Efficient Concurrent Execution of Smart Contracts in Blockchains using Object-based Transactional Memory*

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Outline

1. Introduction
2. Bottleneck in Existing Blockchain Design
3. Challenges in Executing Smart Contract Transactions Concurrently
4. Related Work
5. Proposed Methodology: Multi-threaded Miner and Validator
6. Experimental Evaluation
7. Conclusion and Future Work

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- Blockchain is a distributed, decentralized database or ledger of records.

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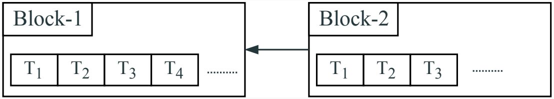

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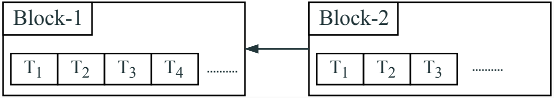

- Miners add blocks to the blockchain, and validators validate each block added to the blockchain.

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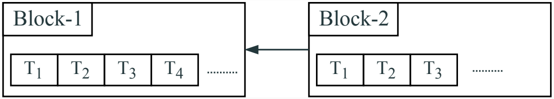

- Miners add blocks to the blockchain, and validators validate each block added to the blockchain.
- Example: Bitcoin[1], **Ethereum**[2], Hyperledger[3], etc.

▸ Execution of Ethereum

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Introduction: Ethereum High Level Design

- Ethereum nodes form a peer-to-peer system.
- Clients (external to the system) wishing to execute smart contracts, contact a peer of the system.

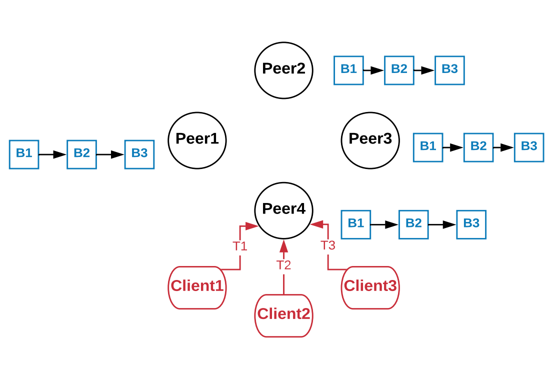

Figure 1: Clients send Transaction T1, T2 and T3 to Miner (Peer4)

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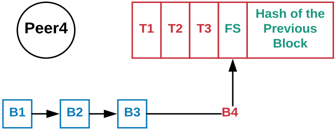

Figure 2: Miner forms a block B4 and computes final state (FS) sequentially

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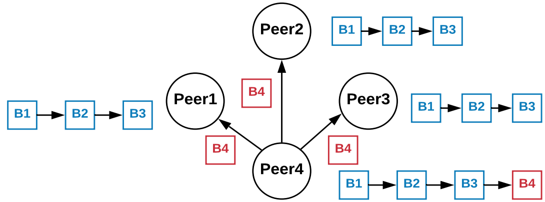

Figure 3: Miner broadcasts the block B4

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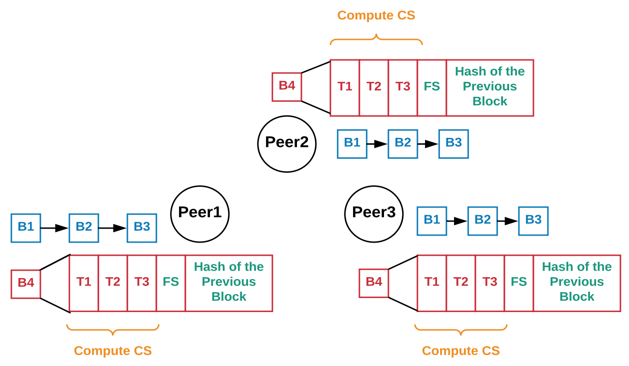

Figure 4: Validators (Peer 1, 2, and 3) compute current state (CS) sequentially

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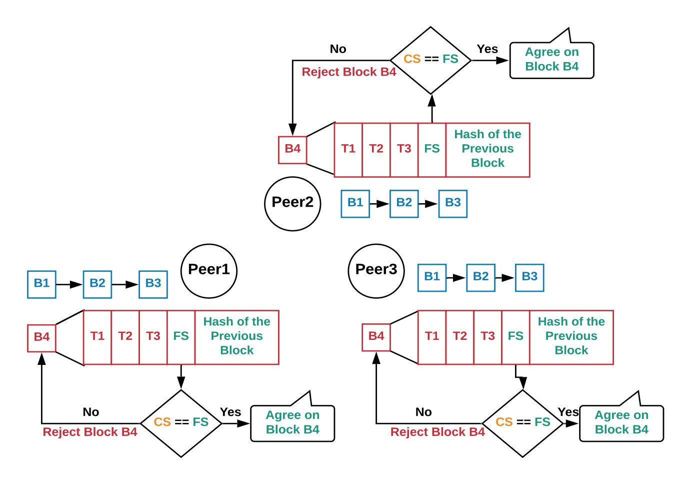

