

Consistency in Transactional Distributed Databases: Protocols and Testing

Hengfeng Wei (魏恒峰)

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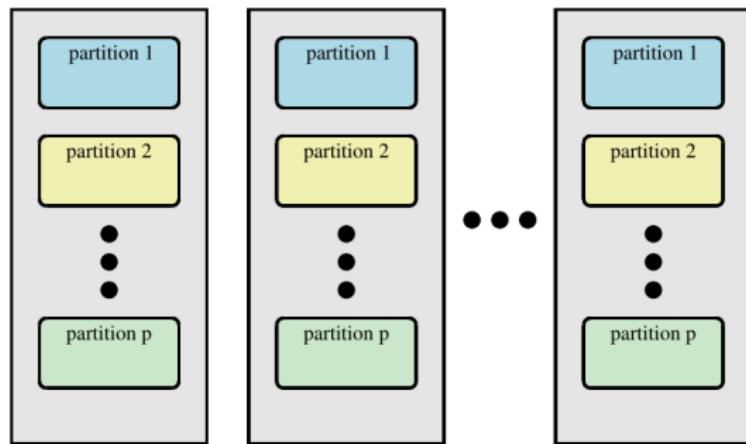
Background

Centralized Databases *vs.* Distributed Databases



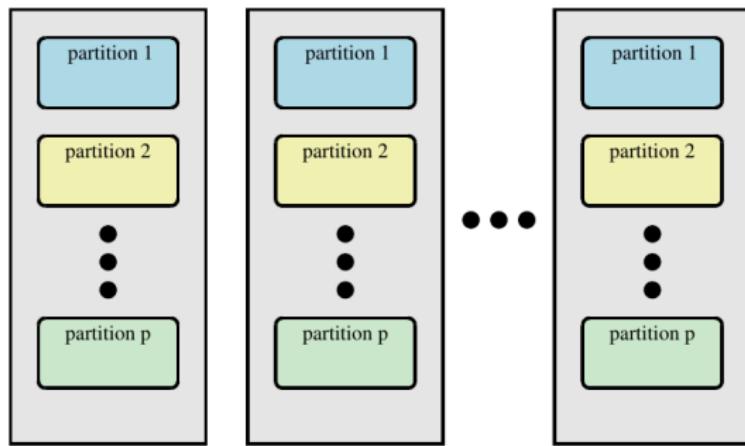
Data Consistency Problem

The Classic “Data Partition + Data Replication” Architecture



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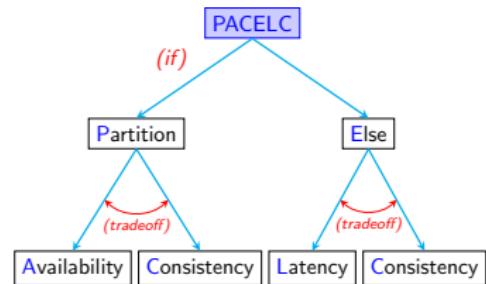
(Distributed) Data Consistency Problem

Data Consistency Problem

(Strong) Consistency, Availability, Latency、Partition tolerance



CAP Theorem
(Brewer@PODC2000)



PACELC Tradeoff
(Abadi@Computer2012)

