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Spectrum: Speedy and Strictly-Deterministic Smart Contract Transactions for Blockchain Ledgers

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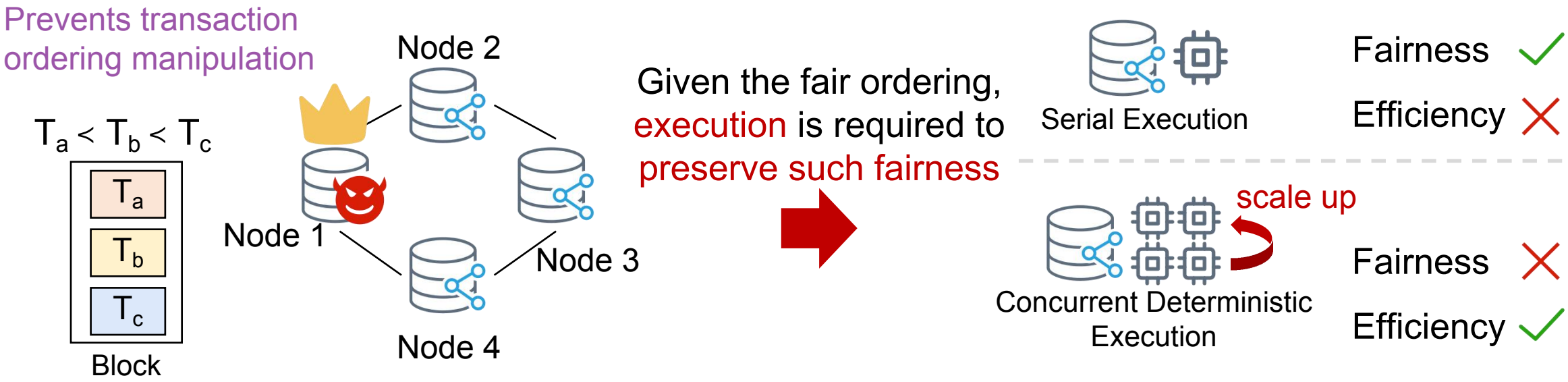
Outline

- Motivation
- Background
- Goals & Contributions
- Methodology
- Evaluation
- Conclusion & Future work

Motivation

- Unlike tranditional databases, blockchain ledgers concern ordering fairness
- Existing deterministic execution schemes fail to preserve both ordering fairness and high performance



Modern Byzantine consensus, e.g., Pompe [OSDI'20]、Themis [CCS'23] incorporate fairness designs

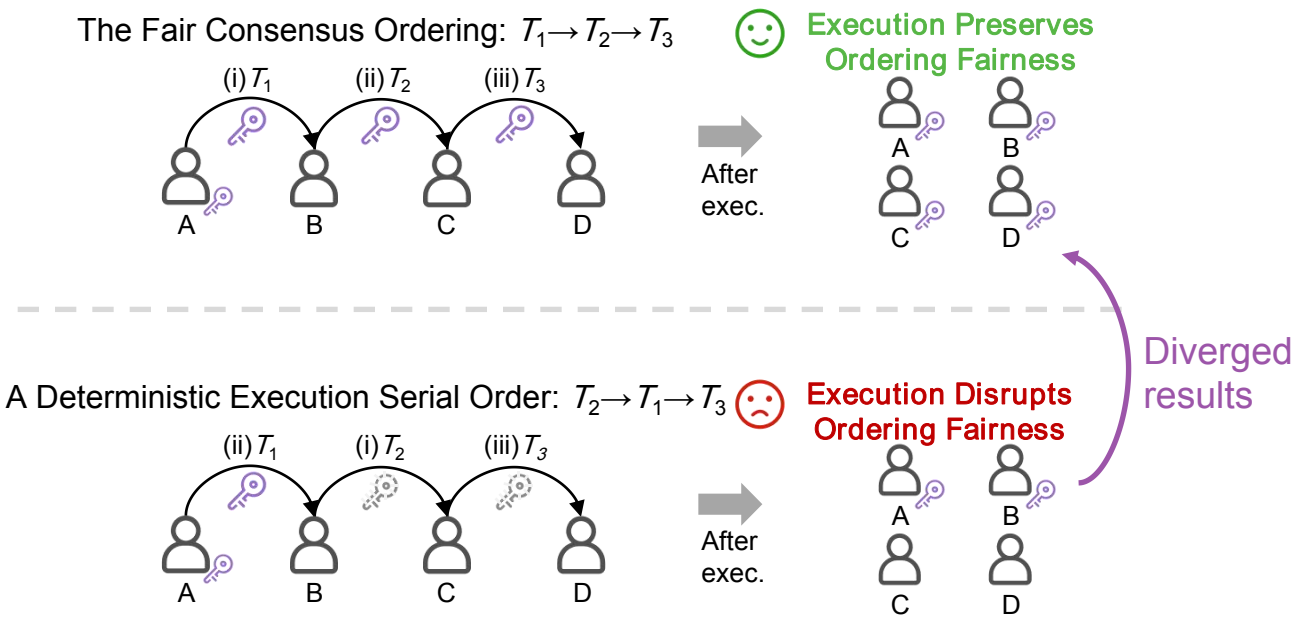
Motivation

- They merely guarantee deterministic serializability, which can lead to a deterministic (consistent across replicas), yet different serial order than the agreed-upon ordering

e.g., AccessControl contract: A caller with access permission can grant it to a specified address

```
contract AccessControl {
    mapping(address => bool) public access;
    function grantAccess(address to) public {
        if (access[msg.sender] != false)
            access[to] = access[msg.sender];
    }
}
```

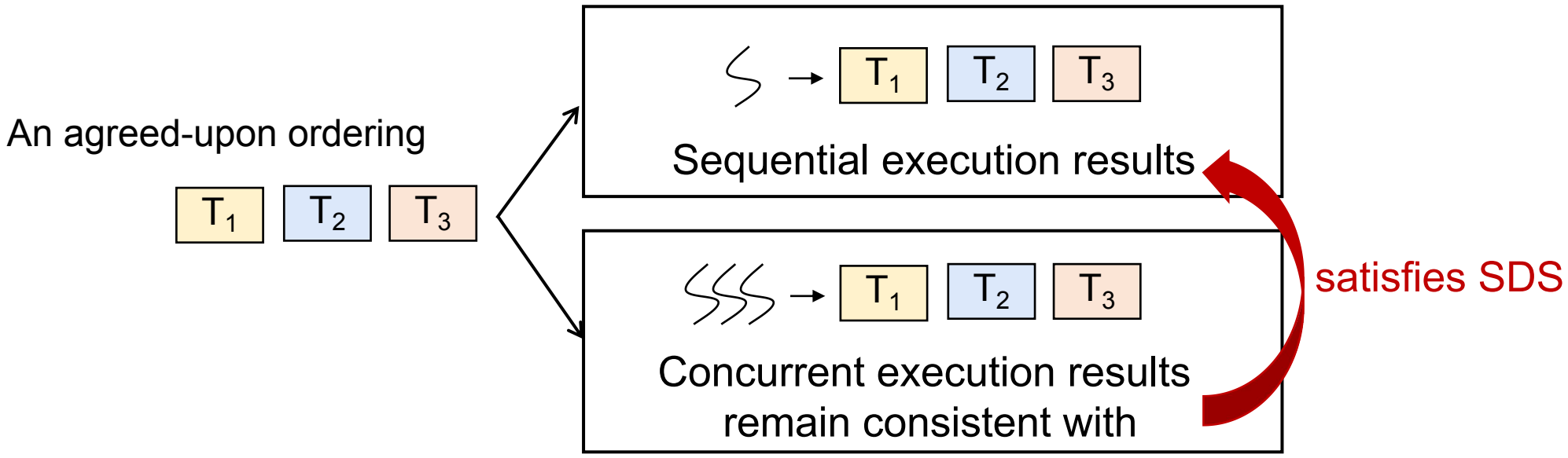
Initially, only A has permission; T_1: A->B, T_2: B->C, T_3: C->D



Merely Determinism Does NOT Preserve Ordering Fairness

Background

- Problem Definition: Strictly-Deterministic Serializability (SDS)
  - Given an agreed ordering of transactions, O: $\{T_1, ..., T_n\}$, an execution schedule of transactions S satisfies **strictly-deterministic serializability** iff its effect is equivalent to the sequential execution of O, which adheres to the transactions commit order, $\{T_1, ..., T_n\}$



Background

- For blockchain ledgers, ensuring SDS in an execution scheme preserves ordering fairness
- But most Deterministic Concurrency Control (DCC) schemes fail to ensure SDS when processing smart contracts with runtime-determined accesses

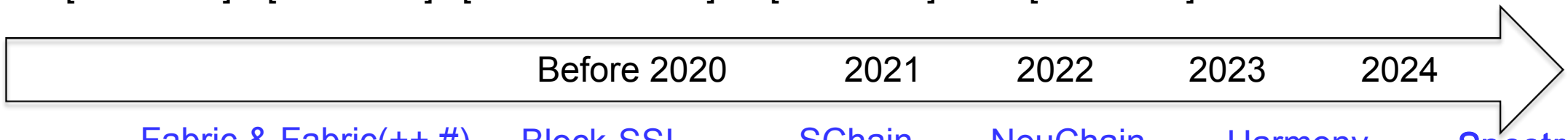
Kindly refer to the paper for an in-depth analysis

