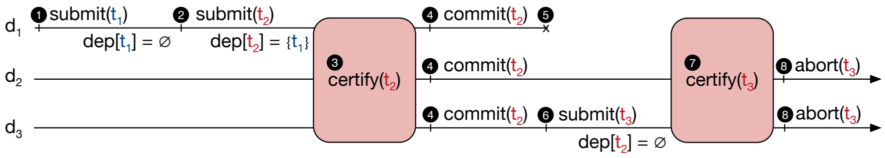



Transaction $t_2$ will never be visible at $d_3$.

No transaction $t_3$ conflicting with $t_2$ can commit (by ConflictOrdering).

# Fault-tolerance of UniStore (II)

UniStore ensures that before a strong transaction commits, all its causal dependencies are uniform, i.e., will eventually become visible at all correct data centers.



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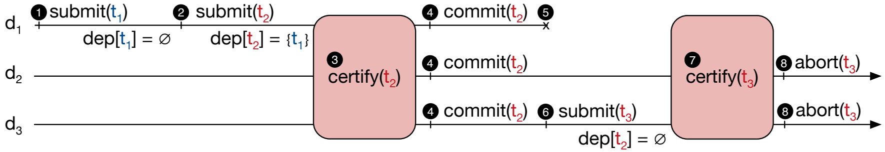


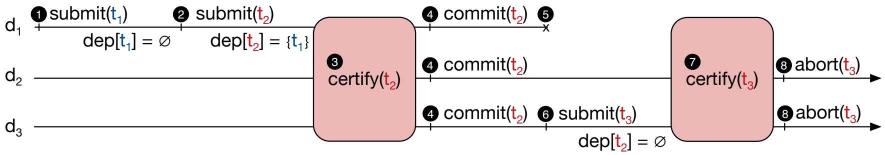

Transaction $t_1$ will eventually be visible at $d_3$.

Transaction $t_2$ will eventually be visible at $d_3$.

Transaction $t_3$ may be committed at $d_3$.

# Performance of UniStore

Causal transactions remain highly-available, i.e., committed locally.




A strong transaction may have to wait for some of its dependencies to become uniform before committing.

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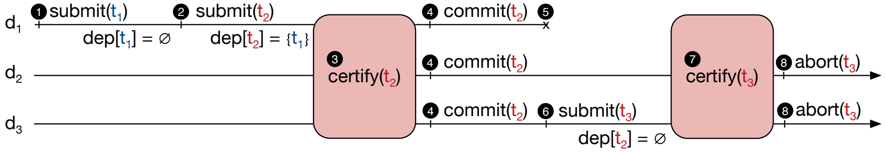


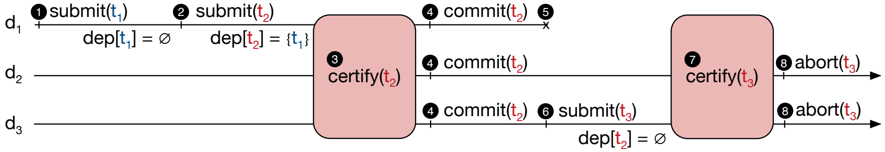

A strong transaction may have to wait for some of its dependencies to become uniform before committing.

However, this may cost too much.

# Performance of UniStore

UniStore makes a remote causal transaction visible to clients only after it is uniform.

Causal transactions are executed on an (almost) uniform snapshot that may be slightly in the past.



# Performance of UNISTORE

UNISTORE makes a remote causal transaction visible to clients only after it is uniform.

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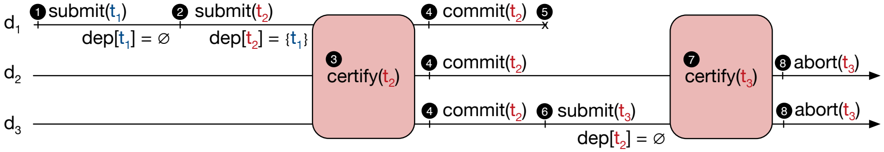



A strong transaction only needs to wait for causal transactions originating at the local data center to become uniform.

# Scalability of UniStore

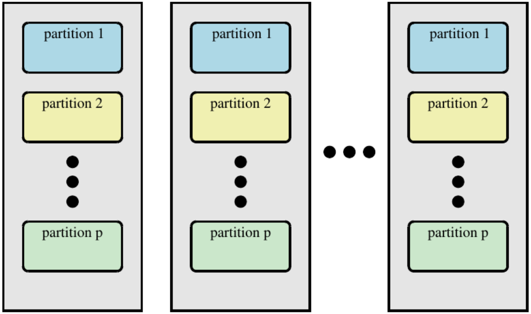
UniStore scales horizontally,

i.e., with the number of machines (partitions) in each data center.