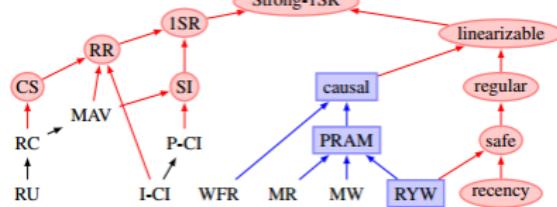
Data Consistency Problem



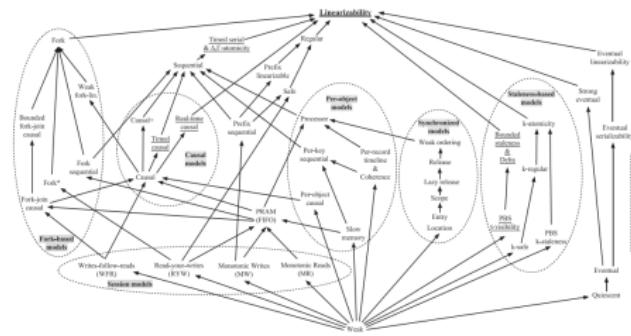
没有一劳永逸的解决方案

Consistency Models

Use various consistency models to capture these tradeoffs



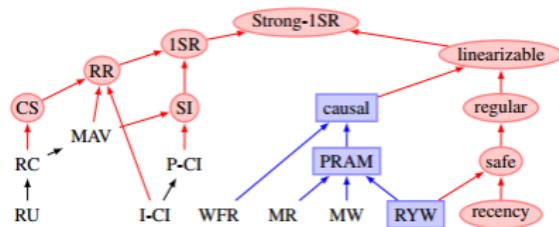
(Bailis@VLDB2012)



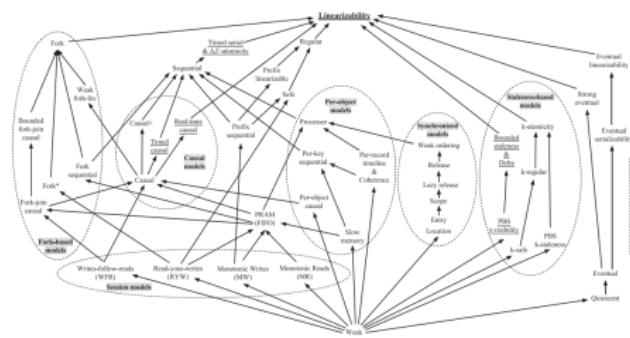
(Viotti@CSUR2016)

Consistency Models

Use various consistency models to capture these tradeoffs



(Bailis@VLDB2012)



(Viotti@CSUR2016)



My Researches

On the data consistency theory around consistency models:

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Computability: What is possible or impossible?

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How to design efficient testing algorithms?

Classic problems with the ever-changing requirements

My Researches (I)

On read/write registers^a (≥ 2014)



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 (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^b (≥ 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)

On distributed transactions^c (≥ 2020)



^c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

ATC'2021 (CCF A)

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

Overview of the Work on UNISTORE

Partial Order-Restrictions (PoR) Consistency

$$\text{CC} < \text{PoR} < \text{SER}$$

CC: CAUSALCONSISTENCY; SER: SERIALIZABILITY

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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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I am fully responsible for developing a rigorous correctness proof:

^dOne 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.

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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^d, and proposed solutions to fix them

^dOne 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.

Why UNI-?

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



Strong Consistency: easy to preserve critical application invariants,
but require global synchronization among data centers

The UNI- Approach

- ▶ Multiple consistency levels coexist in a store

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- ▶ Multiple consistency levels coexist in a store
- ▶ Take **weak consistency** as the default and the baseline
- ▶ Programmers can choose the transactions that should be executed under **strong consistency**
 - ▶ e.g., if the execution of a set of transactions may violate the application violations

The UNI- Approach

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

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Partial Order-Restrictions (PoR) Consistency
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- ▶ PoR allows programmers to classify transactions as either causal or strong.

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 causally independent transactions.

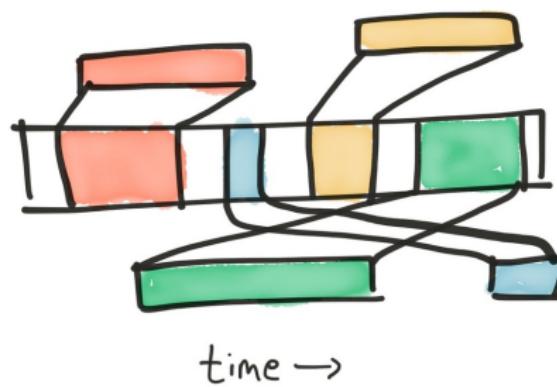
CAUSAL CONSISTENCY

TODO: +fig Clients see updates in an order that respects the potential causality between them.

Causally independent transactions can be executed concurrently.

SERIALIZABILITY

Serializability



All transactions seem to be executed in some **sequential** order.

A Banking Application

DEPOSIT

WITHDRAW

QUERY

INTEREST



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

A Banking Application

DEPOSIT WITHDRAW QUERY INTEREST



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

DEPOSIT operations can be executed under CAUSALCONSISTENCY.