Deterministic Execution Schemes	Execution Paradigm	No Complete R/W Sets	Strict Determinism	Scaling in Contention
▲ HyperLedger Fabric [10]	EOV	✓	✗	✗
▲ Fabric(++, #) [47, 49]	EOV	✓	✗	✓
▲ NeuChain [40]	EV	✓	✗	✗
• Calvin [55], PWV [22]	OE	✗	✗	✓
• Bohm [23], Caracal [45]	OE	✗	✗	✓
• QueCC [43]	OE	✗	✗	✓
• Aria, AriaFB [38]	OE	✓	✗	✓
• Sparkle [36]	OE	✓	✓	✗
▲ Primary-Follower [29]	OE	✓	✗	✓
▲ SSI [39], OCC-DA [24]	OE	✓	✗	✗
▲ OXII [9], PEEP [15]	OE	✗	✗	✓
▲ Harmony [33]	OE	✓	✗	✓
▲ **Spectrum (Ours)**	OE	✓	✓	✓

• Scope of Databases ▲ Scope of Blockchains

Deterministic Concurrency Control (Database)

Calvin [SIGMOD' 12]
Orthrus [SIGMOD' 16]
Sparkle [DSN' 19]
QStore [EDBT' 20]
Caracal [SOSP' 21]
Bohm [VLDB' 15]
PWV [VLDB' 17]
QueCC [Middleware' 18]
Aria [VLDB' 20]
Lotus [VLDB' 22]



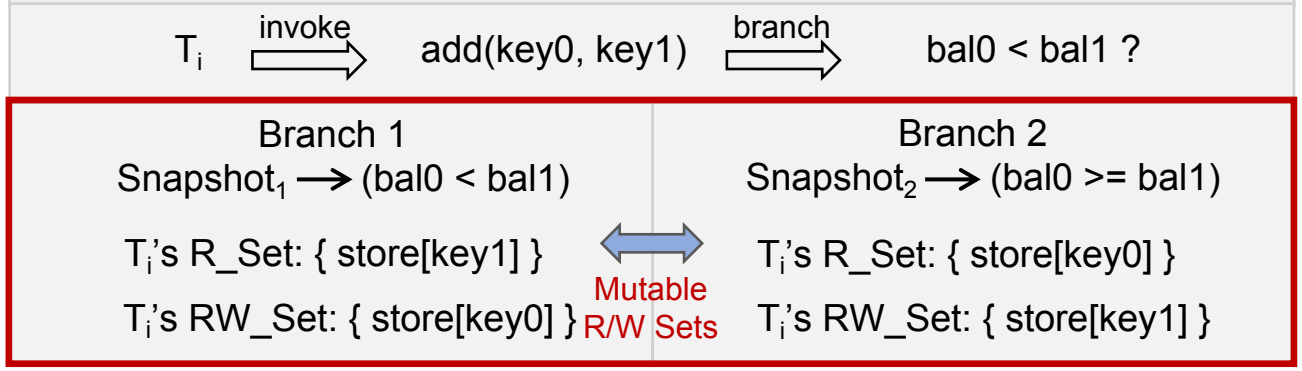
Parallelizing Transactional Smart Contracts (Blockchain)

Fabric & Fabric(++,#) [EuroSys' 18] [SIGMOD' 19, 20]
Block-SSI [VLDB' 19]
OXII [ICDCS' 19]
SChain [VLDB' 21, ICDE'23]
Primary-Follower [TKDE' 21]
NeuChain [VLDB' 22]
OCC-DA [ICSE' 22]
Harmony [SIGMOD' 23]
Block-STM [PPoPP' 23]
Spectrum (Ours)

Background

- Quasi-Turing-complete smart contracts have runtime-determined access patterns

```
1  pragma solidity >=0.8.2 <0.9.0;
2  contract MutableRW {
3    mapping(uint256 => uint256) public store;
4    function add(uint256 key0, uint256 key1) public {
5      uint256 bal0 = store[key0];
6      uint256 bal1 = store[key1];
7      if (bal0 < bal1) store[key0] += bal1;
8      else store[key1] += bal0;
9    }
10 }
```



A Transaction with mutable read/write sets

Runtime-determined nature

whose read/write sets can vary across different snapshots
(Mutable read/write sets)

Most DCC schemes CAN NOT guarantee SDS when handling mutable r/w sets

For inaccurate pre-acquisition or inherent scheme limitations (reordering, violations, etc.)

Goals & Contributions

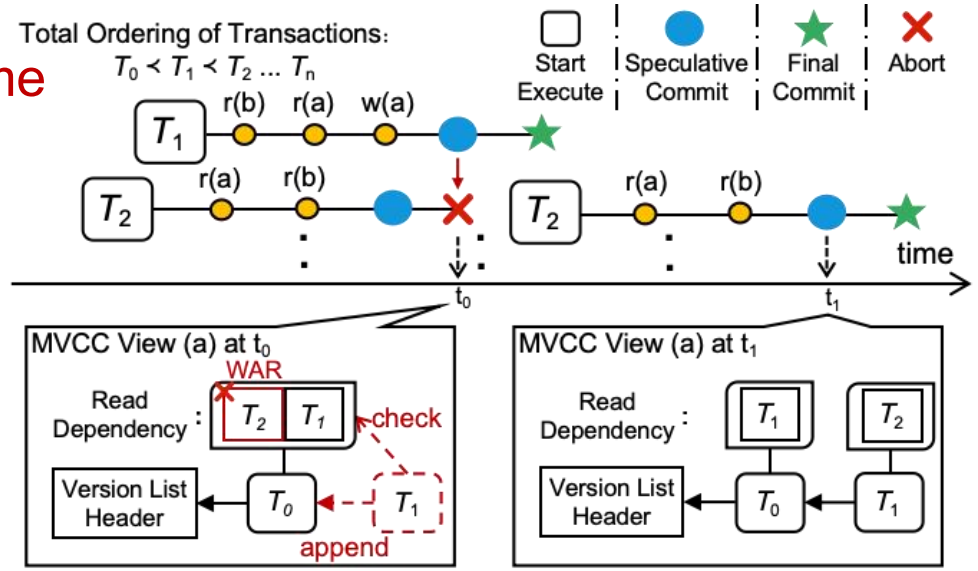
- Design goal
  - Spectrum, a DCC scheme that ensures both strict determinism and high performance (across diverse workloads) for blockchain ledgers

- Key points and contributions
  - Leverages speculative execution to ensure SDS for concurrent smart contract transactions
  - Proposes a partial rollback mechanism with efficient impl.
  - Designs a predictive transaction scheduling method
  - Evaluates by running EVM-Based smart contracts on YCSB, SmallBank and TPC-C alike benchmarks

Two novel optimizations to maintain high performance under contention

Methodology

- #1 Speculative transaction execution
  - Multi-Version Concurrency Control with runtime conflict detection
  - Lets each thread independently execute Txns in speculation => high inter-thread concurrency
  - Transaction lifecycle: 1) Execution; 2) Speculative Commit; 3) Final Commit
  - Detects and aborts any order-violating Txns at runtime
  - Re-executes them with their original seq. numbers
  - Upholds SDS

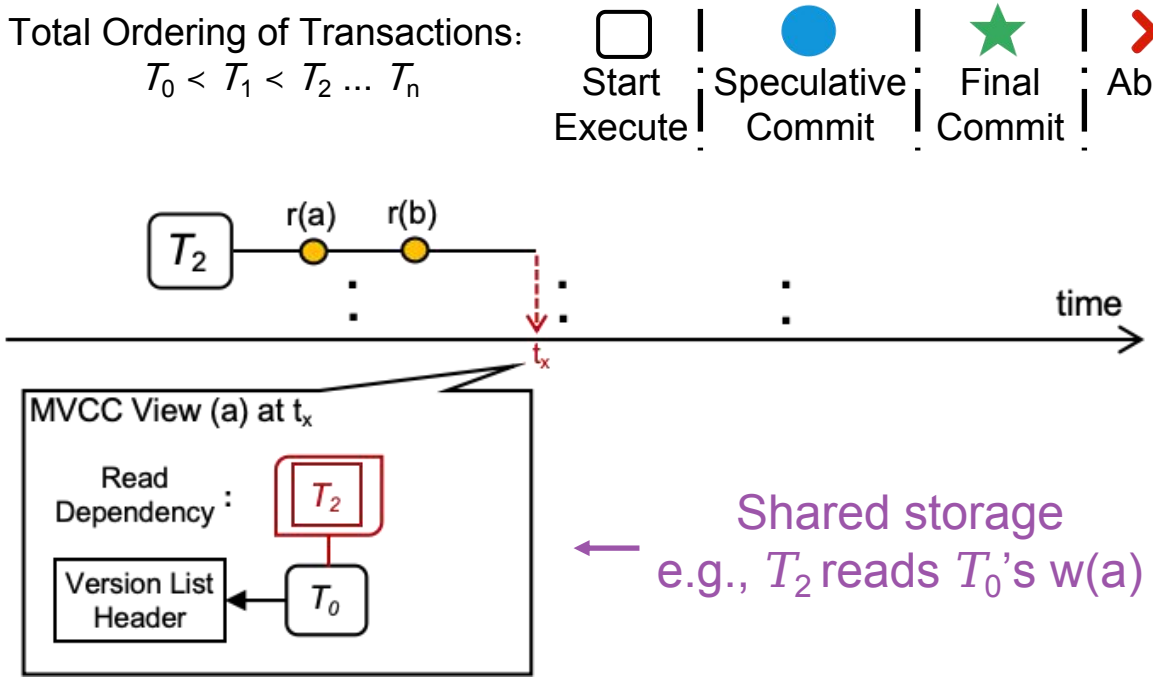


Speculative transaction execution

Methodology

- #1 Speculative transaction execution
  - Transaction lifecycle: 1) Execution; 2) Speculative Commit; 3) Final Commit

1) Execution: runs OPs, reads from shared storage (if not found locally), writes to T's local storage



Shared storage
e.g., T_2 reads T_0's w(a)

Read operations:
T's local storage -> shared storage

(reads the largest preceding version before T and records read dep.)