Figure 5: Validators verify the FS and reach the consensus protocol

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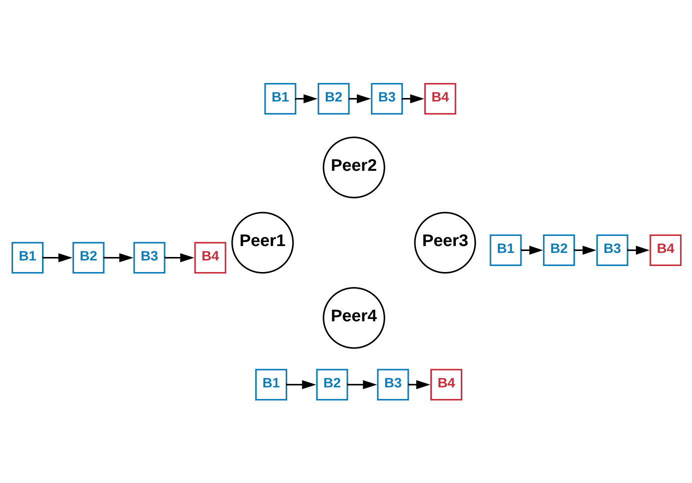

Figure 6: Block B4 successfully added to the blockchain

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Bottleneck in Existing Blockchain: Ethereum

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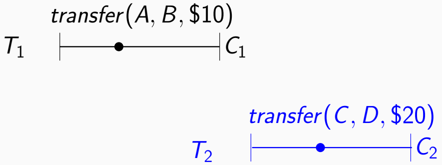
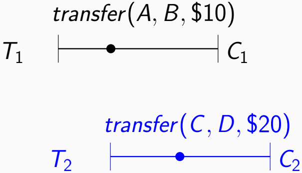


(a) Serial Execution of transactions



(b) Concurrent Execution

Figure 7: Motivation towards concurrent execution over serial

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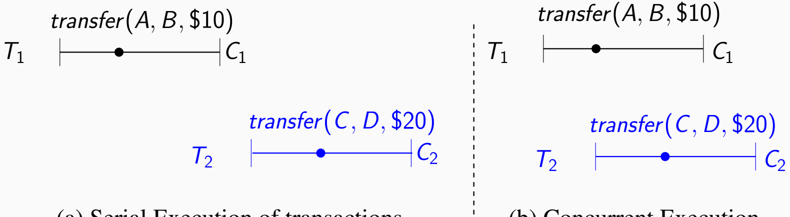

(a) Serial Execution of transactions (b) Concurrent Execution

Figure 7: Motivation towards concurrent execution over serial

- By leveraging multiple threads to execute transactions, we can achieve better efficiency and higher throughput.

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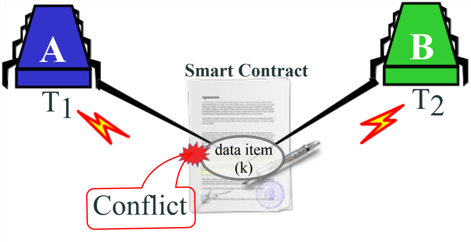
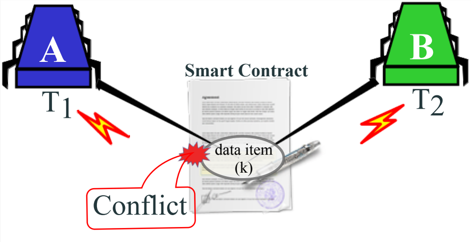


Figure 8: Conflicting access to shared data item.

Concurrent Execution Challenges (1/3)



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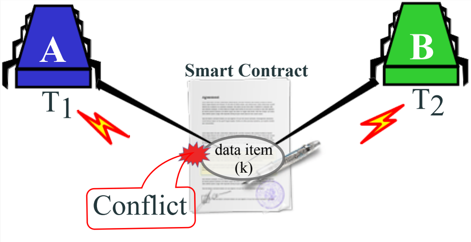

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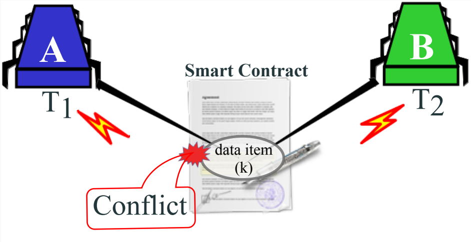

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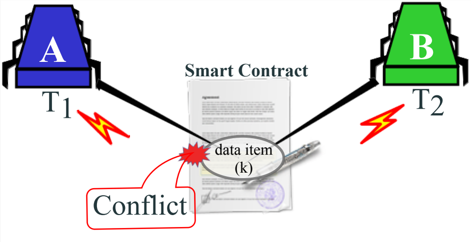

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- Improper use of locks may lead to deadlock.
- Discovering an equivalent serial schedule of concurrent execution of SCTs is difficult.