A Banking Application

DEPOSIT WITHDRAW QUERY INTEREST



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

DEPOSIT operations can be executed under CAUSALCONSISTENCY.

DEPOSIT(50)

A Banking Application

DEPOSIT

WITHDRAW

QUERY

INTEREST



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

A Banking Application

DEPOSIT WITHDRAW QUERY INTEREST



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

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

A Banking Application

DEPOSIT WITHDRAW QUERY INTEREST



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

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

WITHDRAW(60)

The PoR Approach

- ▶ The programmer provides a symmetric **conflict relation** \bowtie on transactions.
- ▶ Any transaction involved in the conflict relation is marked **strong**.
- ▶ PoR ensures that conflicting transactions are executed serially.

A Banking Application

DEPOSIT WITHDRAW QUERY INTEREST



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

Only **WITHDRAW** are marked **strong**.

Declaring that strong transactions

including **WITHDRAW** on the same account conflict.

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?



Liveness of UNISTORE

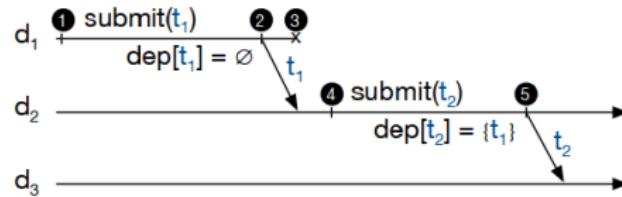
How to ensure **liveness** despite data center failures?



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

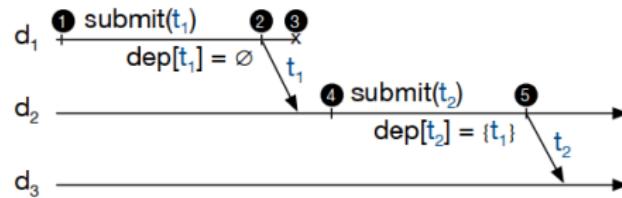
Liveness of Causal Transactions

d_1 crashes before t_1 is replicated to d_3 .



Liveness of Causal Transactions

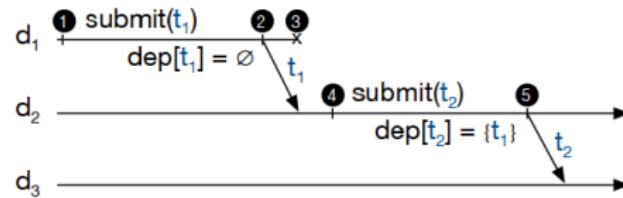
d_1 crashes before t_1 is replicated to d_3 .



Transaction t_2 may never become visible at d_3 .

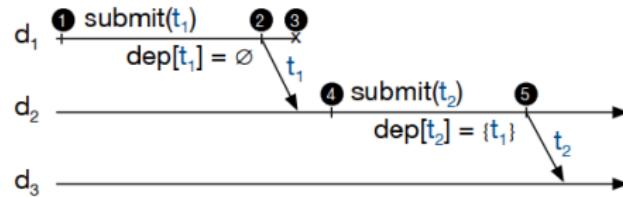
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Liveness of Causal Transactions

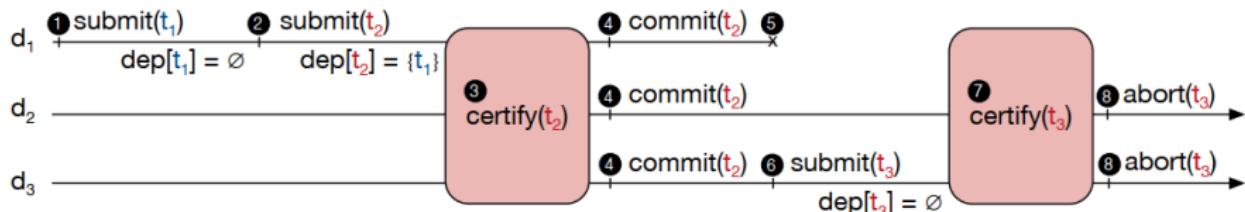
d_1 crashes before t_1 is replicated to d_3 .



