

Consistency in Transactional Distributed Databases: Protocols and Testing

Hengfeng Wei (魏恒峰)

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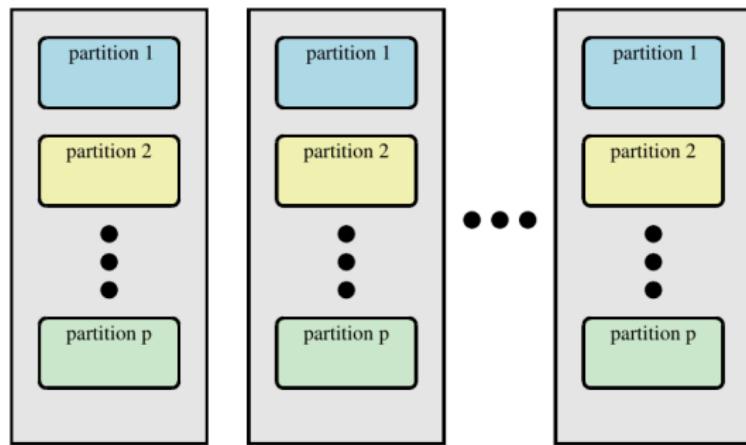
Background

Centralized Databases *vs.* Distributed Databases



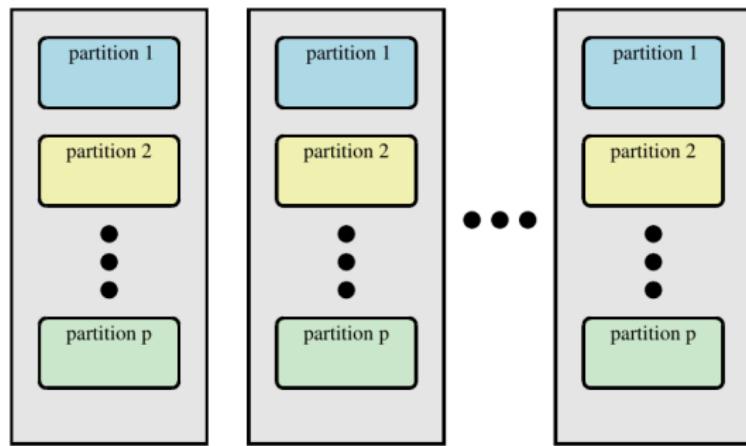
Data Consistency Problem

The Classic “Data Partition + Data Replication” Architecture



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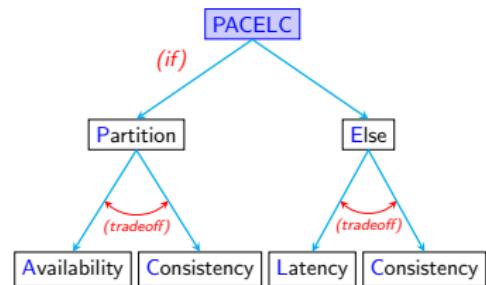
(Distributed) Data Consistency Problem

Data Consistency Problem

(Strong) Consistency, Availability, Latency, Partition tolerance



CAP Theorem
(Brewer@PODC2000)



PACELC Tradeoff
(Abadi@Computer2012)

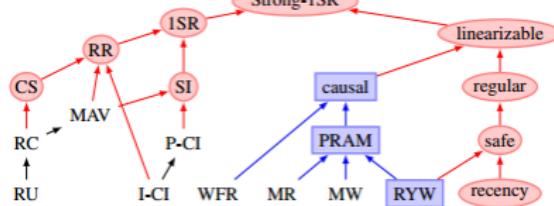
Data Consistency Problem



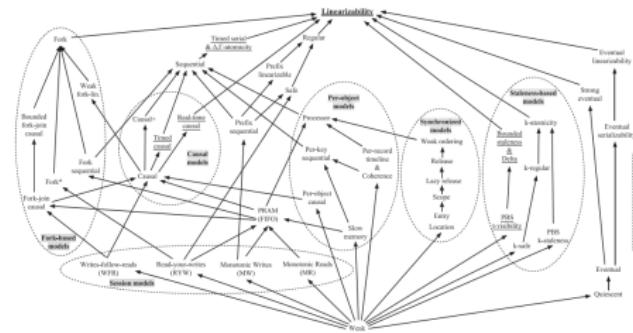
没有一劳永逸的解决方案

Consistency Models

Use various **consistency models** to capture these tradeoffs



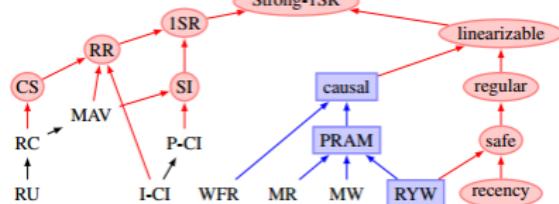
(Bailis@VLDB2012)



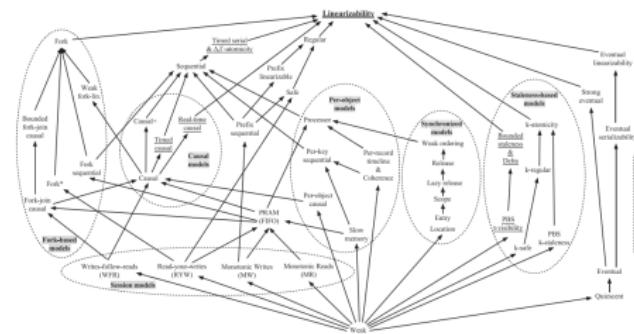
(Viotti@CSUR2016)

Consistency Models

Use various **consistency models** to capture these tradeoffs



(Bailis@VLDB2012)



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My Researches

On the data consistency theory around consistency models:

My Researches

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Computability: What is possible or impossible?