Enables aborting T if a conflict is detected later

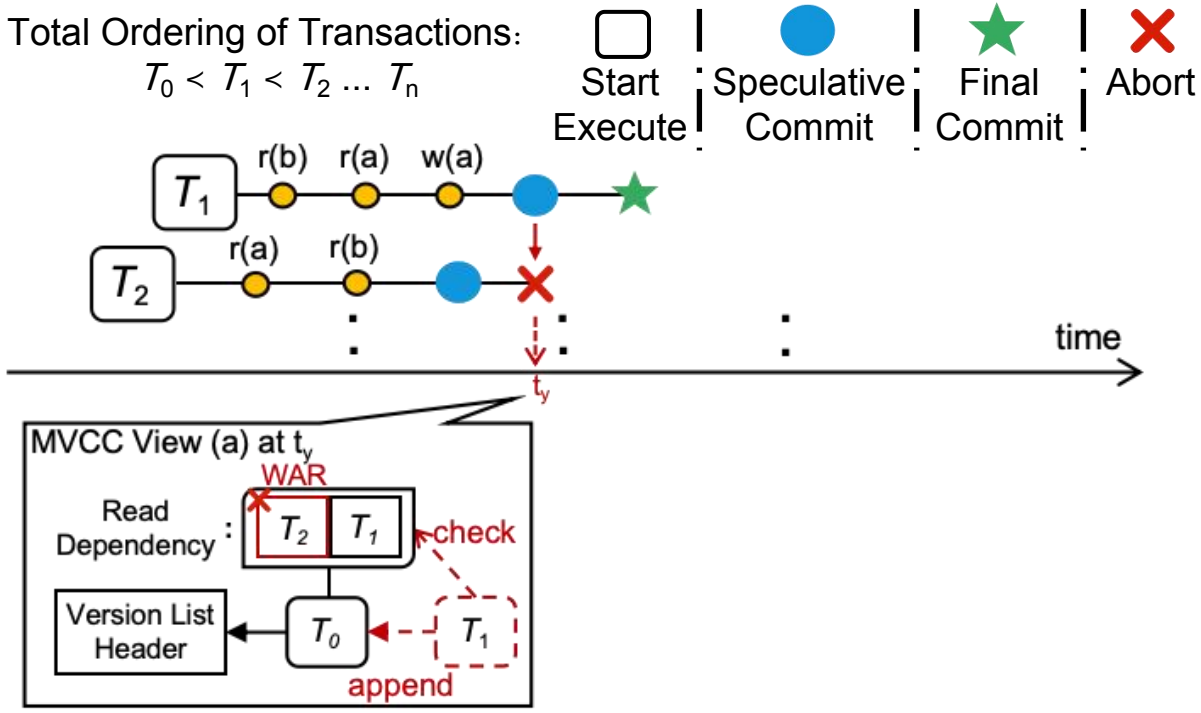
Write operations:
merely inserts to local storage

Speculative transaction execution

Methodology

- #1 Speculative transaction execution
  - Transaction lifecycle: 1) Execution; 2) Speculative Commit; 3) Final Commit

2) Specuative Commit: makes writes visible & detects conflicts & aborts order-violating Txns



Speculative transaction execution

Inserts all local writes to shared storage

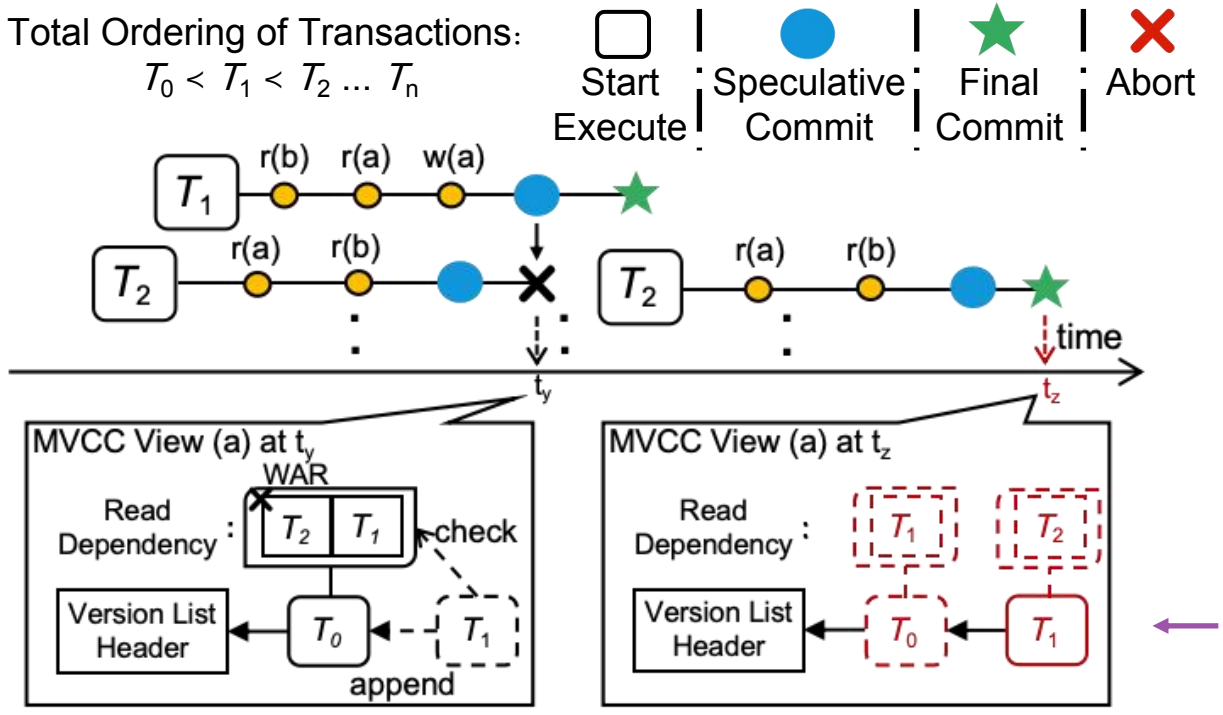
Detects missed reads on newly-inserted writes
e.g., T_2's read missed T_1's w(a)

Aborts those order-violating Txns

Methodology

- #1 Speculative transaction execution
  - Transaction lifecycle: 1) Execution; 2) Speculative Commit; 3) Final Commit

3) Final Commit: updates the tracking counter, cleans redundant versions & deps



FC condition (i): all Txns preceding T have been finally committed

FC condition (ii): T remains unaborted

Promises T no longer to be aborted

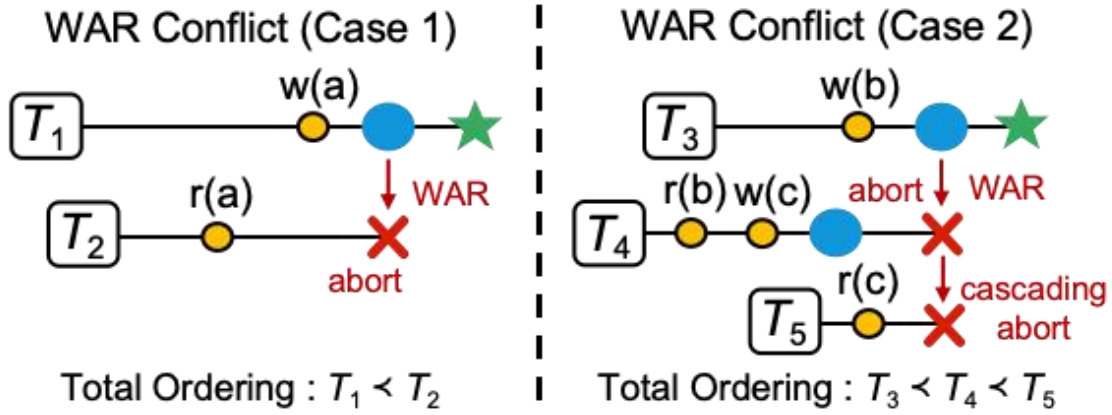
← After T_1, T_2 finally committed

Speculative transaction execution

Methodology

- Conflict types
  - Mis-speculations lead to write-after-read (WAR) conflict (but no WAW or RAW conflicts)
  - WAR conflict: Txn T_i's write W_i (visible til T_i's spec. commit) is missed by T_j's read R_j, where W_i conflicts with R_j and i < j
  - Become scaling bottlenecks under contended workloads

both the **Overhead** and the **Number** of mis-speculations



Exemplifying the WAR Conflict

Methodology

- #2 Fine-Grained transaction rollback

  Traditionally: Complete ↓ Complete ↓

  - When a WAR conflict occurs, the aborted transaction(s) need rollback and re-execute

    Expensive and wasteful for smart contract Txns !!!