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

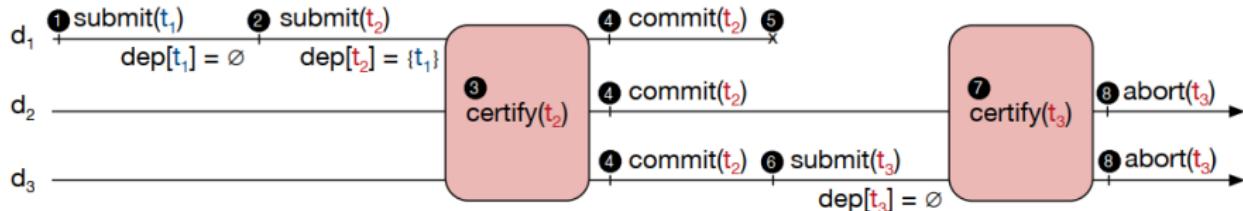
Liveness of Strong Transactions

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Liveness of Strong Transactions

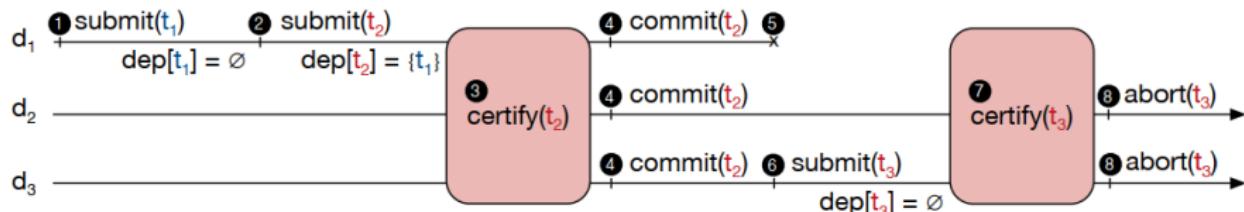
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Liveness of Strong Transactions

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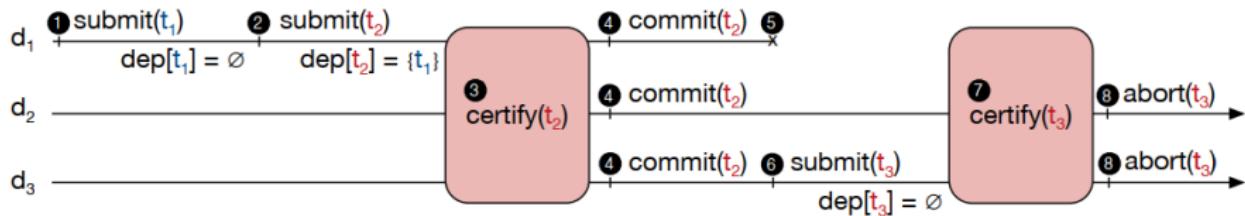


t_2 will never be visible at d_3 .

No transaction t_3 conflicting with t_2 can commit.