# System Model

$$\mathcal{D} = \{1, \ldots, D\} : \text{the set of data centers}$$

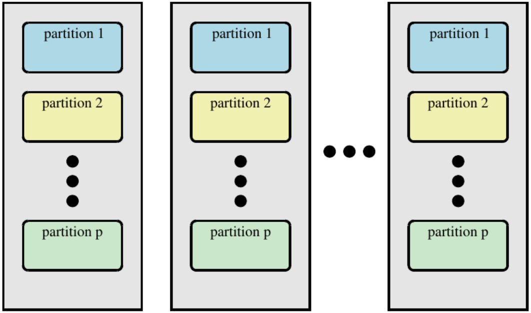
$$\mathcal{P} = \{1, \ldots, N\} : \text{the set of (logical) partitions}$$




$p_d^m$ : the replica of partition $m$ at data center $d$

# System Model

$D = 2f + 1$ and $\leq f$ data centers may fail




Any two replicas are connected by a reliable FIFO channel.

Messages between correct data centers will eventually be delivered.

# System Model

Replicas have loosely synchronized physical clocks.

The correctness of UNISTORE does *not* depend on the precision of clock synchronization.

Fault-tolerant Causal Consistency Protocol

# Requirement: Tracking Uniformity

UniStore makes a remote causal transaction visible to clients only after it is uniform.

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**Definition (Uniform)**

A transaction is uniform if both the transaction and its causal dependencies are guaranteed to be eventually replicated at all correct data centers.

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UniStore makes a remote causal transaction visible to clients only after it is uniform.

**Definition (Uniform)**

A transaction is uniform if both the transaction and its causal dependencies are guaranteed to be eventually replicated at all correct data centers.

A transaction is considered uniform once it is visible at $f+1$ data centers.

# Metadata for Causal Transactions

Each transaction is tagged with a commit vector $commitVec$.

$$commitVec \in [\mathcal{D} \to \mathbb{N}]$$

For a transaction originating at data center $d$,
we call $commitVec[d]$ its local timestamp.

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For a transaction originating at data center $d$,
we call $commitVec[d]$ its local timestamp.

Commit vectors are sent to sibling replicas
via replication and forwarding.

# Metadata for Causal Transactions

Each replica $p_d^m$ maintains the following three vectors:

$$\mathsf{knownVec} \in [\mathcal{D} \to \mathbb{N}]$$

$$\mathsf{stableVec} \in [\mathcal{D} \to \mathbb{N}]$$

$$\mathsf{uniformVec} \in [\mathcal{D} \to \mathbb{N}]$$

# Metadata for Causal Transactions

$$\mathsf{knownVec} \in [\mathcal{D} \to \mathbb{N}]$$

**Property (Property of knownVec)**

For each data center $i$,
the replica $p_d^m$ stores the updates to partition $m$
by transactions originating at $i$ with local timestamps $\leq \mathsf{knownVec}[i]$.

# Metadata for Causal Transactions

$$\mathsf{stableVec} \in [\mathcal{D} \to \mathbb{N}]$$

Property (Property of stableVec)

For each data center $i$,
the data center $d$ stores the updates
by transactions originating at $i$ with local timestamps $\leq \mathsf{stableVec}[i]$.

# Metadata for Causal Transactions

**function** BROADCAST_VECS()
    **send** $\boxed{\text{KNOWNVEC\_LOCAL}}(m, \mathsf{knownVec})$ **to** $p_d^l$, $l \in \mathscr{P}$
    **send** STABLEVEC$(d, \mathsf{stableVec})$ **to** $p_i^m$, $i \in \mathscr{D}$
    **send** KNOWNVEC_GLOBAL$(d, \mathsf{knownVec})$ **to** $p_i^m$, $i \in \mathscr{D}$

$$\mathsf{stableVec} \in [\mathcal{D} \to \mathbb{N}]$$

**when received** KNOWNVEC_LOCAL$(l, knownVec)$
    $\mathsf{localMatrix}[l] \leftarrow knownVec$
    **for** $i \in \mathscr{D}$ **do**
        $\boxed{\mathsf{stableVec}[i] \leftarrow \min\{\mathsf{localMatrix}[n][i] \mid n \in \mathscr{P}\}}$
    $\mathsf{stableVec}[strong] \leftarrow \min\{\mathsf{localMatrix}[n][strong] \mid n \in \mathscr{P}\}$

# Metadata for Causal Transactions

$$\mathsf{uniformVec} \in [\mathcal{D} \to \mathbb{N}]$$

**Property (Property of uniformVec)**

All update transactions originating at $i$
with local timestamps $\le \mathsf{uniformVec}[i]$
are replicated at $f + 1$ data centers including $d$.