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How to prove its correctness?

My Researches

On the data consistency theory around consistency models:

Computability: What is possible or impossible?

Specification: How to define consistency models?

Protocol: How to design a “good” protocol?

How to prove its correctness?

Testing: What is the complexity of testing a consistency model?

How to design efficient testing algorithms?

My Researches (I)

On non-transactional key-value stores (\geq 2014)



My Researches (I)

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](https://doi.org/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](https://doi.org/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](https://doi.org/10.1145/3382734.3405698)

My Researches (II)

On replicated data types^a (≥ 2017)



(a) Google Docs



(b) Apache Wave



(c) Wikipedia



(d) L^TE_X Editor

^a 复制数据类型，是经典数据结构的分布式版本，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](https://doi.org/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](https://doi.org/10.13328/j.cnki.jos.005956)

My Researches (III)

On distributed transactions^b (≥ 2020)



^b分布式事务。每个事务由一组操作构成，这些操作要么都成功，要么都失败。

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

IMDEA Software Institute

Borja de Régil

Hengfeng Wei *

Nanjing University

USENIX ATC'2021

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

Overview of the Work on UNISTORE

Challenges (I): To ensure **liveness** of the system in the presence of data center failures

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Challenges (I): To ensure **liveness** of the system in the presence of data center failures

Challenges (II): To provide a rigorous correctness **proof** of the protocol which is rather complicated

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ATC'2021 (CCF A)

I am fully responsible for developing a 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^c, and proposed solutions to fix them

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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.

Why UNI-?

Weak Consistency:

Strong Consistency:

Why UNI-?

Weak Consistency: low latency, high availability,
but hard to preserve application invariants

Strong Consistency:

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Strong Consistency: easy to preserve application invariants,
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The UNI- Approach

Partial Order-Restrictions (PoR) Consistency
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The UNI- Approach

Partial Order-Restrictions (PoR) Consistency (Li@OSDI'2012, Li@ACT'2018)

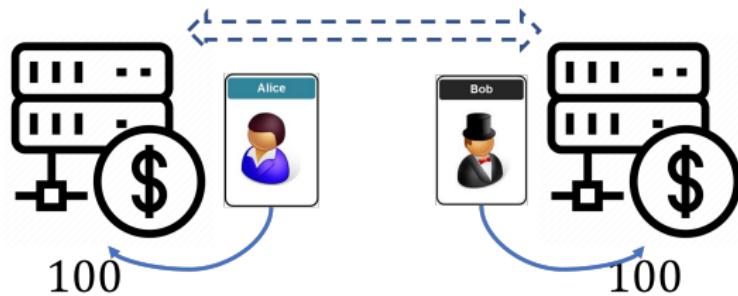
- ▶ PoR allows programmers to classify transactions as either causal or strong.
- ▶ Causal transactions satisfy CAUSALCONSISTENCY:
 - ▶ Clients see updates in an order that respects the potential causality between them.
 - ▶ Causally independent transactions can be executed concurrently.

The UNI- Approach

Partial Order-Restrictions (PoR) Consistency (Li@OSDI'2012, Li@ACT'2018)

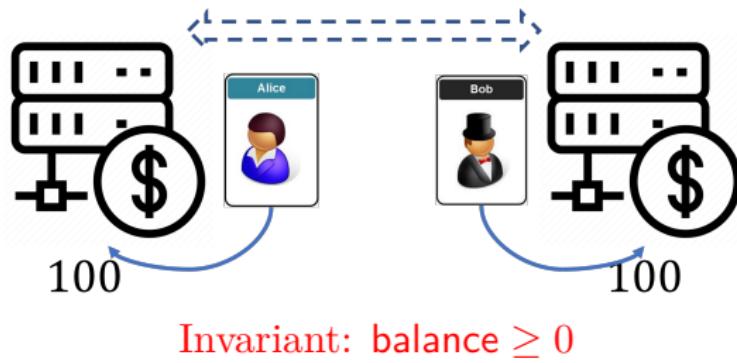
- ▶ PoR allows programmers to classify transactions as either **causal** or **strong**.
- ▶ **Causal** transactions satisfy **CAUSALCONSISTENCY**:
 - ▶ Clients see updates in an order that respects the **potential causality** between them.
 - ▶ **Causally independent** transactions can be executed concurrently.
- ▶ Programmers use **strong** transactions to enforce orders between some conflicting causally independent transactions.
 - ▶ Either t is visible to t' or t' is visible to t .

A Banking Application



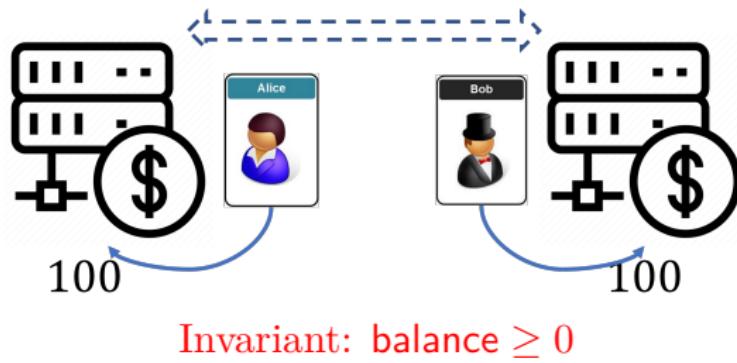
Invariant: $\text{balance} \geq 0$

A Banking Application



DEPOSIT operations can be executed under **CAUSALCONSISTENCY**: locally commit first, then synchronize the updates asynchronously