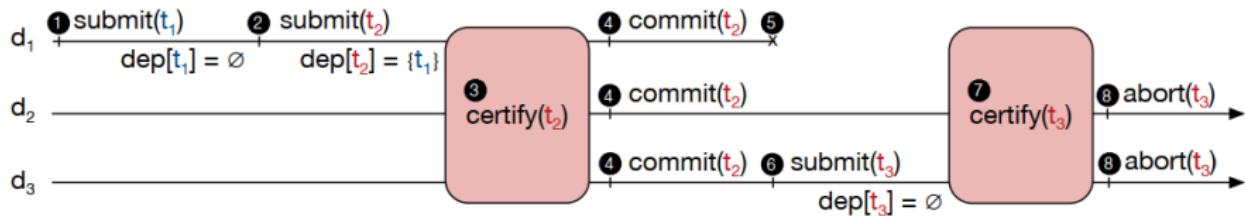
Liveness of Strong Transactions

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

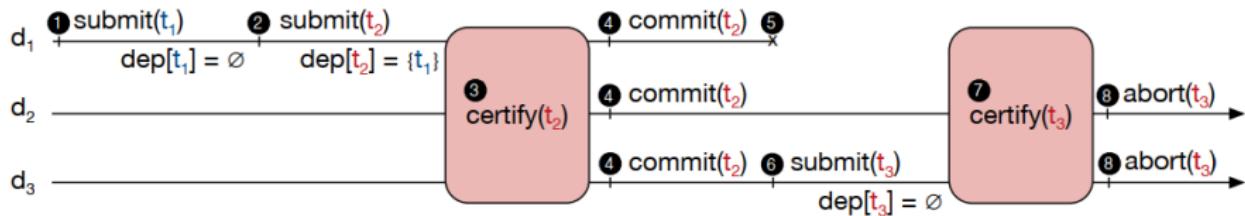
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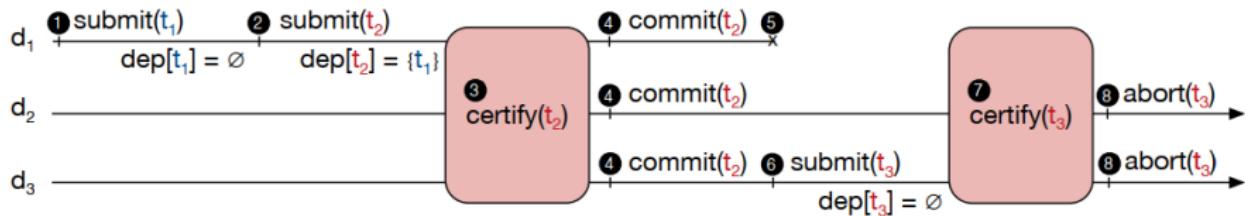


t_1 will eventually be visible at d_3 .

t_2 will eventually be visible at d_3 .

Liveness of Strong Transactions

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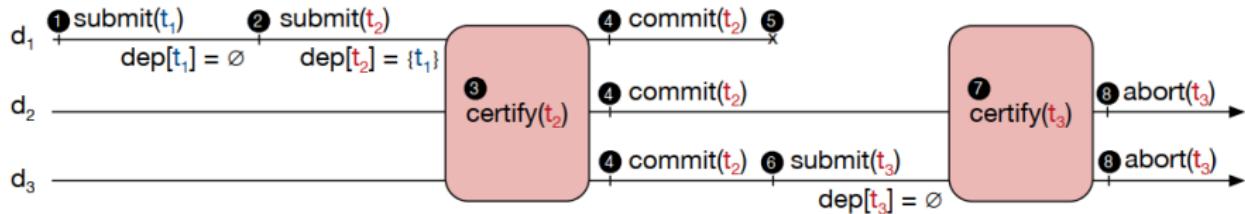
t_1 will eventually be visible at d_3 .

t_2 will eventually be visible at d_3 .

t_3 may be committed at d_3 .

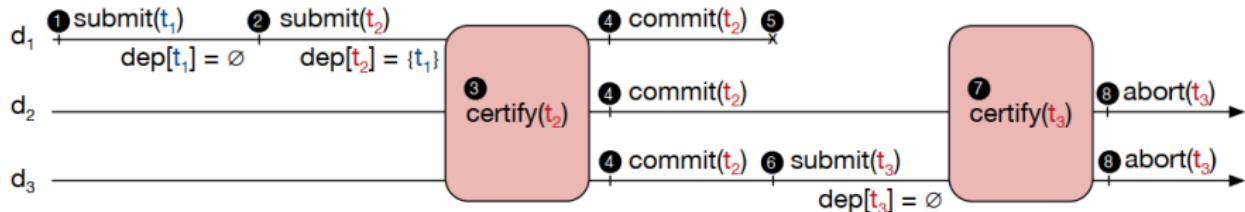
Minimizing the Latency of Strong Transactions

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Minimizing the Latency of Strong Transactions

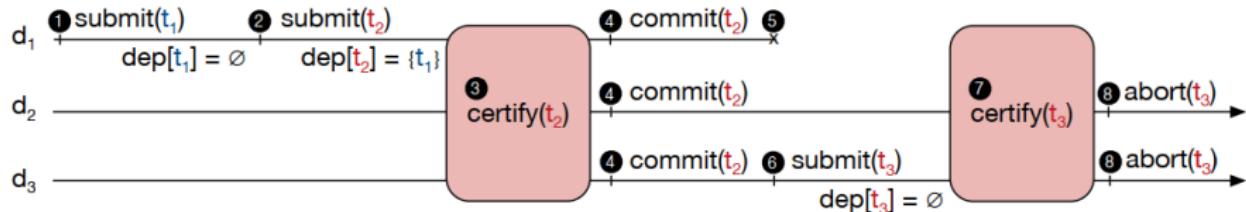
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t_2 waits for local t_1 to become uniform before committing.