# Metadata for Causal Transactions

**function** BROADCAST_VECS()
    **send** KNOWNVEC_LOCAL($m$, knownVec) **to** $p_d^l$, $l \in \mathscr{P}$
    **send** $\boxed{\text{STABLEVEC}}$($d$, stableVec) **to** $p_i^m$, $i \in \mathscr{D}$
    **send** KNOWNVEC_GLOBAL($d$, knownVec) **to** $p_i^m$, $i \in \mathscr{D}$

$$\mathsf{uniformVec} \in [\mathcal{D} \to \mathbb{N}]$$

**when received** STABLEVEC($i$, *stableVec*)
    stableMatrix[$i$] $\leftarrow$ *stableVec*
    $G \leftarrow$ all groups with $\boxed{f+1}$ replicas that include $p_d^m$
    **for** $j \in \mathscr{D}$ **do**
        **var** $ts \leftarrow \max\{\boxed{\min\{\mathsf{stableMatrix}[h][j] \mid h \in g\}} \mid g \in G\}$
        uniformVec[$j$] $\leftarrow \max\{\mathsf{uniformVec}[j], ts\}$

# Metadata for Causal Transactions

$$\mathsf{uniformVec} \in [\mathcal{D} \to \mathbb{N}]$$

**Lemma**

*All update transactions*
*with commit vectors* $\le$ $\mathsf{uniformVec}$ *are uniform.*

# Metadata for Causal Transactions

$$\mathsf{uniformVec} \in [\mathcal{D} \to \mathbb{N}]$$

**Lemma**

*All update transactions*
*with commit vectors* $\leq \mathsf{uniformVec}$ *are uniform.*

UniStore makes a remote causal transaction visible to clients only after it is uniform.

# Causal Consistency Protocol: Start

$\mathsf{pastVec}$ : causal past of client

1: **function** $\boxed{\text{START}()}$
2: p ← a random partition in data center *d*
3: ⟨tid, *snapVec*⟩ ← **send** START_TX(pastVec) **to** p
4: pastVec ← *snapVec*
5: **return** tid

$\forall i \in \mathcal{D} \setminus \{d\}$, all transactions originating at $i$

with local timestamps $\le \mathsf{pastVec}[i]$ are already uniform.

# Causal Consistency Protocol: Start

Causal transactions are executed on an (almost) uniform snapshot.

```
function START_TX(V)
    for i ∈ 𝒟 \ {d} do
        uniformVec[i] ← max{V[i], uniformVec[i]}
    var tid ← generate_tid()
    snapVec[tid] ← uniformVec
    snapVec[tid][d] ← max{V[d], uniformVec[d]}
    snapVec[tid][strong] ← max{V[strong], stableVec[strong]}
    return ⟨tid, snapVec[tid]⟩
```

snapVec$[tid][d]$ ensures "read-your-writes".

# Causal Consistency Protocol: Update

**function** $\boxed{\text{UPDATE}(k, v)}$
    $\_ \leftarrow$ **send** DO_UPDATE$(\mathsf{tid}, k, v)$ **to** p
    **return** ok

**function** $\boxed{\text{DO\_UPDATE}(tid, k, v)}$
    **var** $l \leftarrow \mathsf{partition}(k)$
    $\boxed{\mathsf{wbuff}[tid][l][k] \leftarrow v}$
    $\mathsf{rset}[tid][l] \leftarrow \mathsf{rset}[tid][l] \cup \{k\}$
    **return** ok

$\mathsf{wbuff}[tid][l]$ : buffer for the latest local update on each key

# Causal Consistency Protocol: Read

**function** READ($k$)
    $\langle v, c \rangle \leftarrow$ **send** DO_READ(tid, $k$, lc) **to** p
    **if** $c \neq \perp$ **then**
        lc $\leftarrow$ max{lc, $c$}
    **return** $v$

**function** DO_READ($tid, k, c$)
    lc $\leftarrow$ max{lc, $c$}
    **var** $l \leftarrow$ partition($k$)
    **if** wbuff[$tid$][$l$][$k$] $\neq \perp$ **then**
        **return** $\langle$wbuff[$tid$][$l$][$k$], $\perp\rangle$
    $\langle v, c \rangle \leftarrow$ **send** READ_KEY(snapVec[$tid$], $k$) **to** $p_d^l$
    rset[$tid$][$l$] $\leftarrow$ rset[$tid$][$l$] $\cup \{k\}$
    **return** $\langle v, c \rangle$

# Causal Consistency Protocol: Read

Causal transactions are executed on an (almost) uniform snapshot.