  - Partial rollback mechanism:

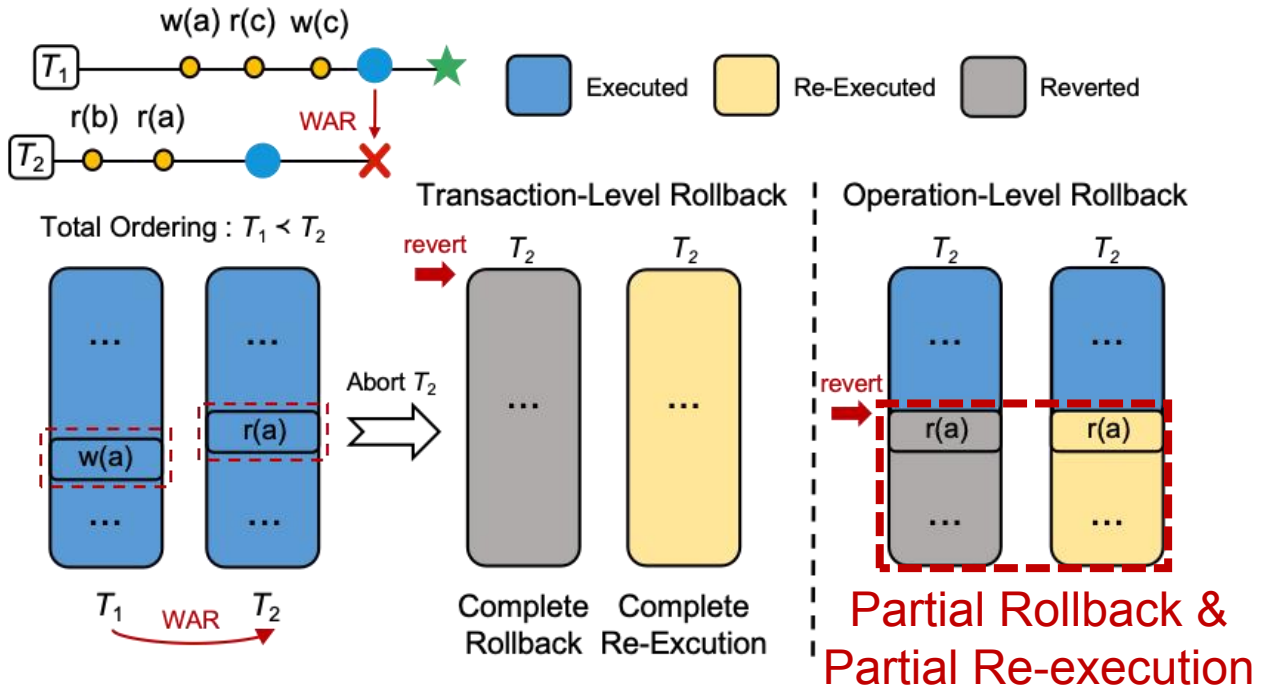
    Only the operations impacted by the conflict

    need to be rollbacked and re-executed

  - Avoids wasting CPU resources

    & Saves re-execution overhead

    Reduces the overhead per mis-speculation



Comparison of transation- and operation-level rollback

Methodology

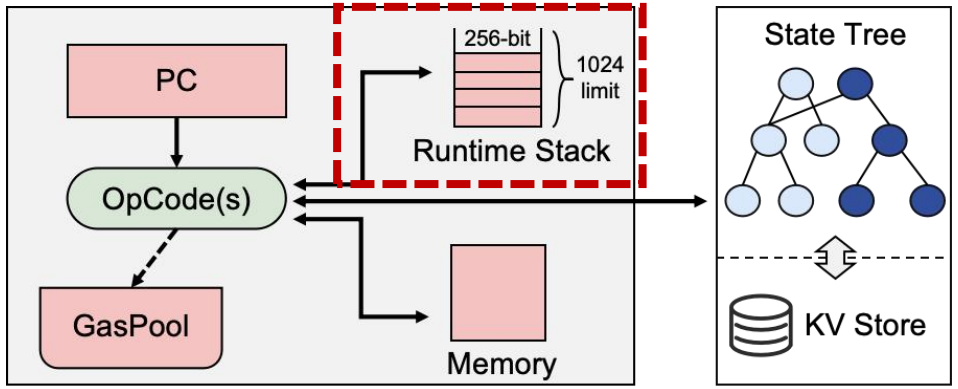
- Implementing partial rollback in stack-based EVM

CoW at the 'segment' level (consecutive stack elements)

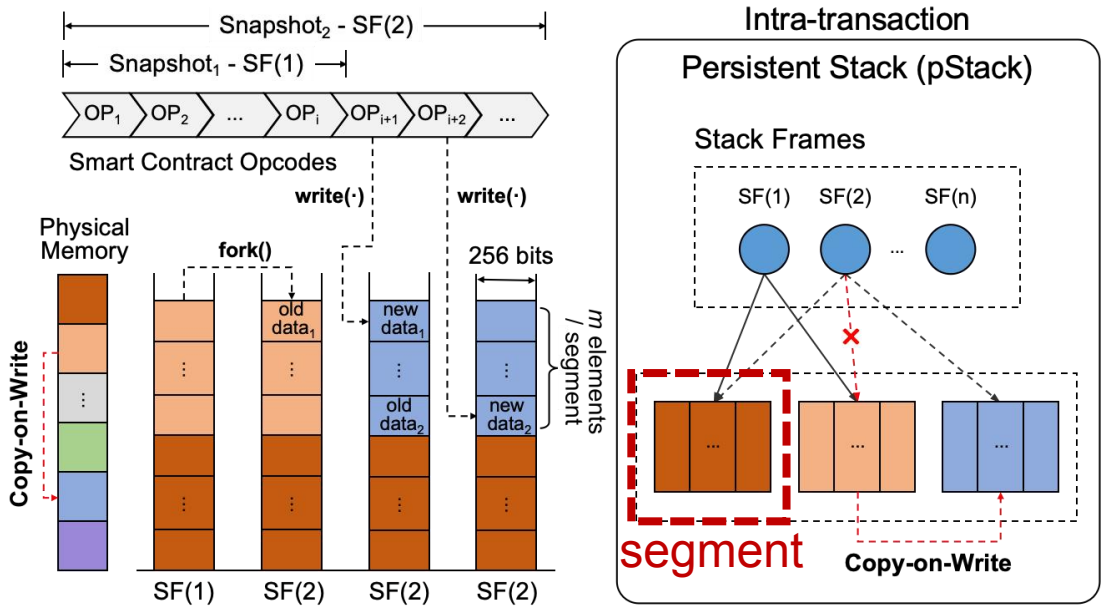
  - pStack, a persistent stack with Copy-on-Write (CoW) mechanism <=> replacing EVM's Stack
  - Efficiently restores and operates on multiple stack snapshots, (i.e., checkpoints)

Exposes three primitives: 1. write(elementIndex, value); 2. fork(); 3. rollback(snapshotID)

Replaces EVM's Stack with pStack for efficient checkpointing



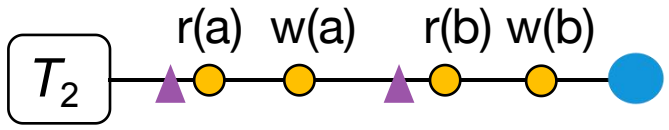
Ethereum Virtual Machine (EVM) structure



pStack-based stack frame management

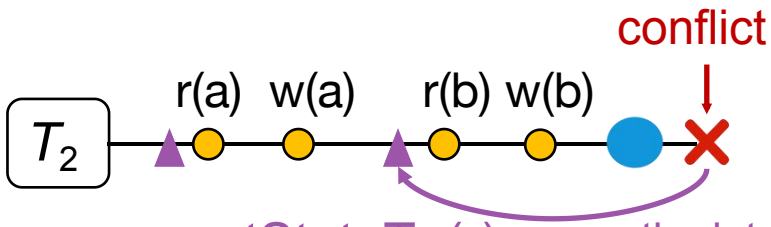
Methodology

- Integrates partial rollback implementation with speculative execution
- Makes a checkpoint before an external read, i.e., SLOAD with the read not in local storage
- Rollbacks to a checkpointed state right before the conflict occurs
- Low checkpoint memory cost & cache-friendly



▲ makeCheckpoint(·):