Minimizing the Latency of Strong Transactions

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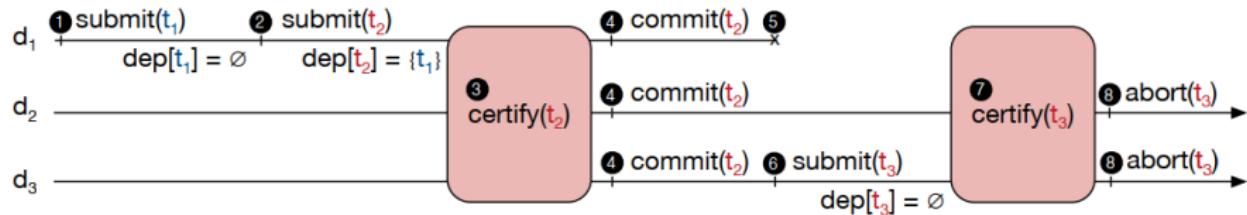


t_2 waits for **local** t_1 to become uniform before committing.

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

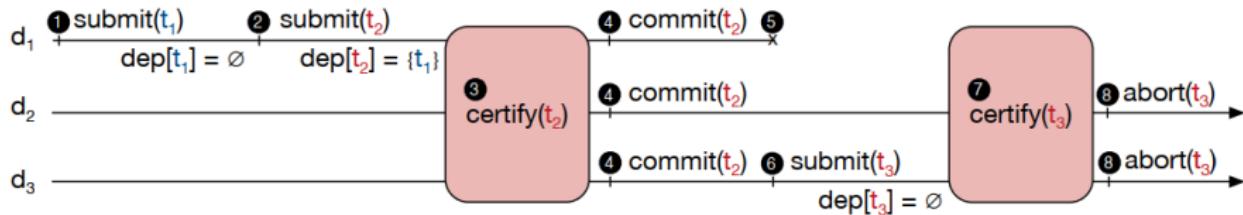
Minimizing the Latency of Strong Transactions

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



Minimizing the Latency of Strong Transactions

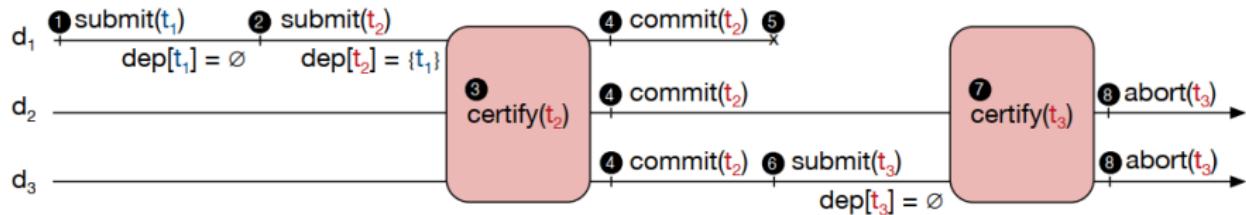
Let **causal transactions** be executed on an (almost) **uniform snapshot** that may be slightly in the past.



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.



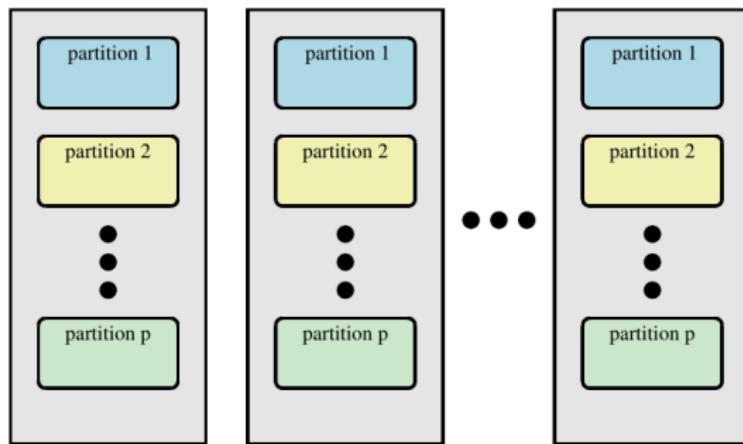
Make a **remote causal transaction** visible only **after it is uniform**.