Solution: We use *Software Transactional Memory Systems (STMs)* to solve these challenges.

Concurrent Execution Challenges (2/3)

- Validator may incorrectly reject a valid block proposed by the miner. We call such error as **False Block Rejection (FBR)** error.

[5] Dickerson, T., Gazzillo, P., Herlihy, M., Koskinen, E.: Adding Concurrency to Smart Contracts. PODC, 2017

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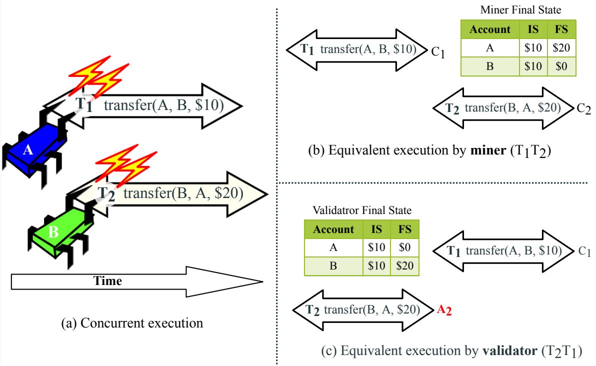

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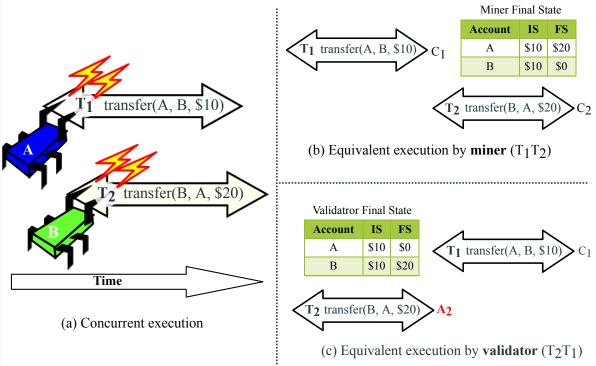

Miner Final State

Account	IS	FS
A	$10	$20
B	$10	$0

Validatror Final State

Account	IS	FS
A	$10	$0
B	$10	$20

Solution: Miner appends the *Block Graph (BG)*[5,6] in the proposed block to avoid the FBR error.

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Concurrent Execution Challenges (3/3)

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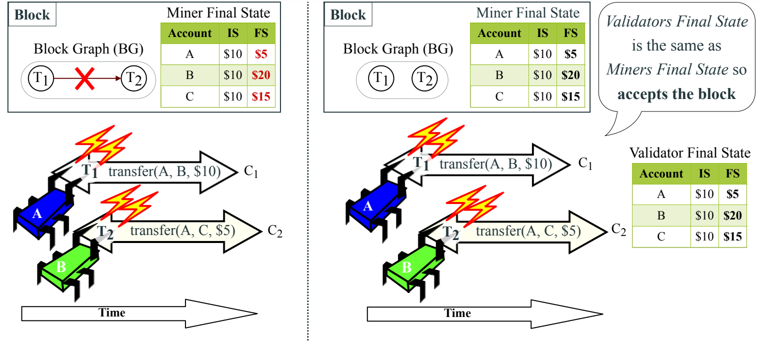

Miner Final State (a):

Account	IS	FS
A	$10	$5
B	$10	$20
C	$10	$15

Miner Final State (b):

Account	IS	FS
A	$10	$5
B	$10	$20
C	$10	$15

Validator Final State:

Account	IS	FS
A	$10	$5
B	$10	$20
C	$10	$15

(a) Concurrent execution by **malicious miner**

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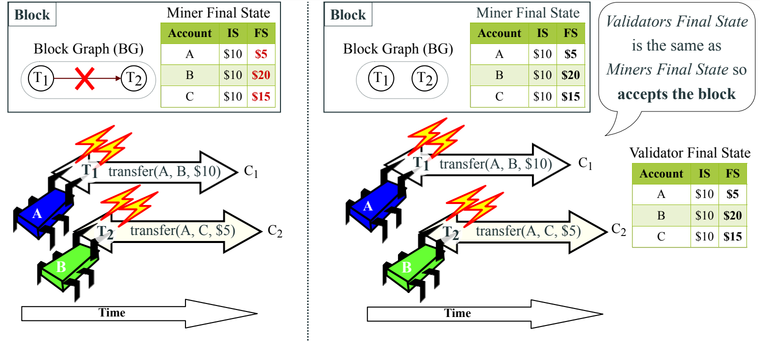

(a) Concurrent execution by **malicious miner** (b) Concurrent execution by **validator**

Solution: We propose a *Smart Multi-threaded Validator (SMV)* to detect EMB error and rejects the corresponding blocks.