**when received** READ_KEY($snapVec, k$) **from** $p$
  **for** $i \in \mathscr{D} \setminus \{d\}$ **do**
    uniformVec$[i] \gets \max\{snapVec[i], \text{uniformVec}[i]\}$
  **wait until** knownVec$[d] \geq snapVec[d]$ $\land$ knownVec$[strong] \geq snapVec[strong]$
  $\langle v, commitVec, c \rangle \gets$ snapshot(opLog$[k]$, $snapVec$) ▷ returns the latest $commitVec$ (in terms of Lamport clock order in Definition 50) such that $commitVec \leq snapVec$
  **send** $\langle v, c \rangle$ **to** $p$

**wait** : ensure that it is as up-to-date as required by the snapshot

# Causal Consistency Protocol: Commit

```
function COMMIT_CAUSAL_TX()
    ⟨vc, c⟩ ← send COMMIT_CAUSAL(tid, lc) to p
    pastVec ← vc
    lc ← c
    return ok
```

# Causal Consistency Protocol: Commit

Read-only transactions returns immediately.

**function** $\boxed{\text{COMMIT\_CAUSAL}(tid, c)}$

    $\mathsf{lc} \leftarrow \mathsf{max}\{\mathsf{lc}, c\} + 1$

    **if** $\forall l \in \mathscr{P}.\ \mathsf{wbuff}[tid][l] = \emptyset$ **then**

        **return** $\langle \mathsf{snapVec}[tid], \mathsf{lc} \rangle$

    **var** $commitVec \leftarrow \mathsf{snapVec}[tid]$

    **send** $\boxed{\text{PREPARE}}(tid, \mathsf{wbuff}[tid][l], \mathsf{snapVec}[tid])$ **to** $p_d^l$, $l \in \mathscr{P}$

    **for all** $l \in \mathscr{P}$ **do**

        $\boxed{\textbf{wait receive}\ \text{PREPARE\_ACK}}(tid, ts)$ **from** $p_d^l$

        $commitVec[d] \leftarrow \mathsf{max}\{commitVec[d], ts\}$

    **send** $\boxed{\text{COMMIT}}(tid, commitVec, \mathsf{lc})$ **to** $p_d^l$, $l \in \mathscr{P}$

    **return** $\langle commitVec, \mathsf{lc} \rangle$

2PC protocol for update transactions

# Causal Consistency Protocol: Commit

$ts$ : prepare timestamp from its local clock

**when received** PREPARE$(tid, wbuff, snapVec)$ **from** $p$
    **for** $i \in \mathscr{D} \setminus \{d\}$ **do**
        $\mathsf{uniformVec}[i] \leftarrow \max\{snapVec[i], \mathsf{uniformVec}[i]\}$
    **var** $\boxed{ts \leftarrow \mathsf{clock}}$
    $\mathsf{preparedCausal} \leftarrow \mathsf{preparedCausal} \cup \{\langle tid, wbuff, ts\rangle\}$
    **send** PREPARE_ACK$(tid, ts)$ **to** $p$

# Causal Consistency Protocol: Commit

**wait** : ensure that its local clock is up-to-date

**when received** COMMIT$(tid, commitVec, c)$

  $\boxed{\textbf{wait until } \mathsf{clock} \geq commitVec[d]}$

  $\langle tid, wbuff, \_\rangle \leftarrow \mathsf{find}(tid, \mathsf{preparedCausal})$

  $\boxed{\mathsf{preparedCausal}} \leftarrow \mathsf{preparedCausal} \setminus \{\langle tid, \_, \_\rangle\}$

  **for all** $\langle k, v\rangle \in wbuff$ **do**

    $\mathsf{opLog}[k] \leftarrow \mathsf{opLog}[k] \cdot \langle v, commitVec, c\rangle$

  $\boxed{\mathsf{committedCausal}[d]} \leftarrow \mathsf{committedCausal}[d] \cup \{\langle tid, wbuff, commitVec, c\rangle\}$

$\mathsf{committedCausal}[d]$ : for replication

# Causal Consistency Protocol: Replication

**Property (Property of knownVec)**

For each data center $i$,

the replica $p_d^m$ stores the updates to partition $m$

by transactions originating at $i$ with local timestamps $\leq \mathsf{knownVec}[i]$.