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

System Model and Notations

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

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



Fault-tolerant Causal Consistency Protocol

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

- ▶ Tracking causality (*commitVec*)
- ▶ Representing causally consistent snapshots (*snapshotVec*)
- ▶ Tracking what is replicated where

Tracking What is Replicated Where

Make a **remote causal transaction** visible 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.

Tracking What is Replicated Where

Make a **remote causal transaction** visible 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.

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

Each replica maintains three vectors:

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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

Fault-tolerant Causal Consistency Protocol

- ▶ Causal transactions are executed on a uniform snapshot.
- ▶ Read-only transactions returns immediately.
- ▶ Update transactions commit using a variant of 2PC protocol.

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

Adding Strong Transactions

PoR ensures that conflicting transactions are executed serially.

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

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

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

Adding Strong Transactions

Each replica maintains three vectors:

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

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

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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

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

Adding Strong Transactions

- ▶ A **strong** transaction waits for local causal dependencies to become uniform before committing.

Adding Strong Transactions

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- ▶ Uses optimistic concurrency control protocol

Adding Strong Transactions

- ▶ A **strong** transaction waits for local causal dependencies to become uniform before committing.
- ▶ Uses optimistic concurrency control protocol
 - ▶ First *speculatively* execute **strong** transactions locally

Adding Strong Transactions

- ▶ A **strong** transaction waits for local causal dependencies to become uniform before committing.
- ▶ Uses optimistic concurrency control protocol
 - ▶ First *speculatively* execute **strong** transactions locally
 - ▶ Then certify them globally using a *transaction certification service* (TCS)

Strong Consistency Protocol: Commit

Multi-Shot Distributed Transaction Commit

Gregory Chockler

Royal Holloway, University of London, UK

Alexey Gotsman¹

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

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

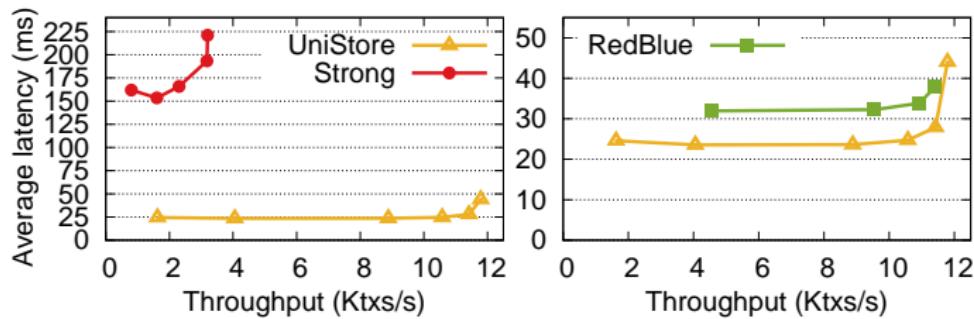
IMDEA Software Institute, Madrid, Spain

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).

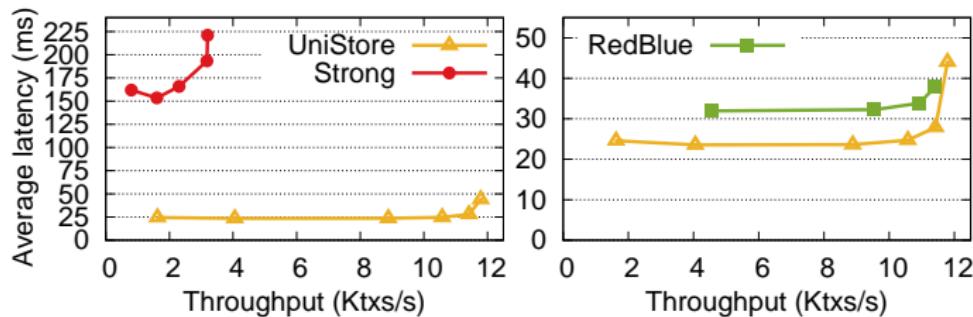
Q1 : Does UNISTORE Combine Causal and Strong Consistency Effectively?