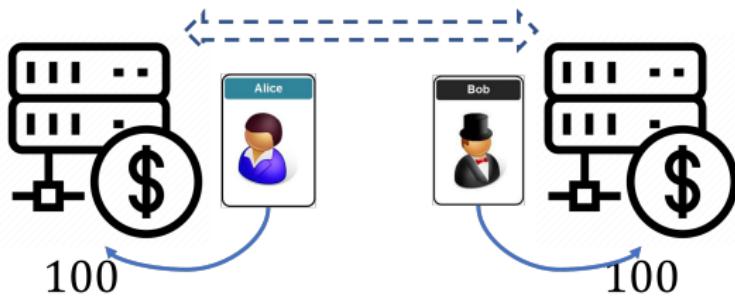
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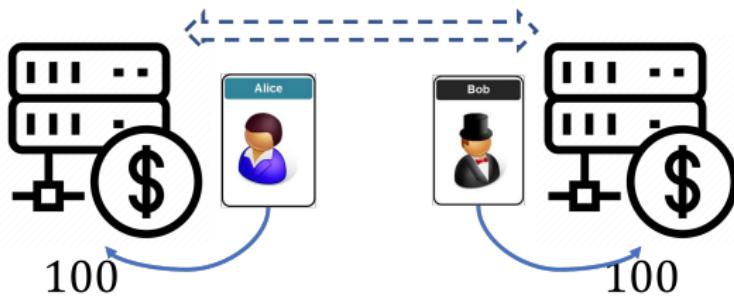
DEPOSIT(50)

A Banking Application



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

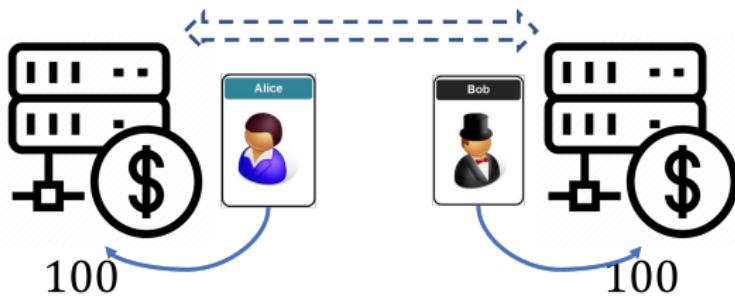
A Banking Application



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

However, CAUSALCONSISTENCY also allows two causally independent **WITHDRAW** to execute concurrently, without knowing each other.

A Banking Application

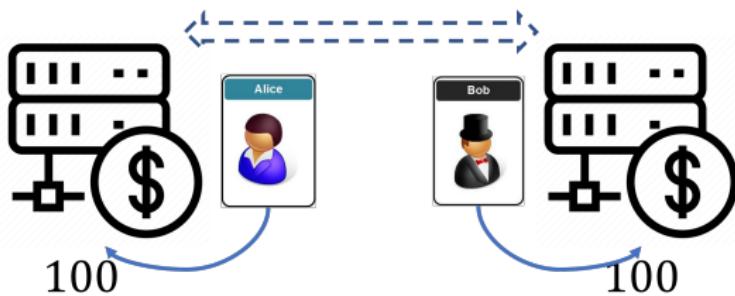


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WITHDRAW(60) produces $-20 < 0$

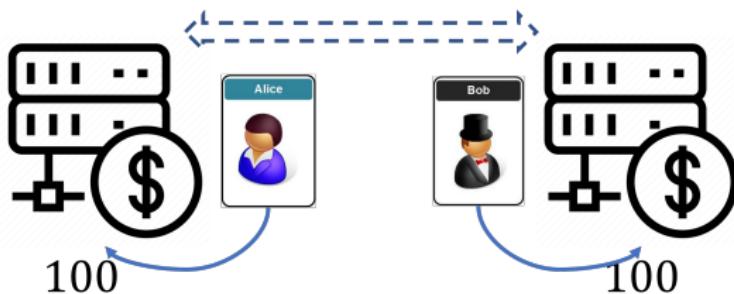
A Banking Application



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

Only **WITHDRAW** on the same account are marked **strong**.

A Banking Application



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

Only **WITHDRAW** on the same account are marked **strong**.

One of **WITHDRAW(60)** aborts.

Related Work

non-transactional

Hagit Attiya and Roy Friedman. “A Correctness Condition for High-Performance Multiprocessors”. In: *SIAM Journal on Computing* 27.6 (1998), pp. 1637–1670

Hagit Attiya, Soma Chaudhuri, Roy Friedman, and Jennifer L. Welch. “Shared Memory Consistency Conditions for Nonsequential Execution: Definitions and Programming Strategies”. In: *SIAM Journal on Computing* 27.1 (1998), pp. 65–89



Related Work

not fault-tolerant

Valter Balegas, Sérgio Duarte, Carla Ferreira, Rodrigo Rodrigues, Nuno Preguiça, Mahsa Najafzadeh, and Marc Shapiro. “Putting Consistency Back into Eventual Consistency”. In: *Proceedings of the Tenth European Conference on Computer Systems*. EuroSys ’15. 2015

Cheng Li, Daniel Porto, Allen Clement, Johannes Gehrke, Nuno Preguiça, and Rodrigo Rodrigues. “Making Geo-replicated Systems Fast As Possible, Consistent when Necessary”. In: *Proceedings of the 10th USENIX Conference on Operating Systems Design and Implementation*. OSDI ’12. 2012, pp. 265–278

Cheng Li, Nuno Preguiça, and Rodrigo Rodrigues. “Fine-Grained Consistency for Geo-Replicated Systems”. In: *Proceedings of the 2018 USENIX Conference on Usenix Annual Technical Conference*. USENIX ATC ’18. 2018, pp. 359–371

Liveness of UNISTORE



Liveness of UNISTORE

How to ensure **liveness** despite data center failures?