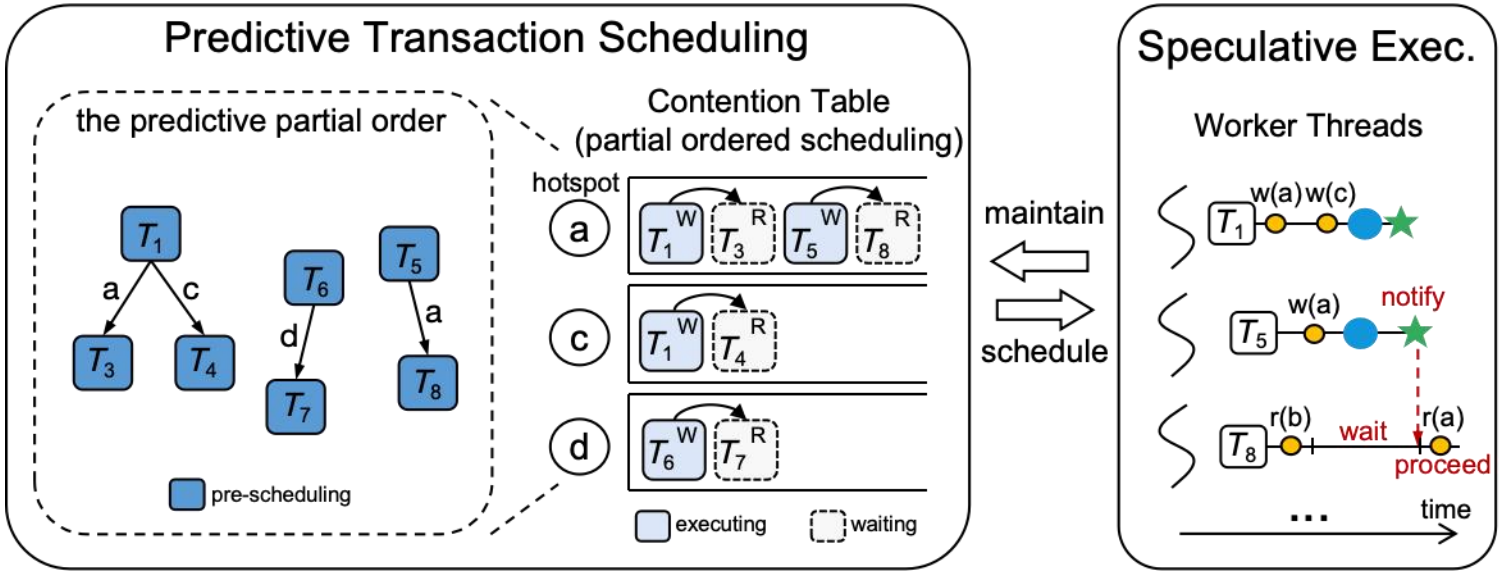
- EVM.pStack.fork()
- Records PC, Memory
- EVM.addCheckpoint(·)



- EVM.getCheckpoint(·)
- Sets PC, Memory
- EVM.pStack.rollback(·)

Methodology

- #3 Predictive transaction scheduling serving as 'hints'
  - Only requires partial a-priori read/write sets to pre-schedule potentially conflicting transactions
  - If the prediction is correct, it effectively reduces the number of runtime mis-speculations
  - Independent scheduling across replicas (ensures SDS despite different predictions)



Predictive scheduling optimization

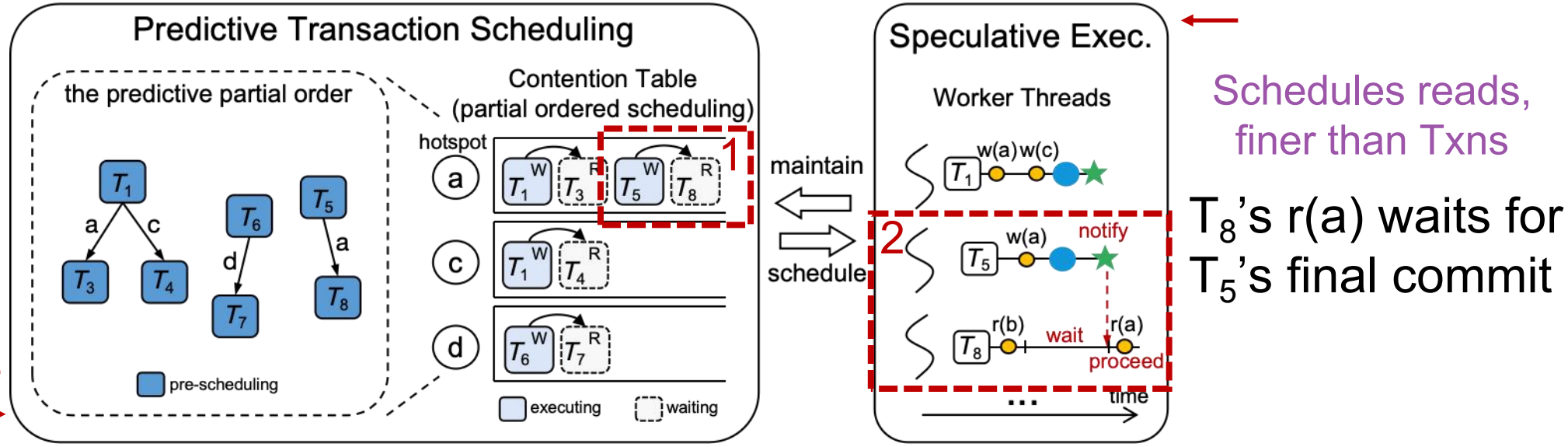
Methodology

- Key intution: wait for preceding conflicting Txns to be finally committed => avoid WAR conflicts
- Sched. Algorithm (efficiency and correctness): concurrent maintenance and sequential granting
- Schedules only highly-conflicted keys and predicted WAR conflicts
- Superior parallelism than Calvin's single-threaded ordered lock pre-scheduling

2. Runtime scheduling

Example:
pre-acquired rw_set

T_5 : w(a)
T_8 : r(a)



Schedules reads, finer than Txns

T_8's r(a) waits for T_5's final commit

1. Pre-maintenance

Predictive scheduling optimization

Evaluation

- Testbed
  - 2x Intel Xeon Gold 6330 CPU (28C56T each) with 256GB DRAM
- Benchmarks
  - YCSB & SmallBank & TPC-C alike smart contracts (written in Solidity)
  - Uniform workload and Skewed workload (controlled by *Zipf*)
- Baselines (incl. SOTA DCC schemes)
  - Serial
  - Calvin
  - Aria, AriaFB
  - Sparkle

Benchmark	Transaction Type (# of reads/writes)	call ratio
YCSB	Get&Set (5r5w)	100%
SmallBank	Six standard functions (2r0w, 2r1w, 1r1w * 2, 2r2w * 2)	equal probability
TPC-C	NewOrder, Delivery, Payment (4r5w/orderline, deliver 10 orderlines, 1r1w)	N:D:P = 11:11:1

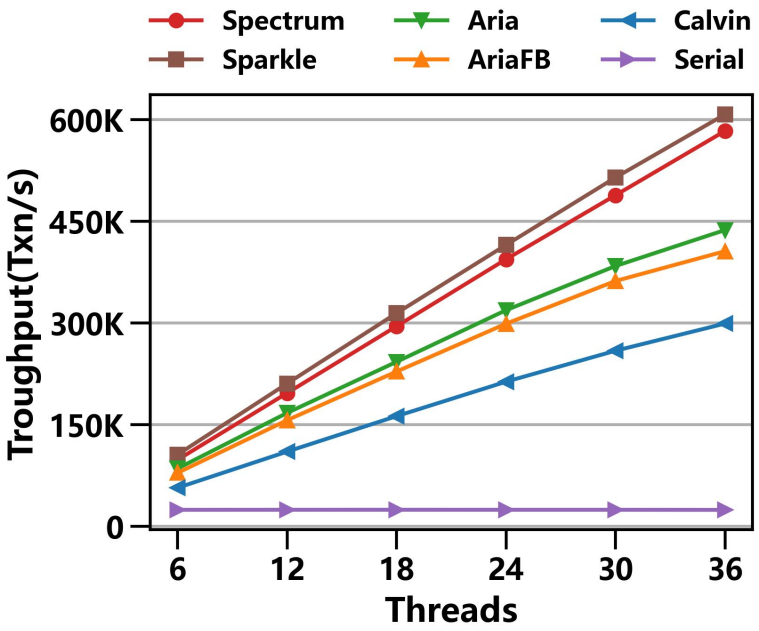
Kindly refer to our paper for further impl. and experiments