**function** PROPAGATE_LOCAL_TXS()
  **if** $\mathsf{preparedCausal} = \emptyset$ **then**
    $\boxed{\mathsf{knownVec}[d] \leftarrow \mathsf{clock}}$
  **else**
    $\boxed{\mathsf{knownVec}[d] \leftarrow \min\{ts \mid \langle \_, \_, ts \rangle \in \mathsf{preparedCausal}\} - 1}$
  **var** $txs \leftarrow \{\langle \_, \_, commitVec, c \rangle \in \mathsf{committedCausal}[d] \mid commitVec[d] \leq \mathsf{knownVec}[d]\}$
  **if** $txs \neq \emptyset$ **then**
    **send** $\boxed{\text{REPLICATE}(d, txs)}$ **to** $p_i^m, i \in \mathscr{D} \setminus \{d\}$
    $\mathsf{committedCausal}[d] \leftarrow \mathsf{committedCausal}[d] \setminus txs$
  **else**
    **send** $\boxed{\text{HEARTBEAT}(d, \mathsf{knownVec}[d])}$ **to** $p_i^m, i \in \mathscr{D} \setminus \{d\}$

HEARTBEAT : for liveness

Adding Strong Transactions

# Requirement: ConflictOrdering

$$\forall t_1, t_2 \in T_{strong}.\ t_1 \bowtie t_2 \implies t_1 \prec t_2 \lor t_2 \prec t_1.$$

Each strong transaction is assigned a scalar strong timestamp.

$$\mathit{commitVec} \in [\mathcal{D} \cup \{\mathit{strong}\} \to \mathbb{N}]$$

# Metadata for Strong Transactions

$$\mathsf{knownVec} \in [\mathcal{D} \cup \{strong\} \to \mathbb{N}]$$

Property (Property of $\mathsf{knownVec}[strong]$)

Replica $p_d^m$ stores the updates to $m$ by all strong transactions with $commitVec[strong] \le \mathsf{knownVec}[strong]$.

# Metadata for Strong Transactions

$$\mathsf{stableVec} \in [\mathcal{D} \cup \{strong\} \to \mathbb{N}]$$

5: **when received** KNOWNVEC_LOCAL($l, knownVec$)
6: $\quad$ $\mathsf{localMatrix}[l] \leftarrow knownVec$
7: $\quad$ **for** $i \in \mathscr{D}$ **do**
8: $\quad\quad$ $\mathsf{stableVec}[i] \leftarrow \min\{\mathsf{localMatrix}[n][i] \mid n \in \mathscr{P}\}$
9: $\quad$ $\mathsf{stableVec}[strong] \leftarrow \min\{\mathsf{localMatrix}[n][strong] \mid n \in \mathscr{P}\}$

**Property (Property of $\mathsf{stableVec}[strong]$)**

Data center $d$ stores the updates by all strong transactions with $commitVec[strong] \leq \mathsf{knownVec}[strong]$.

# Metadata for Strong Transactions

$$\mathsf{uniformVec} \in [\mathcal{D} \to \mathbb{N}]$$

**when received** STABLEVEC($i$, $stableVec$)
    $\mathsf{stableMatrix}[i] \leftarrow stableVec$
    $G \leftarrow$ all groups with $f+1$ replicas that include $p_d^m$
    **for** $j \in \mathscr{D}$ **do**
        **var** $ts \leftarrow \max\{\min\{\mathsf{stableMatrix}[h][j] \mid h \in g\} \mid g \in G\}$
        $\mathsf{uniformVec}[j] \leftarrow \max\{\mathsf{uniformVec}[j], ts\}$

The commit protocol for strong transactions guarantees their uniformity.

# Strong Consistency Protocol: Commit

**function** COMMIT_STRONG($tid$, $c$)
    $\boxed{\text{UNIFORM\_BARRIER}(\text{snapVec}[tid])}$
    $\langle d, vc, c \rangle \leftarrow \boxed{\text{CERTIFY}}(tid, \text{wbuff}[tid], \text{rset}[tid], \text{snapVec}[tid], c)$
    $\text{lc} \leftarrow \max\{\text{lc}, c\} + 1$
    **return** $\langle d, vc, \text{lc} \rangle$

A strong transaction only needs to wait for causal transactions originating at the local data center to become uniform.