Live ness of UNISTORE

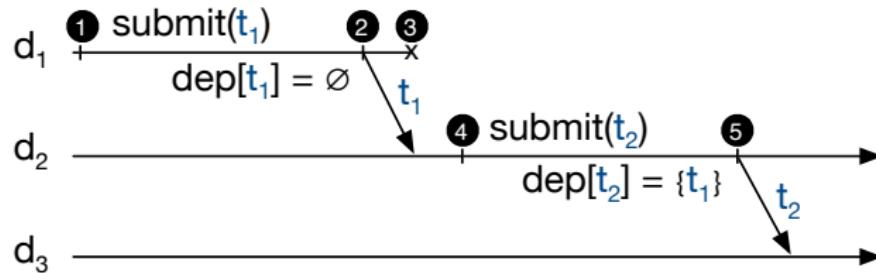
How to ensure **liveness** despite data center failures?



A transaction that is either **strong** or **originates at a correct data center** eventually become **visible** at all correct data centers.

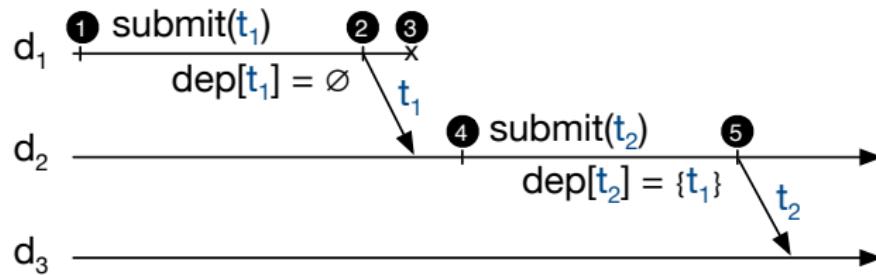
Liveness of Causal Transactions

d_1 crashes before t_1 is replicated to d_3 .



Liveness of Causal Transactions

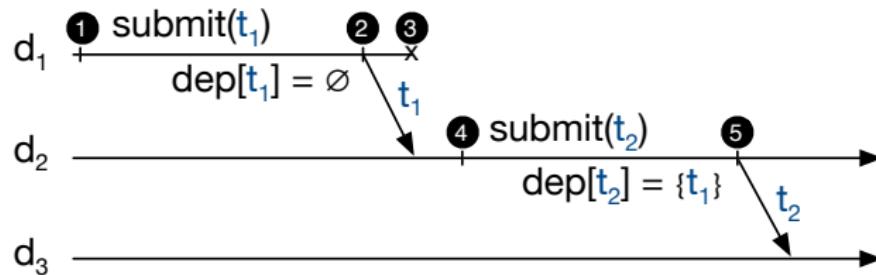
d_1 crashes before t_1 is replicated to d_3 .



Transaction t_2 may never become visible at d_3 .

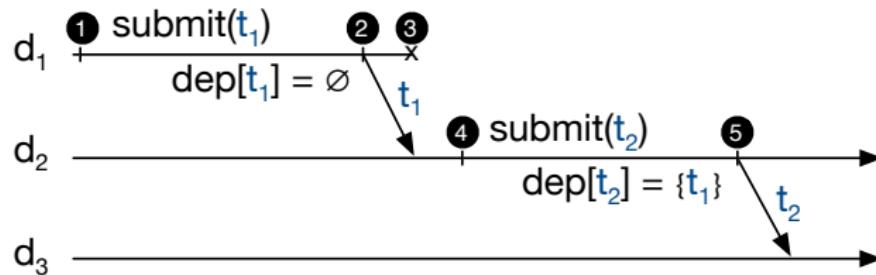
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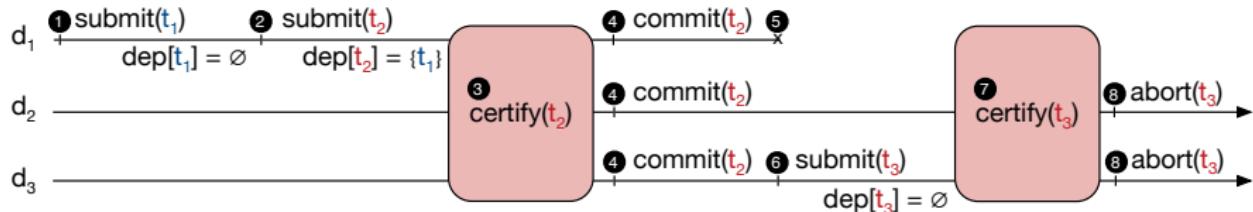
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d_2 need to **forward** causal transactions to other data centers.

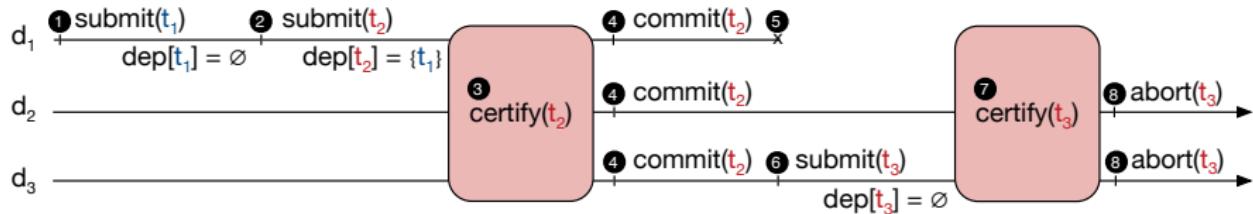
Liveness of Strong Transactions

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Liveness of Strong Transactions