Evaluation

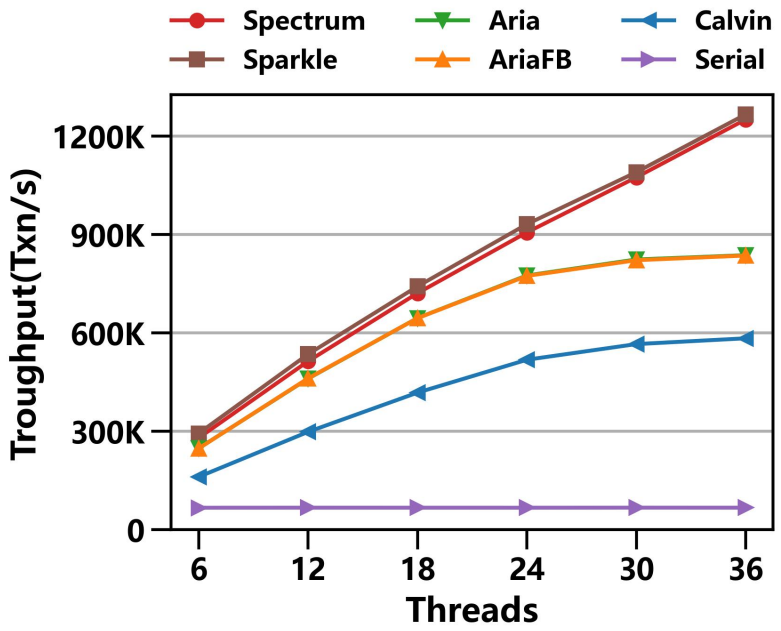
- Throughput of varying threads

  superior parallelism, no locking and phase synchronization

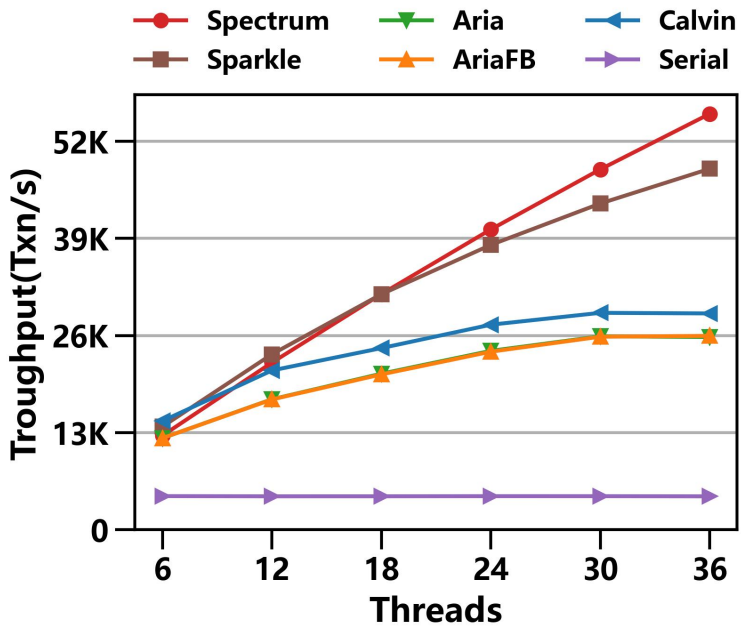
  - Under the uniform workload, both Spectrum and Sparkle scale well within 36 threads, and outperfrom Aria (1.3x~2.1x), AriaFB (1.4x~2.1x), Calvin (1.7x~1.9x) and Serial (12.7x~24.2x)



YCSB (Uniform)



SmallBank (Uniform)



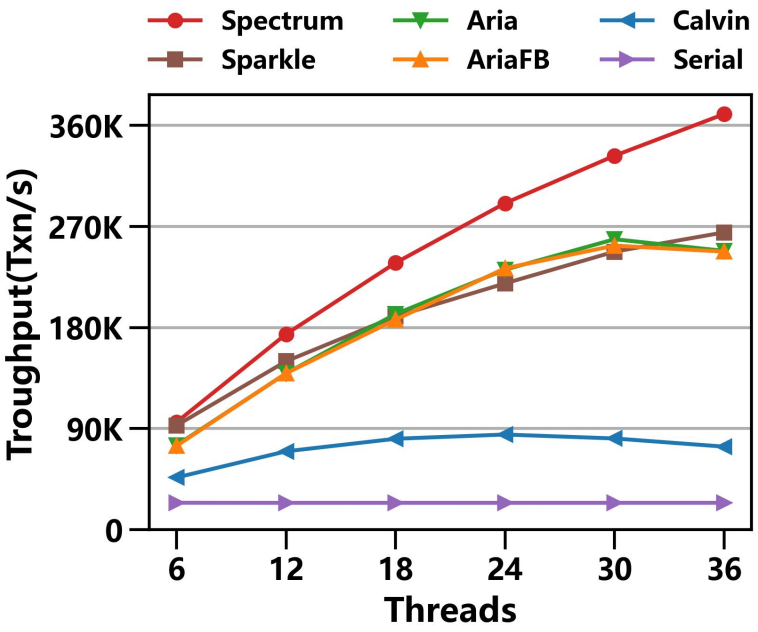
TPC-C (10 orderlines/order)

Evaluation

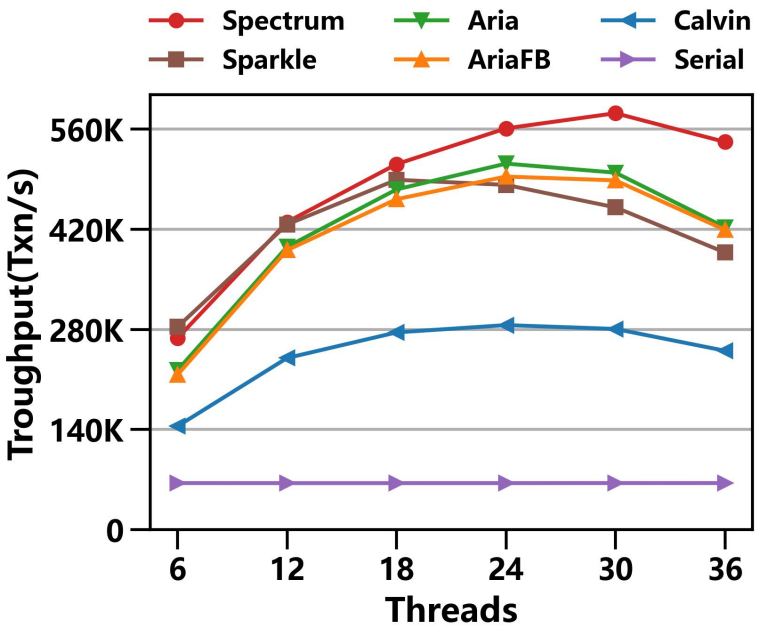
- Throughput of varying threads

only applies partial rollback

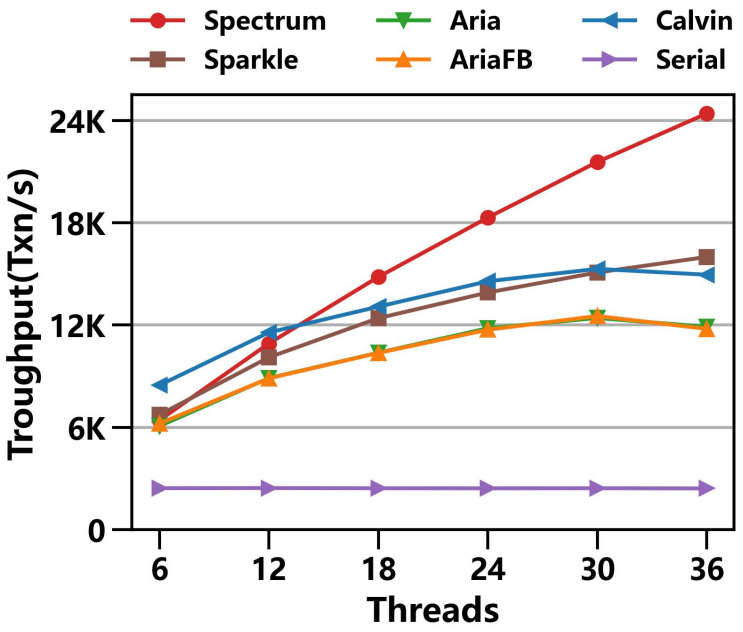
  - Under the skewed workload, Spectrum achieves the highest peak throughput
  - Up to 1.6x, 2.1x and 5.0x higher throughput than Sparkle, Aria, and Calvin



YCSB (Zipf = 0.9)



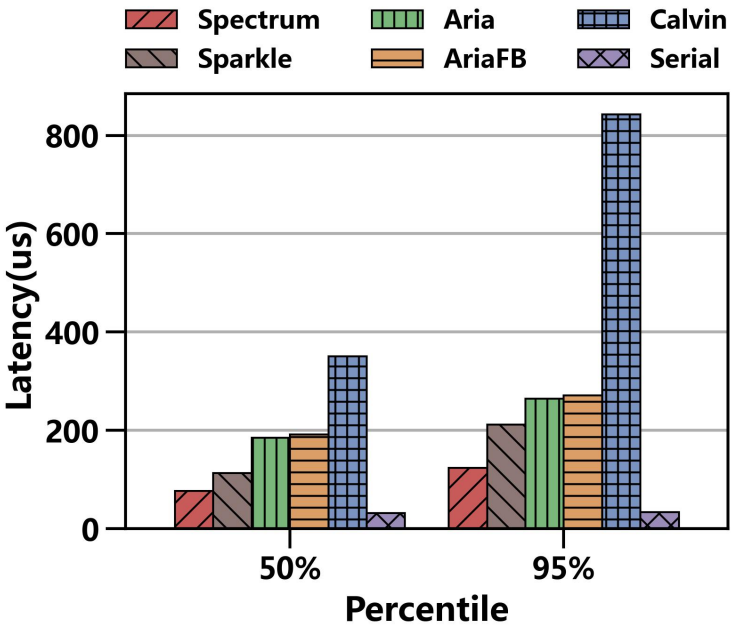
SmallBank (Zipf = 1.1)



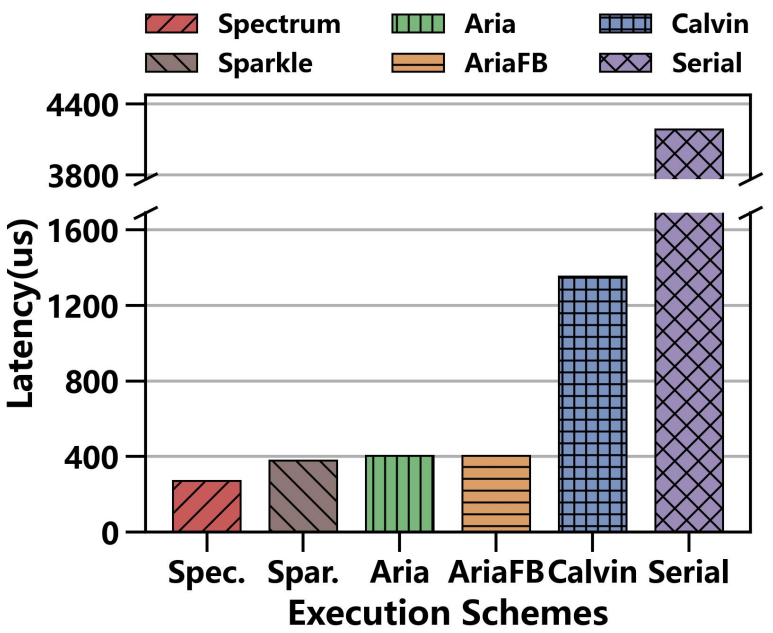
TPC-C (20 orderlines/order)