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Related Work

There are a few papers in literature that work on concurrent execution of SCTs in the blockchain.

Solution	Miner Approach	Locks	Require Block Graph	Validator Approach	Handle Malicious Miner
Dickerson et al.[7]	Pessimistic ScalaSTM	Yes	Yes	Fork-join	Yes
Anjana et al.[8]	Optimistic RWSTM	No	Yes	Decentralized	No
Saraph and Herlihy[9]	Bin-based approach	Yes	No	Bin-based	No
Proposed Approach	**Optimistic ObjectSTM**	**No**	**Yes**	**Decentralized**	**Yes**

7 Dickerson, T., Gazzillo, P., Herlihy, M., Koskinen, E.: Adding Concurrency to Smart Contracts. PODC, 2017.

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9 Saraph, V., Herlihy, M.: An Empirical Study of Speculative Concurrency in Ethereum Smart Contracts. Tokenomics, 2019.

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- Hash Table based OSTMs export the following methods:
  - STM_begin()
  - STM_insert()
  - STM_delete()
  - STM_lookup()
  - STM_tryC()
  - STM_Abort()

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A Thread Safe Integration of STMs in Smart Contracts

Listing 1: Transfer function

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transfer(s_id, r_id, amt) {
  if(amt > bal[s_id])
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6  }
```

Listing 2: Transfer function using STM