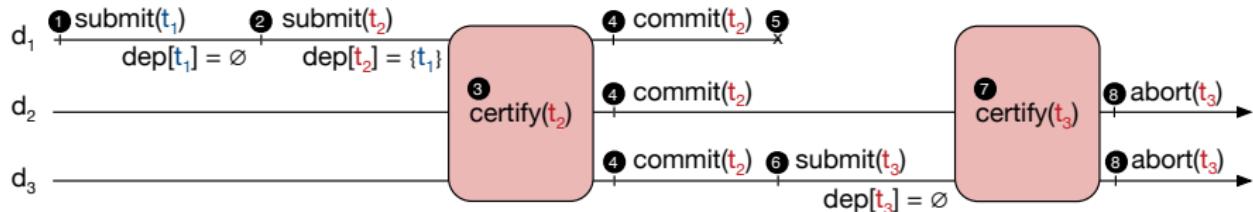
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Liveness of Strong Transactions

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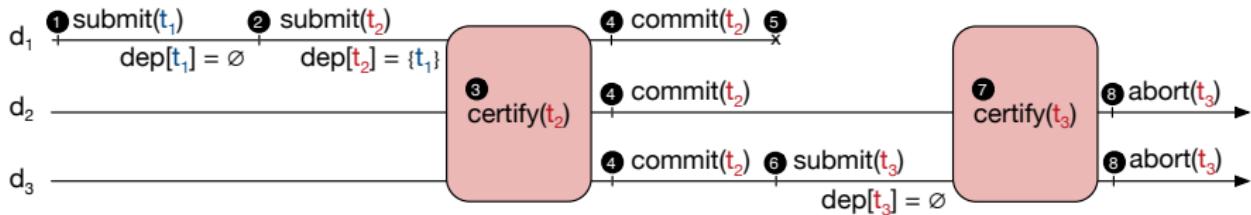


t_2 will never be visible at d_3 .

No transaction t_3 conflicting with t_2 can commit.

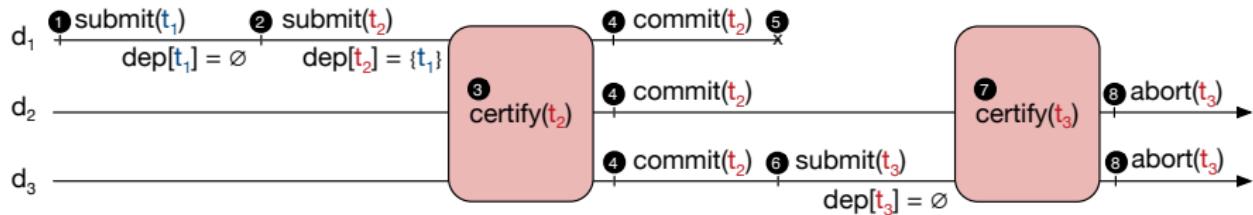
Liveness of Strong Transactions

A **strong** transaction should wait for all its **causal dependencies** to become **uniform** before committing.
(eventually become visible at all correct data centers)



Liveness of Strong Transactions

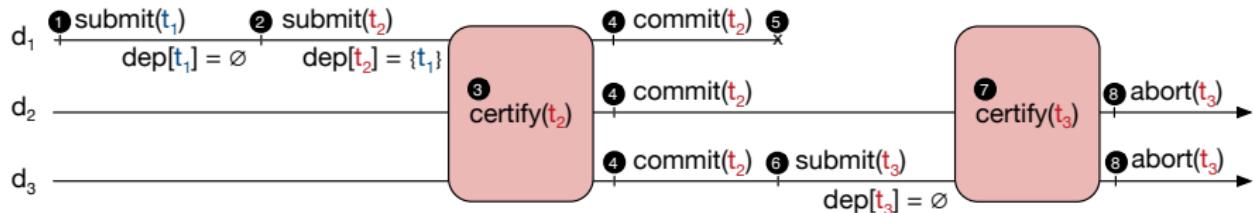
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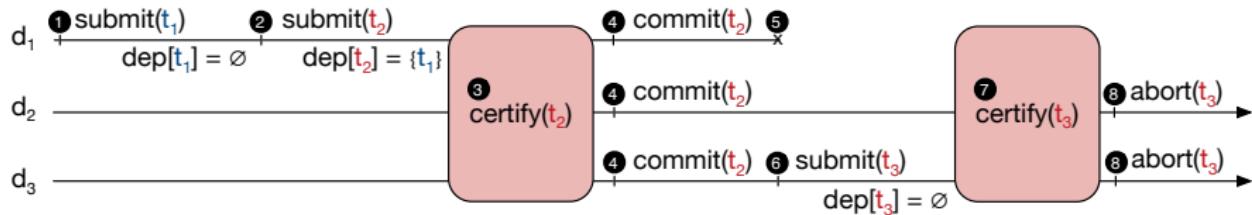


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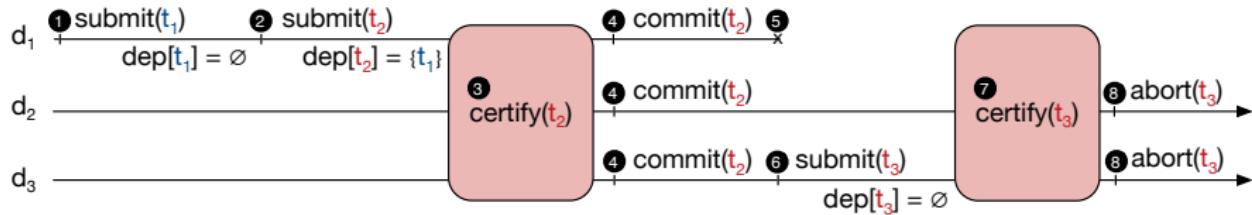
t_1 will eventually be visible at d_3 .

t_2 will eventually be visible at d_3 .

t_3 may be committed at d_3 .