Evaluation

- Transaction and Block latency
  - Serial has the lowest tx latency, then Spectrum, Sparkle, Aria variants, and Calvin (the highest)
  - Spectrum realizes the lowest block latency, reducing it by 28.3%, 32.8%, 33.1%, 80.0%, and 93.5% compared to Sparkle, Aria, AriaFB, Calvin, and Serial, respectively



p50, p95 Tx latency (YCSB, Zipf = 0.9)

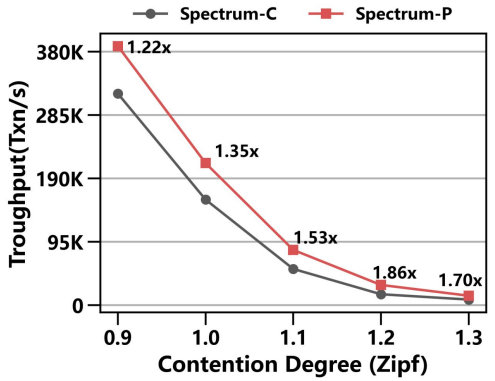


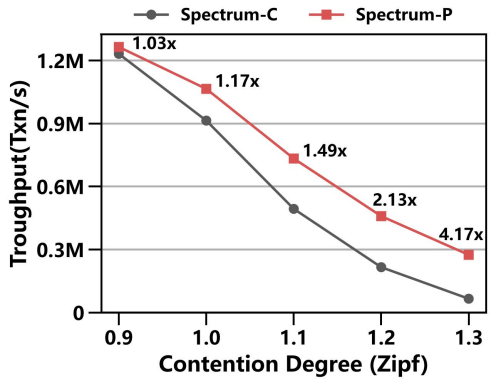
Block latency (YCSB, Zipf = 0.9)

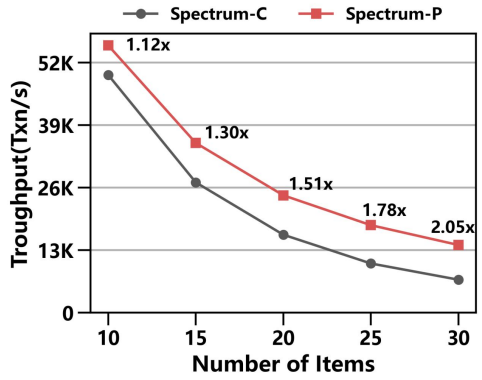
Evaluation

- Evaluation of partial rollback (re-execution overhead)
  - Partial rollback effectively reduces the number of operations to be rollbacked and re-executed, by 79.8%(YCSB), 57.6%(Smallbank) and 64.9%(TPC-C), compared to complete rollback

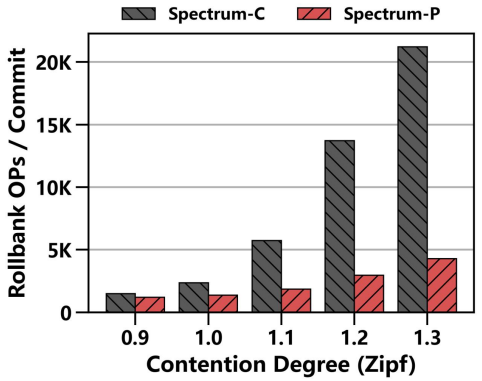
Scheme throughput in varying Zipf



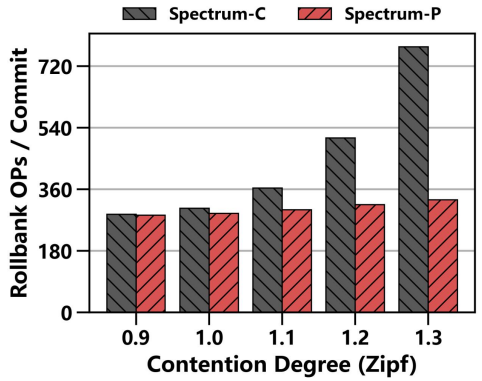




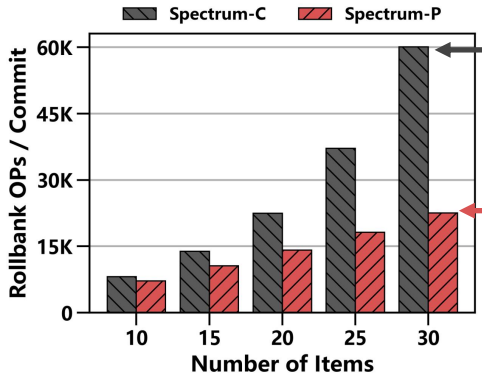
Rollback operations per committed tx



YCSB



SmallBank



TPC-C

with complete rollback

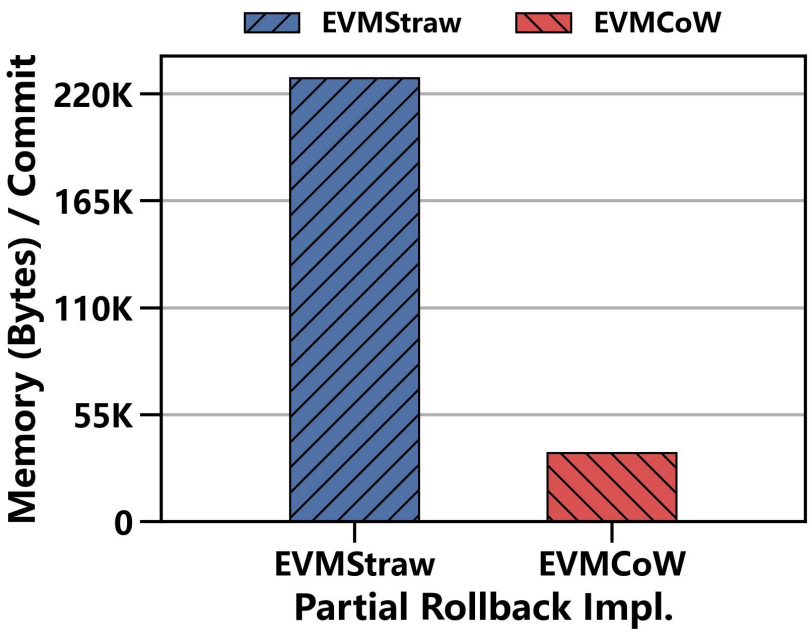
with partial rollback

Evaluation

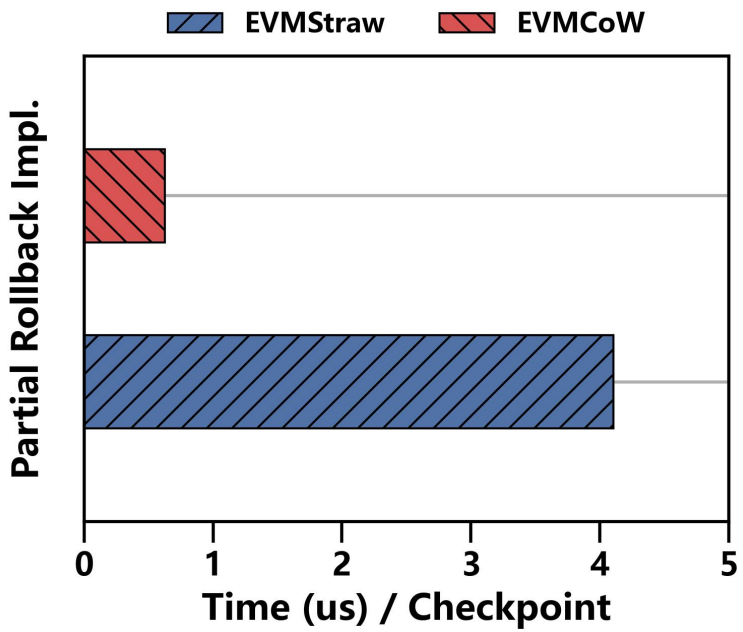
- Evaluation of partial rollback (efficiency of pStack)

strawman: copies all stack elements when checkpointing
pStack: uses Copy-on-Write mechanism for checkpointing