```
7  transfer(s_id, r_id, amt) {
8    t_id = STM_begin();
9    s_bal = STM_lookup(s_id);
10   if(amt > s_bal) {
11     abort(t_id);
12     throw;
13   }
14   STM_delete(s_id, amt);
15   STM_insert(r_id, amt);
16   if(STM_tryC(t_id)!= SUCCESS)
17     goto Line 8;//Trans aborted
18 }
```

Block Graph (1/2)

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- **Multi-threaded miner** uses addVert() and addEdge() methods of BG.
- Later, validators re-execute the same SCTs concurrently and deterministically relying on the BG.
- Two SCTs that do not have a path can execute concurrently.

Block Graph (2/2)

- **SMV** uses searchGlobal() and decInCount() methods of BG. ▸ SMV

[11] Herlihy, M., Koskinen, E.: Transactional Boosting: A Methodology for Highly-concurrent Transactional Objects. PPoPP, 2008.

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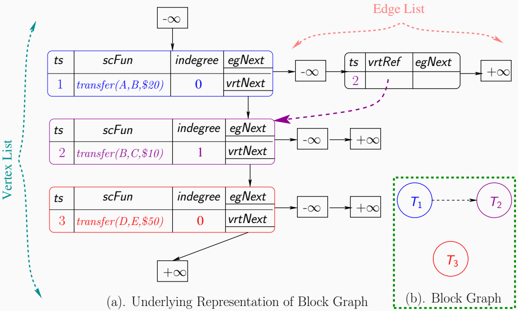

Figure 9: Data structure of BG

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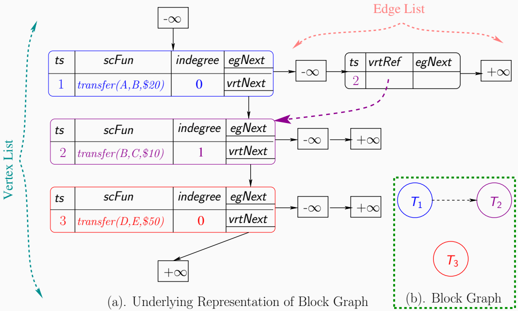

(a). Underlying Representation of Block Graph (b). Block Graph

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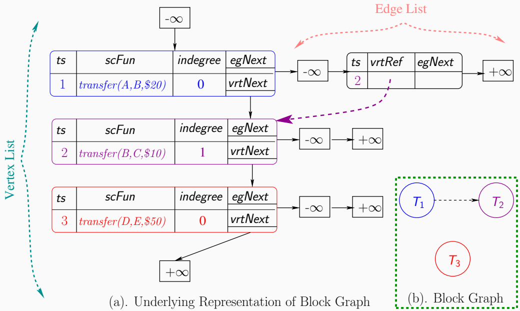

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- This also reduces the size of the BG leading to a smaller communication cost than RWSTMs.

[11] Herlihy, M., Koskinen, E.: Transactional Boosting: A Methodology for Highly-concurrent Transactional Objects. PPoPP, 2008.

Greater Concurrency: Multi-Version OSTM based Miner

- *Multi-Version OSTMs (MVOSTMs)*[12] maintain multiple versions for each shared data item and provide greater concurrency relative to *Single-Version OSTMs (SVOSTMs)*.

12 Juyal, C., Kulkarni, S., Kumari, S., Peri, S., Somani, A.: An innovative approach to achieve compositionality efficiently using multi-version object based transactional systems. SSS, 2018.

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- MVOSTM-based BG has fewer edges than an SVOSTM-based BG, and further reduces the size of the BG leading to a smaller communication cost.

▸ MVOSTM

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Outline

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2. Bottleneck in Existing Blockchain Design

3. Challenges in Executing Smart Contract Transactions Concurrently

4. Related Work

5. Proposed Methodology: Multi-threaded Miner and Validator

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- We converted smart contracts from Solidity to **C++** language for multi-threaded execution.

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Workload	SCTs	Threads	Shared data items
Workload 1 (W1)	50 - 300	50	500
Workload 2 (W2)	100	10 - 60	500

Results: Multi-threaded Miner Speedup

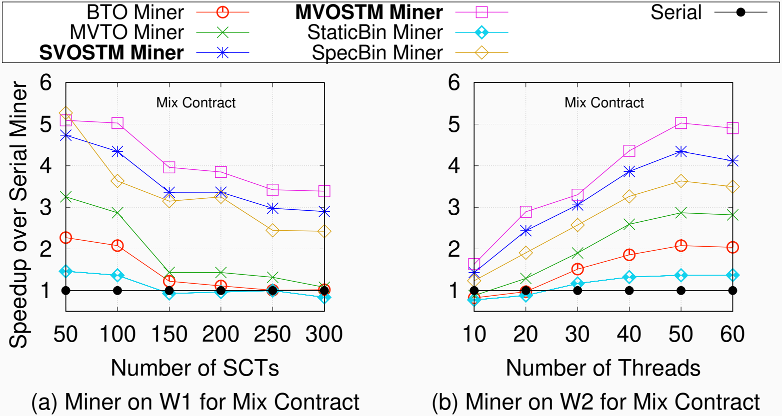
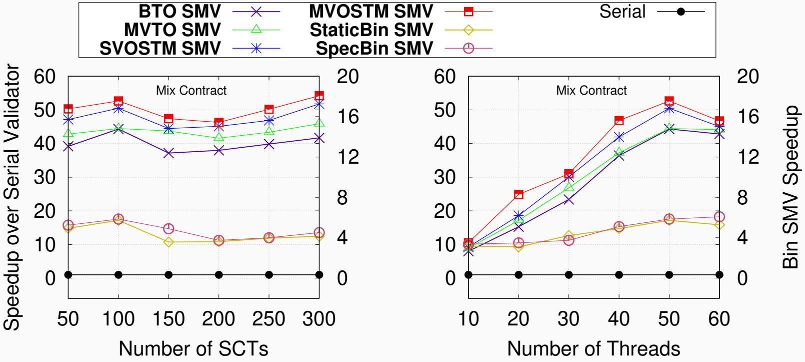


Figure 10: Speedup of Multi-threaded miner over Serial miner

- **MVOSTM, SVOSTM**, MVTO, BTO, Speculative Bin, and Static Bin miner provide an average speedup of **3.91**×**, 3.41**×, 1.98×, 1.5×, 3.02×, and 1.12×, over Serial miner, respectively.