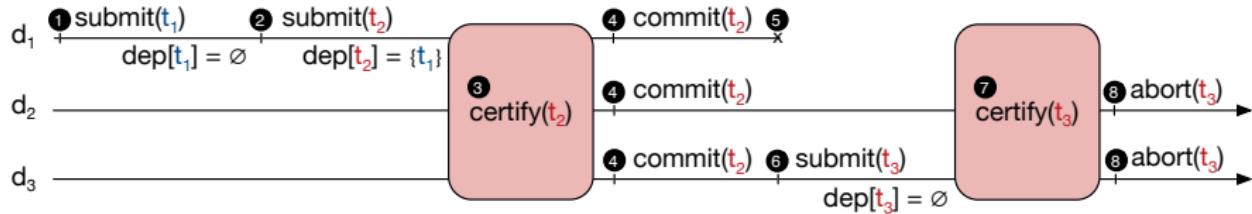
Minimizing the Latency of Strong Transactions

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Minimizing the Latency of Strong Transactions

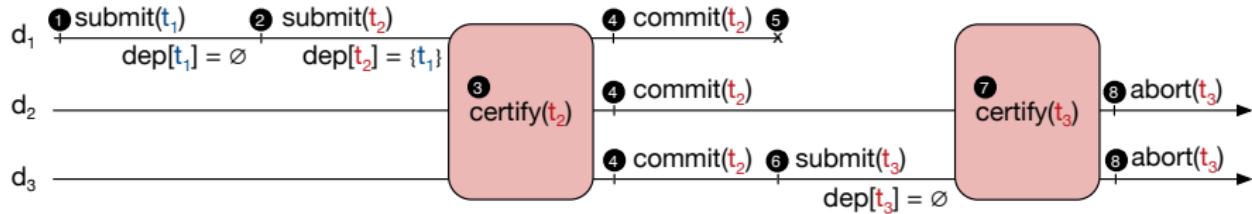
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t_2 waits for local t_1 to become uniform before committing.

Minimizing the Latency of Strong Transactions

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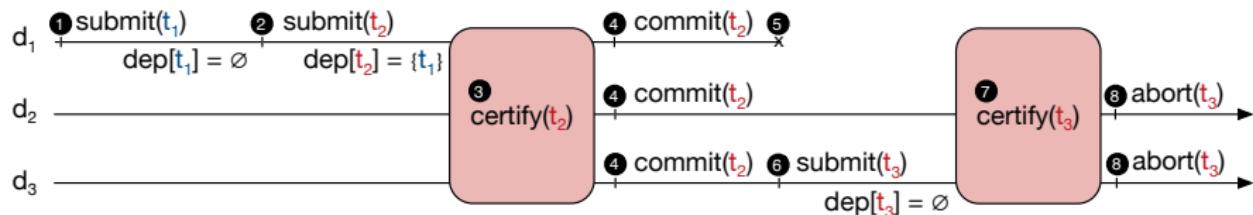


t_2 waits for local t_1 to become uniform before committing.

However, it may cost too much to wait for remote causal dependencies to become uniform.

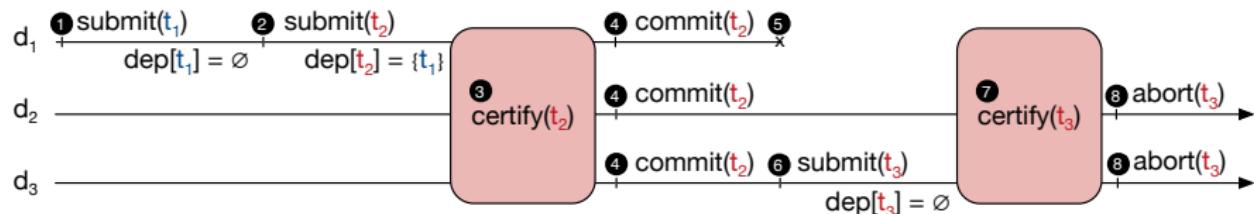
Minimizing the Latency of Strong Transactions

Let **causal transactions** be executed on an (almost) **uniform snapshot** that may be slightly in the past.



Minimizing the Latency of Strong Transactions

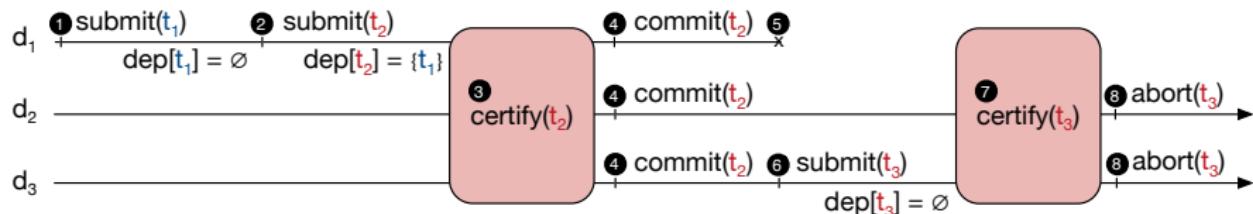
Let **causal transactions** be executed on an (almost) **uniform snapshot** that may be slightly in the past.



Make a **remote causal transaction** visible only **after it is uniform**.

Minimizing the Latency of Strong Transactions

Let **causal transactions** be executed on an (almost) **uniform snapshot** that may be slightly in the past.



Make a **remote causal transaction** visible only **after it is uniform**.

A **strong** transaction does *not* need to wait for **remote causal dependencies** to become uniform before committing.