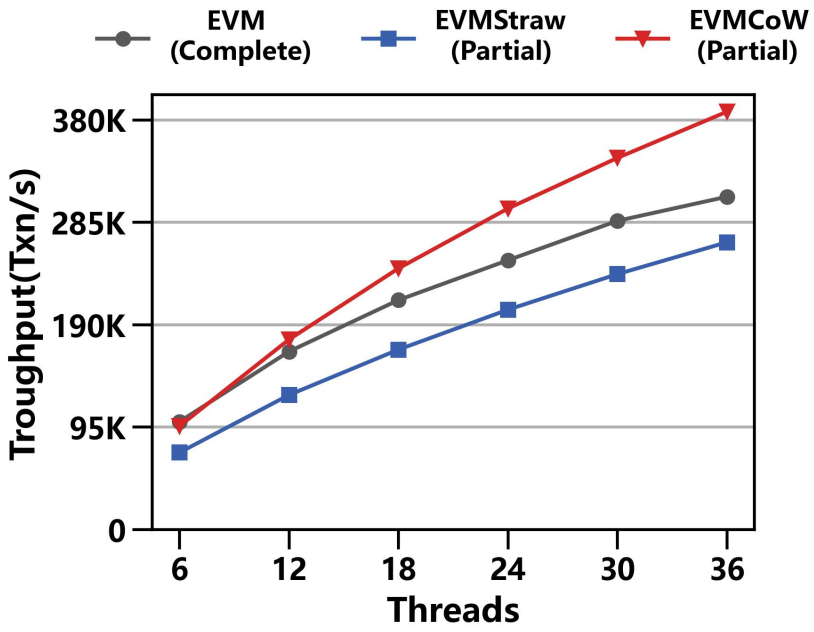
  - pStack saves 84.8% checkpointing memory cost and largely reduces creation time
  - pStack enhances throughput by 31.2% compared to the strawman approach
    - efficient impl. and cache-friendness



Memory Cost



Checkpointing Time Cost



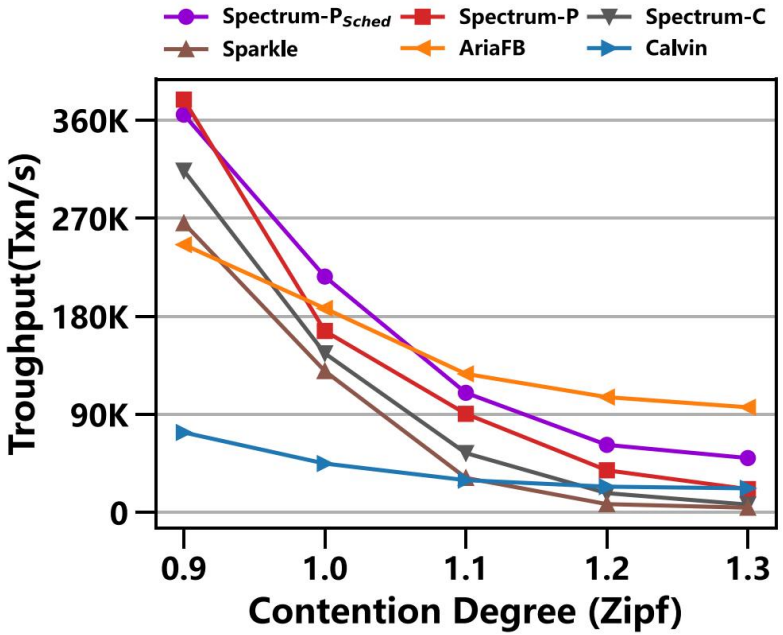
Integrated YCSB Throughput

Evaluation

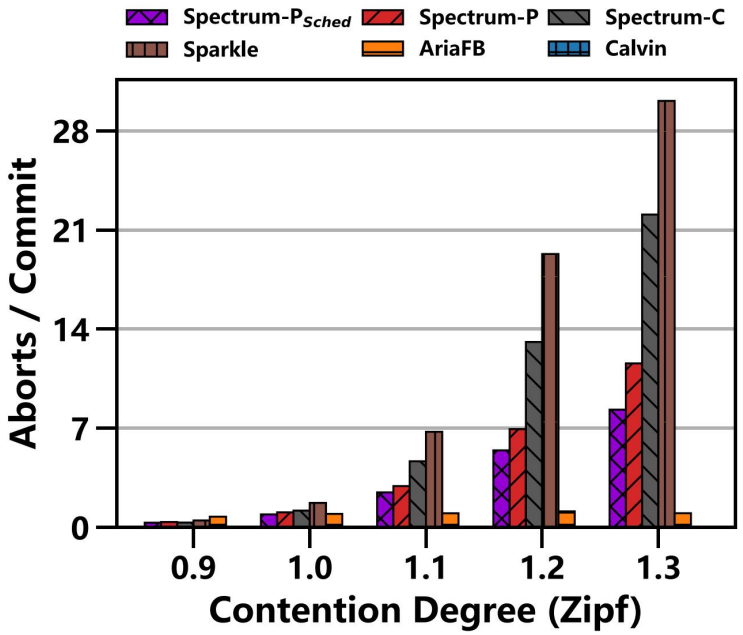
- Evaluation of predictive scheduling

Spectrum-P$_{Sched}$ implements both predictive scheduling and partial rollback
Spectrum-P only applies partial rollback
Spectrum-C employs neither of these optimizations

  - Spectrum-P$_{Sched}$ outperforms Spectrum-P by 2.3x and Spectrum-C by 6.8x
  - Predictive scheduling further reduces aborts (number of mis-speculations) by 28.2% to 62.3%



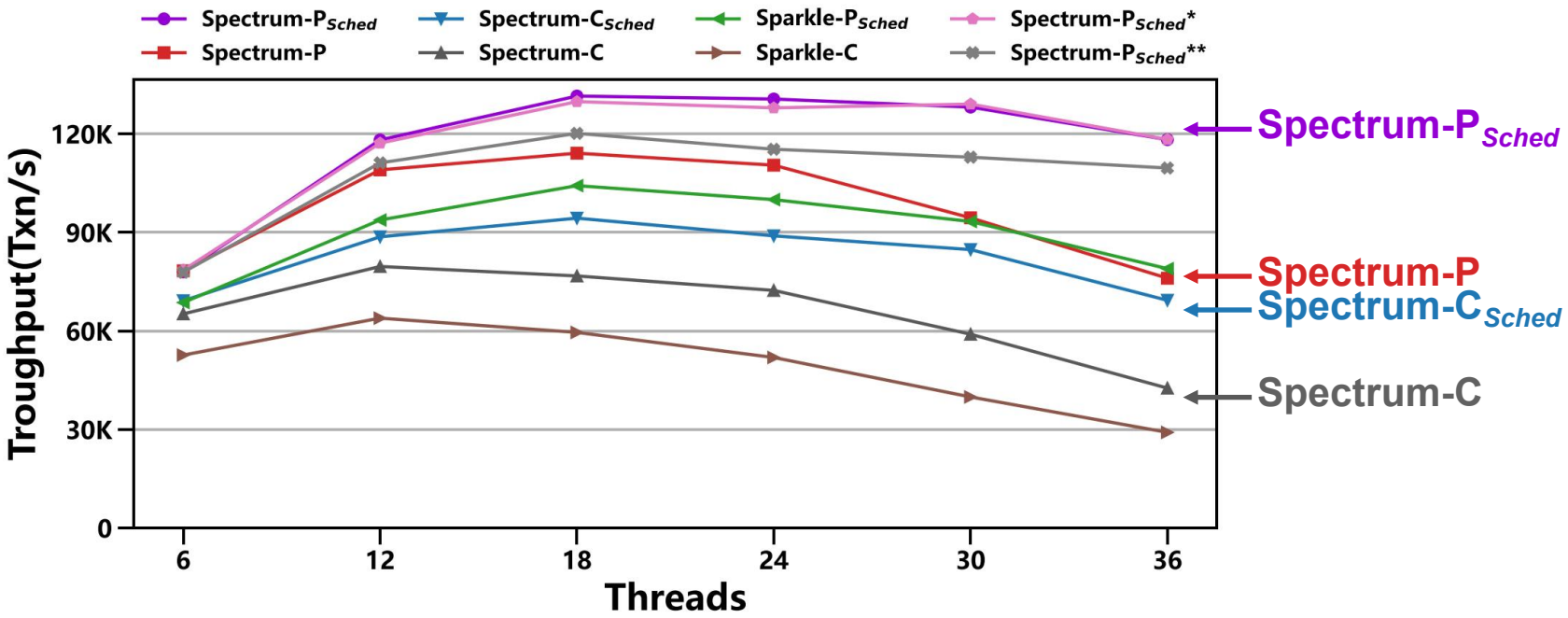
Throughput of varying Zipf (YCSB)



Aborts/Commit in Varying Zipf (YCSB)

Evaluation

- Ablation Studies on Integrated Optimizations
  - The improvement of using only pre-scheduling (Spectrum-C$_{Sched}$, 1.6x) is less than that of using only partial rollback (Spectrum-P, 1.8x), but leveraging both yields the best performance (Spectrum-P$_{Sched}$, 2.8x than Spectrum-C).



Throughput of Varying Threads (YCSB, Zipf = 1.1)

Conclusion & Future work

- Spectrum achieves both fair smart contract execution (by ensuring strict determinism) and high performance for blockchain ledgers
  - Speculative execution produces the same agreed-upon serial order with superior parallelism
  - Two novel optimizations: operation-level rollback & predictive scheduling
  - 1.4x ~ 4.1x higher throughput than SOTA DCC schemes (on YCSB,SmallBank,TPC-C alike smart contracts)
- Future work
  - Intra-transaction parallelism
  - Data-partitioned sharding settings

https://github.com/jacklightChen/spectrum

Paper Details

Source Code

Thank you for listening!

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