**function** UNIFORM_BARRIER($V$, $c$)
    $\text{lc} \leftarrow \max\{\text{lc}, c\} + 1$
    **wait until** $\boxed{\text{uniformVec}[d] \geq V[d]}$
    **return** lc

# Strong Consistency Protocol: Commit

**function** COMMIT_STRONG($tid$, $c$)

$\boxed{\text{UNIFORM\_BARRIER}(\mathsf{snapVec}[tid])}$

$\langle d, vc, c \rangle \leftarrow \boxed{\text{CERTIFY}}(tid, \mathsf{wbuff}[tid], \mathsf{rset}[tid], \mathsf{snapVec}[tid], c)$

$\mathsf{lc} \leftarrow \max\{\mathsf{lc}, c\} + 1$

**return** $\langle d, vc, \mathsf{lc} \rangle$

$$\langle d \in \{\text{COMMIT}, \text{ABORT}\}, vc \rangle \leftarrow \text{CERTIFY}(t)$$

# Strong Consistency Protocol: Commit

**function** COMMIT_STRONG($tid, c$)
  $\boxed{\text{UNIFORM\_BARRIER}(\mathsf{snapVec}[tid])}$
  $\langle d, vc, c\rangle \leftarrow \boxed{\text{CERTIFY}}(tid, \mathsf{wbuff}[tid], \mathsf{rset}[tid], \mathsf{snapVec}[tid], c)$
  $\mathsf{lc} \leftarrow \max\{\mathsf{lc}, c\} + 1$
  **return** $\langle d, vc, \mathsf{lc}\rangle$

$$\langle d \in \{\text{COMMIT}, \text{ABORT}\}, vc\rangle \leftarrow \text{CERTIFY}(t)$$

**Multi-Shot Distributed Transaction Commit**


**Gregory Chockler**
Royal Holloway, University of London, UK

**Alexey Gotsman**[1]
IMDEA Software Institute, Madrid, Spain


## White-Box Atomic Multicast


Alexey Gotsman, IMDEA Software Institute
Anatole Lefort, Télécom SudParis
Gregory Chockler, Royal Holloway, University of London


2PC across partitions + Paxos among replicas of each partition

uses white-box optimizations that minimize the commit latency

# Strong Consistency Protocol: Deliver

**upon** DELIVER_UPDATES($W$)

  **for** $\langle k, v, commitVec, c \rangle \in W$ in $\boxed{commitVec[strong] \text{ order}}$ **do**

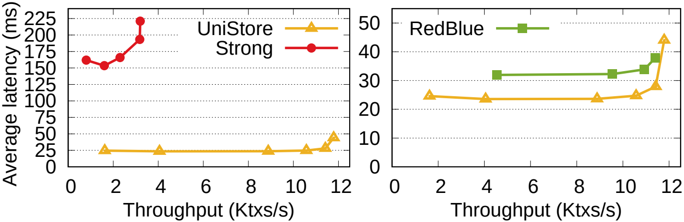
    $\mathsf{opLog}[k] \leftarrow \mathsf{opLog}[k] \cdot \langle v, commitVec, c \rangle$

    $\mathsf{knownVec}[strong] \leftarrow commitVec[strong]$

# Evaluation

# Performance of UniStore

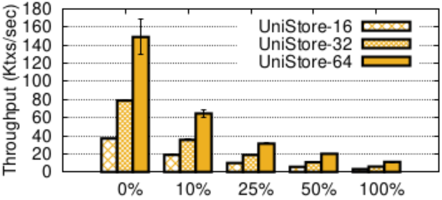
Throughput: 5% and 259% higher than RedBlue and Strong




RUBiS benchmark: throughput vs. average latency.

Latency: 24ms vs. 32ms of RedBlue and 162ms of Strong

# Scalability of UniStore




Scalability when varying the ratio of strong transactions.

UniStore is able to scales almost linearly.

# Evaluation

For more evaluations, please refer to the paper.

# Conclusion

UniStore is a fast, scalable, and fault-tolerant

transactional distributed key-value store

that supports a combination of weak and strong consistency.

# Conclusion

UNISTORE is a fast, scalable, and fault-tolerant

transactional distributed key-value store

that supports a combination of weak and strong consistency.

"We expect the key ideas in UNISTORE to pave the way
for practical systems that combine causal and strong consistency."


Hengfeng Wei (hfwei@nju.edu.cn)

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