Fault-tolerant Causal Consistency Protocol

UNISTORE relies on various vector clocks $\in [\mathcal{D} \rightarrow \mathbb{N}]$ for

- ▶ Tracking causality (*commitVec*)
- ▶ Tracking what is replicated where (for uniformity)

Tracking What is Replicated Where

Each replica maintains three vectors:

knownVec: track the set of transactions replicated at this replica

Tracking What is Replicated Where

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stableVec: track the set of transactions replicated at its local data center

Tracking What is Replicated Where

Each replica maintains three vectors:

knownVec: track the set of transactions replicated at this replica

stableVec: track the set of transactions replicated at its local data center

uniformVec: track the set of transactions replicated at $f + 1$ data centers

Adding Strong Transactions

PoR ensures that conflicting transactions are executed serially.

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Assigning to each **strong transaction** a scalar *strong timestamp*.

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$$[\mathcal{D} \rightarrow \mathbb{N}] \quad vs. \quad [\mathcal{D} \cup \{\text{strong}\} \rightarrow \mathbb{N}]$$

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Assigning to each **strong transaction** a scalar *strong timestamp*.

$$[\mathcal{D} \rightarrow \mathbb{N}] \quad vs. \quad [\mathcal{D} \cup \{\text{strong}\} \rightarrow \mathbb{N}]$$

$$\textit{commitVec} \in [\mathcal{D} \cup \{\text{strong}\} \rightarrow \mathbb{N}]$$

Adding Strong Transactions

Each replica maintains three vectors:

`knownVec[strong]`: track the set of `strong` transactions replicated at this replica

`stableVec[strong]`: track the set of `strong` transactions replicated at its local data center d

`uniformVec`: We do not extend `uniformVec`, since the commit protocol for `strong` transactions automatically guarantees their uniformity.

Proof of Correctness

We use the (vis, ar) formal specification framework.

A Framework for Transactional Consistency Models with Atomic Visibility

Andrea Cerone, Giovanni Bernardi, and Alexey Gotsman

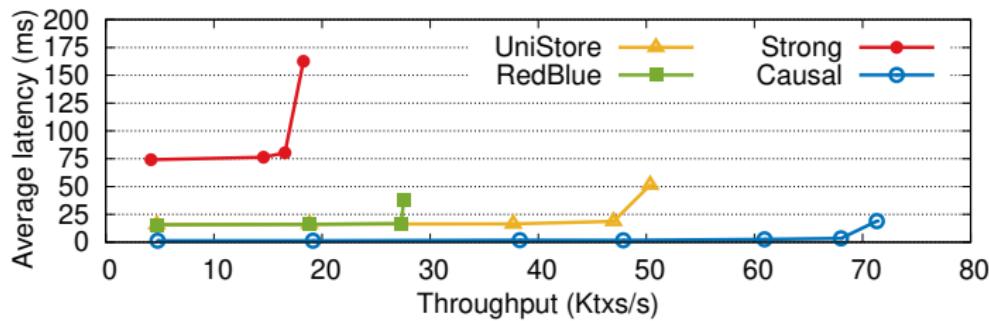
IMDEA Software Institute, Madrid, Spain

Proof of Correctness

The key is to **construct** the appropriate “visibility” (*vis*) relation and the “arbitration” (*ar*) relation between transactions such that

- ▶ The desired properties of various vector clocks hold.
- ▶ The **liveness** property holds (**hard**).

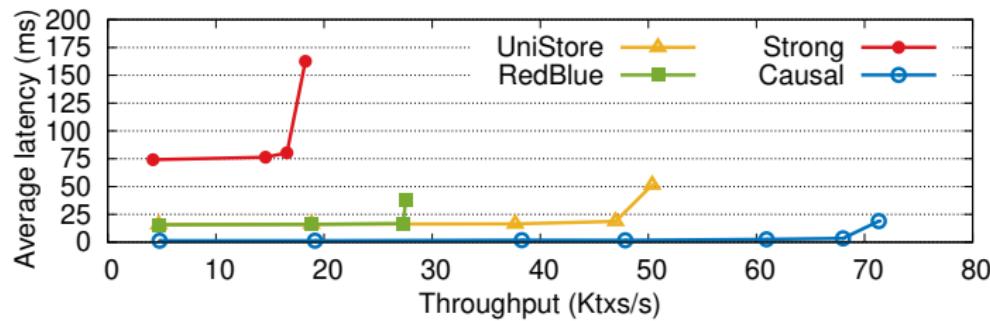
Q1 : Does UNISTORE Combine Causal and Strong Consistency Effectively?



RUBiS benchmark: throughput vs. average latency.

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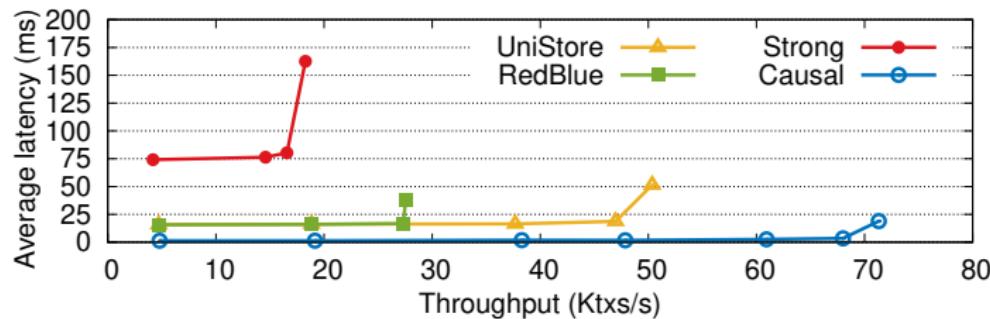
Throughput: 72% and 183% higher than REDBLUE and STRONG,
45% lower than CAUSAL



RUBiS benchmark: throughput vs. average latency.

Q1 : Does UNISTORE Combine Causal and Strong Consistency Effectively?