Results: SMV Speedup



(a) SMV on W1 for Mix Contract (b) SMV on W2 for Mix Contract

Figure 11: Speedup of SMV over Serial validator

- **MVOSTM, SVOSTM, MVTO, BTO, Speculative Bin,** and **Static Bin Decentralized SMVs** provide an average speedup of **48.45**×, **46.35**×, **43.89**×, **41.44**×, **5.39**×, and **4.81**× over Serial validator, respectively.

Results: Malicious Block

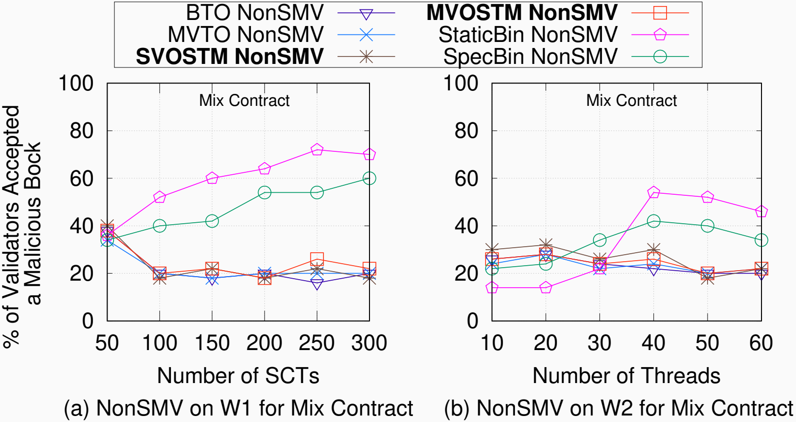


Figure 12: Percentage of NonSMV accepting a malicious block

- Acceptance of even a single malicious block result in the blockchain going into inconsistent state.

▸ Other Experiments.

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- We developed an efficient framework for concurrent execution of SCTs by a multi-threaded miner using two protocols, SVOSTM and MVOSTM of optimistic STMs[13].

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Conclusion

- We developed an efficient framework for concurrent execution of SCTs by a multi-threaded miner using two protocols, SVOSTM and MVOSTM of optimistic STMs[13].
- To avoid FBR errors, the multi-threaded miner captures the dependencies among SCTs in the form of a BG.

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- To handle EMB error, we proposed SMV that re-executes SCTs concurrently relying on the BG provided by the miner.
- The proposed approach achieves significant performance gain over the state-of-the-art SCTs execution framework.

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Future Work

- A malicious miner can intentionally append a BG in a block with additional edges to delay other miners. Preventing such a malicious miner would be an immediate future work.

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- EVM does not support multi-threading, so, another research direction is to design a multi-threaded EVM.
- Another interesting direction is to apply concurrency in the nested execution of SCTs.

Collaborators

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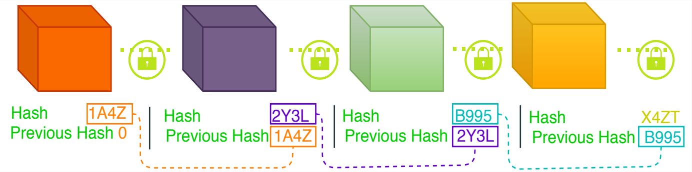
Thanks!

Introduction: Blockchain



return

Read-Write STM (RWSTM) v/s Object-based STM (OSTM)

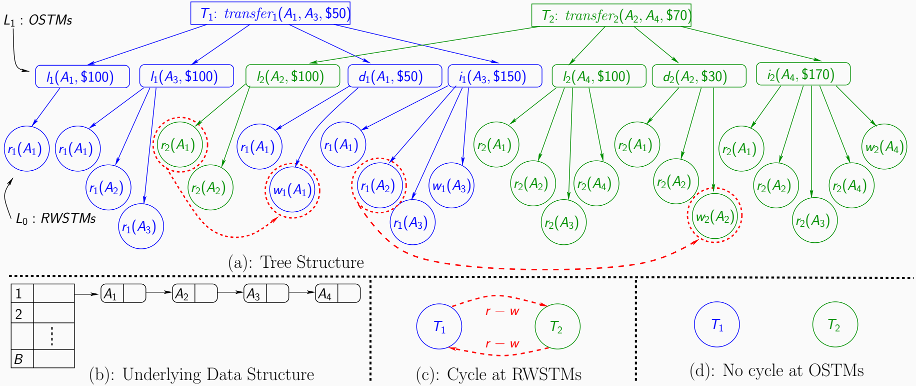
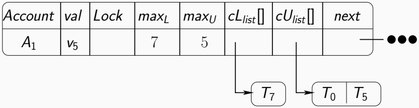
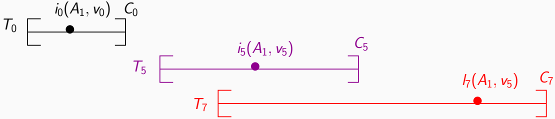


Figure 13: (a) Two SCTs T_1 and T_2 in the form of a tree structure which is working on a hash-table with B buckets where four accounts (shared data items) A_1, A_2, A_3 and A_4 are stored in the form of a list depicted in (b). T_1 transfers \$50 from A_1 to A_3 and T_2 transfers \$70 from A_2 to A_4. After checking the sufficient balance using lookup (l), SCT T_1 deletes (d) \$50 from A_1 and inserts (i) it to A_3 at higher-level (L_1). At lower-level 0 (L_0), these operations involve read (r) and write (w) to both accounts A_1 and A_3. Since, its conflict graph has a cycle either T_1 or T_2 has to abort (see (c)); However, execution at L_1 depicts that both transactions are working on different accounts and the higher-level methods are isolated. So, we can prune this tree and isolate the transactions at higher-level with equivalent serial schedule $T_1 T_2$ or $T_2 T_1$ as shown in (d).