RUBiS benchmark: throughput vs. average latency.

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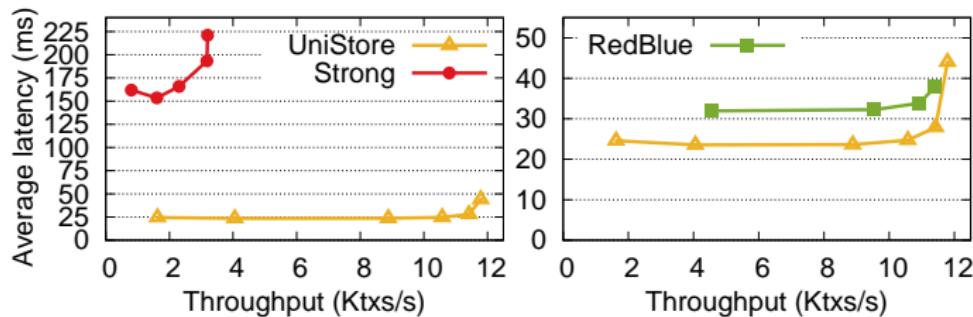
Throughput: 72% and 183% higher than REDBLUE and STRONG,
45% lower than CAUSAL



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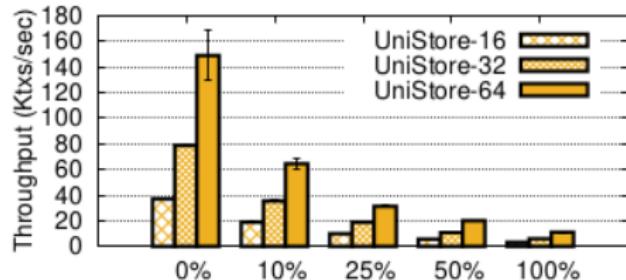
Throughput: 72% and 183% higher than REDBLUE and STRONG,
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RUBiS benchmark: throughput vs. average latency.

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?

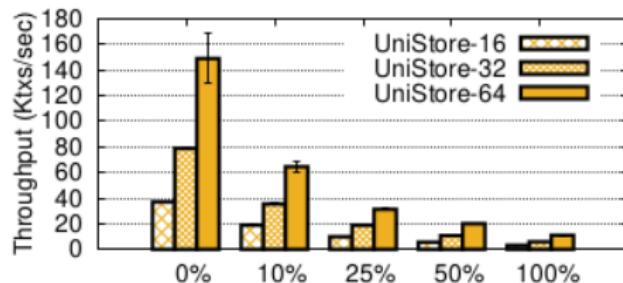


Scalability when varying the ratio of strong transactions with uniform data access (top) and under contention (bottom).

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

Scales almost linearly (top):

9.76% throughput drop compared to the optimal scalability.

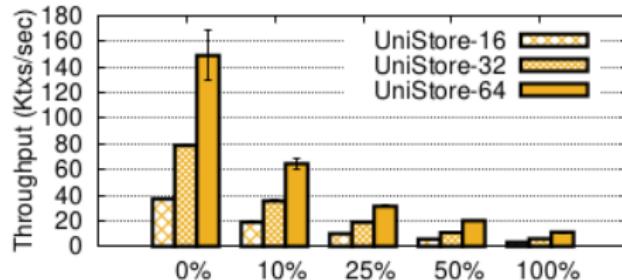


Scalability when varying the ratio of strong transactions with uniform data access (top) and under contention (bottom).

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

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Throughput penalty of tracking
uniformity

7.97% throughput drop on average

Update visibility delay (ms)

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**.

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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, **Zhenge Chen**,
Hengfeng Wei
Nanjing University

Si Liu, David Basin
ETH Zurich

Haixiang Li, Anqun Pan
Tencent Inc.

Utilizing SMT solvers to efficiently check SI violations

Plans in the Near Future

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



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