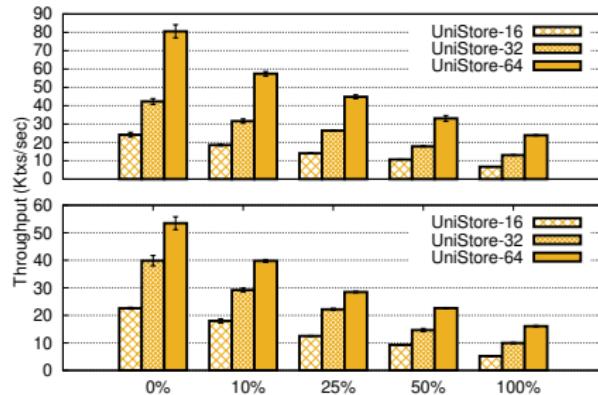
Throughput: 72% and 183% higher than REDBLUE and STRONG,
45% lower than CAUSAL



RUBiS benchmark: throughput vs. average latency.

Average latency: 16.5ms of UNISTORE *vs.* 80.4ms of STRONG,
comparable to that of REDBLUE

Q₂ : How does UNISTORE Scale with the Number of Machines?

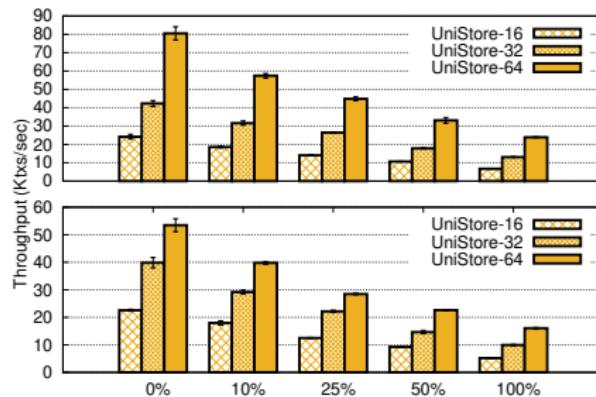


Scalability when varying the ratio of strong transactions with uniform data access
(top) and under contention (bottom).

Q₂ : How does UNISTORE Scale with the Number of Machines?

Scales almost **linearly** (top):

9.76% throughput drop compared to the optimal scalability.

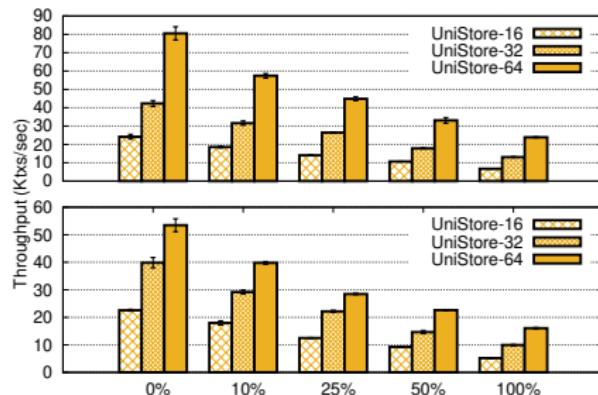


Scalability when varying the ratio of strong transactions with uniform data access
(top) and under contention (bottom).

Q₂ : How does UNISTORE Scale with the Number of Machines?

Scales almost **linearly** (top):

9.76% throughput drop compared to the optimal scalability.

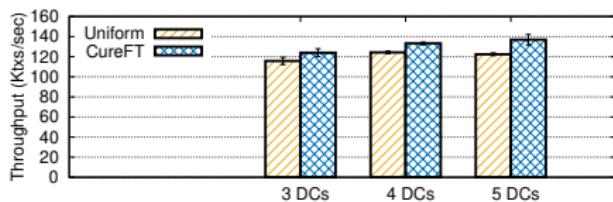


Scalability when varying the ratio of strong transactions with uniform data access (top) and under contention (bottom).

Under contention (bottom): 17.15% throughput drop



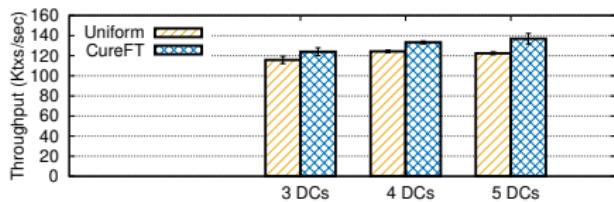
Q₃ : What is the Cost of Uniformity?



Throughput penalty of tracking
uniformity

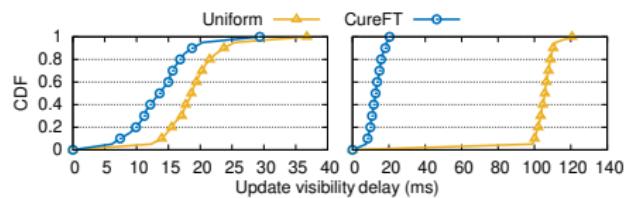
7.97% throughput drop on average

Q₃ : What is the Cost of Uniformity?



Throughput penalty of tracking
uniformity

7.97% throughput drop on average



5ms ~ 92ms at the 90th percentile

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.”

Work in Progress: Testing

Efficient Black-box Checking of Snapshot Isolation in Databases

Kaile Huang, Zheng Chen,
Hengfeng Wei
Nanjing University

Si Liu, David Basin
ETH Zurich

Haixiang Li, Anqun Pan
Tencent Inc.

The SI checking problem is known to be NP-hard.

We utilize SMT solvers to design an efficient checking algorithm.

Plans in the Near Future

- ▶ To design SMT solvers dedicated to transactional consistency checking
- ▶ To design *reconfigurable* transactional consistency protocols



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