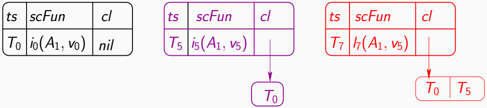
Data Structure of SVOSTM to Maintain Conflicts



(a) Structure of Shared data-item



(b) Timeline View



(c) Transactions Conflict List

Figure 14: Underlying Data Structure of SVOSTM

return

Block Graph: Components

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  1. **Return value from (rvf) edge:** If $STM\_tryC_i()$ on k by a committed transaction T_i completed before $rv_j(k, v)$ on key k by T_j in history H such that T_j returns a value $v \neq \mathcal{A}$ then there exist an *rvf edge* from T_i to T_j, i.e., $T_i \rightarrow T_j$;

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  2. **Multi-version (mv) edge:** consider a triplet, $STM\_tryC_i(), rv_m(k, v)$, $STM\_tryC_j()$ in which $(updSet(T_i) \cap updSet(T_j) \cap rvSet(T_m) \neq \emptyset)$, (two committed transactions T_i and T_j update the key k with value v and u respectively) and $(u, v \neq \mathcal{A})$; then

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     2.1 If $STM\_tryC_i() <_H STM\_tryC_j()$ then there exist a *mv edge* from T_m to T_j.
     2.2 If $STM\_tryC_j() <_H STM\_tryC_i()$ then there exist a *mv edge* from T_j to T_i.

Data Structure of MVOSTM to Maintain Conflicts

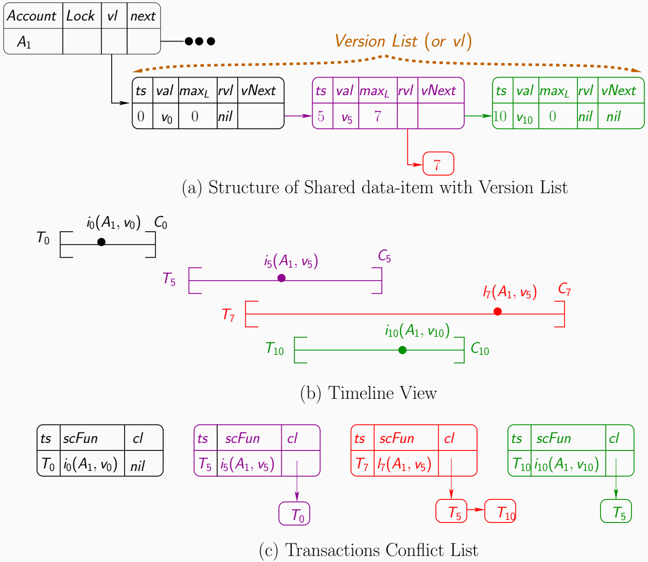

Figure 15: Underlying Data Structure of SVOSTM

Single-version v/s Multi-version OSTMs

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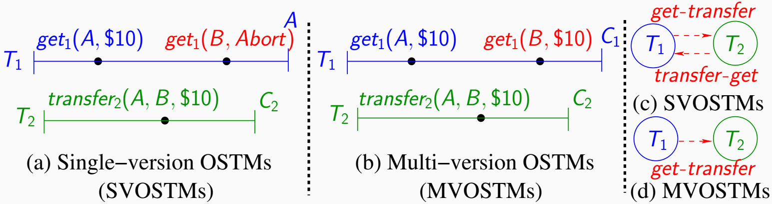

Figure 16: (a) Transaction T_1 gets the balance of two accounts A and B (both initially \$10), while transaction T_2 transfers \$10 from A to B and T_1 aborts. Since, its conflict graph has a cycle (see (c)); (b) When T_1 and T_2 are executed by MVOSTM, T_1 can read the old versions of A and B. This can be serialized, as shown in (d).

Correctness Criteria: Opacity

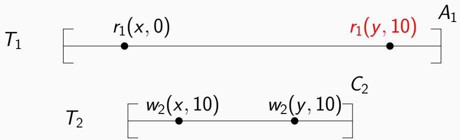

Figure 17: History H is not Opaque

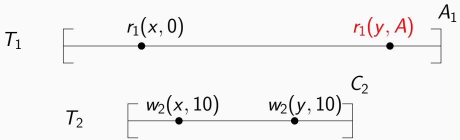

Figure 18: Opaque History H

return

Smart Multi-threaded Validator

SMV maintains two global counters (gUC: global update counter and gLC: global lookup counter) and two local counters (lUC and lLC) for each shared data item k to identifies the EMB error.

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Lookup(k):

- **If**(k.gUC == k.lUC)
  1. Atomically increment the global lookup counter, k.gLC.
  2. Increment k.lLC by 1.
  3. Lookup key k from a shared memory.

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Insert(k, v)/Delete(k):

- **If**(k.gLC == k.lLC && k.gUC == k.lUC)
  1. Atomically increment the global update counter, k.gUC.
  2. Increment k.lUC by 1.
  3. Insert/delete key k to/from shared memory.

  else miner is malicious.

▸ return

Algorithm 1: SMV(scFun): Execute scFun with atomic global lookup/update counter.

```
// scFun is a list of steps.
while (scFun.steps.hasNext()) do
    curStep = scFun.steps.next(); //Get the next step to execute.
    switch (curStep) do
        case lookup(k): do
            // Check for update counter (uc) value.
            if (k.gUC == k.lUC_i) then
                Atomically increment the global lookup counter, k.gLC;
                Increment k.lLC_i by 1;//Maintain k.lLC_i in transaction local log.
                Lookup k from a shared memory;
            end
            else
                return ⟨Miner is malicious⟩;
            end
        end
        case insert(k, v): do
            // Check lookup/update counter value.
            if ((k.gLC == k.lLC_i) && (k.gUC == k.lUC_i)) then
                Atomically increment the global update counter, k.gUC;
                Increment k.lUC_i by 1;//Maintain k.lUC_i in transaction local log.
                Insert k in shared memory with value v;
            end
            else
                return ⟨Miner is malicious⟩;
            end
        end
    end
end
Atomically decrements the k.gLC and k.gUC corresponding to each shared data-item key k;
```

▸ return

```
// scFun is a list of steps.
while (scFun.steps.hasNext()) do
    curStep = scFun.steps.next(); //Get the next step to execute.
    switch (curStep) do
        case delete(k): do
            // Check lookup/update counter value.
            if ((k.gLC == k.lLC_i) && (k.gUC == k.lUC_i)) then
                Atomically increment the global update counter, k.gUC;
                Increment k.lUC_i by 1; //Maintain k.lUC_i in transaction local.
                Delete k in shared memory;
            end
            else
                return ⟨Miner is malicious⟩;
            end
        end
    end
end
Atomically decrements the k.gLC and k.gUC corresponding to each shared data-item key k;
```

▸ return

Results: BG Depth

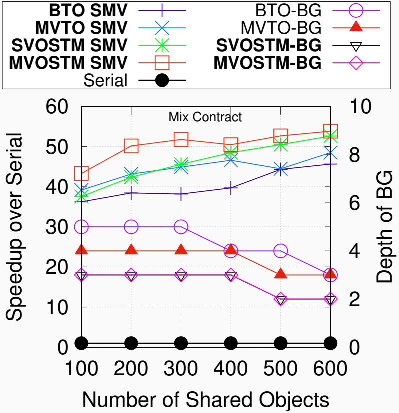

Figure 19: Speedup of SMV over serial and depth of BG for W3

Results: Dependencies in BG

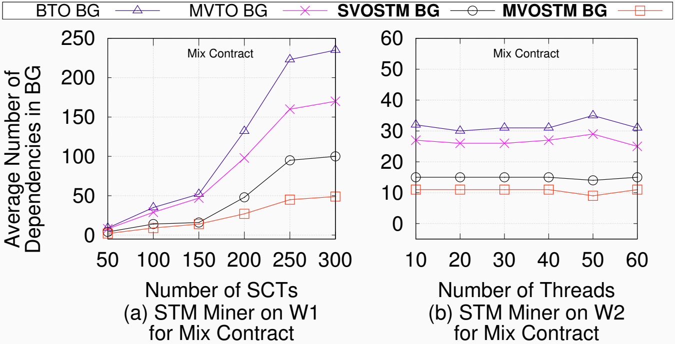

Figure 20: Average number of dependencies in BG for mix contract on W1 and W2

Results: Average Speedup by Multi-threaded Miner

Table 1: Overall average speedup on all workloads by multi-threaded miner over serial miner

Contract	Multi-threaded Miner					
	BTO Miner	**MVTO Miner**	**SVOSTM Miner**	**MVOSTM Miner**	**StaticBin Miner**	**SpecBin Miner**
Coin	1.596	1.959	4.391	5.572	1.279	6.689
Ballot	0.960	1.065	2.229	2.431	1.175	2.233
Auction	2.305	2.675	3.456	3.881	1.524	2.232
Mix	1.596	2.118	3.425	3.898	1.102	3.080
Total Avg. Speedup	*1.61*	*1.95*	*3.38*	*3.95*	*1.27*	*3.56*

Results: Average Speedup by Smart Multi-threaded Validator

Table 2: Overall average speedup on all workloads by SMV over serial validator

Contract	Smart Multi-threaded Validator (SMV)					
	BTO SMV	MVTO SMV	SVOSTM SMV	MVOSTM SMV	StaticBin SMV	SpecBin SMV
Coin	26.576	28.635	30.344	32.864	5.296	7.565
Ballot	26.037	28.333	33.695	36.698	3.570	3.780
Auction	27.772	31.781	29.803	32.709	4.694	5.214
Mix	36.279	39.304	42.139	45.332	4.279	4.463
Total Avg. Speedup	*29.17*	*32.01*	*34.00*	*36.90*	*4.46*	*5.26*

▸ return