Maat: Analyzing and Optimizing Overcharge on Blockchain Storage

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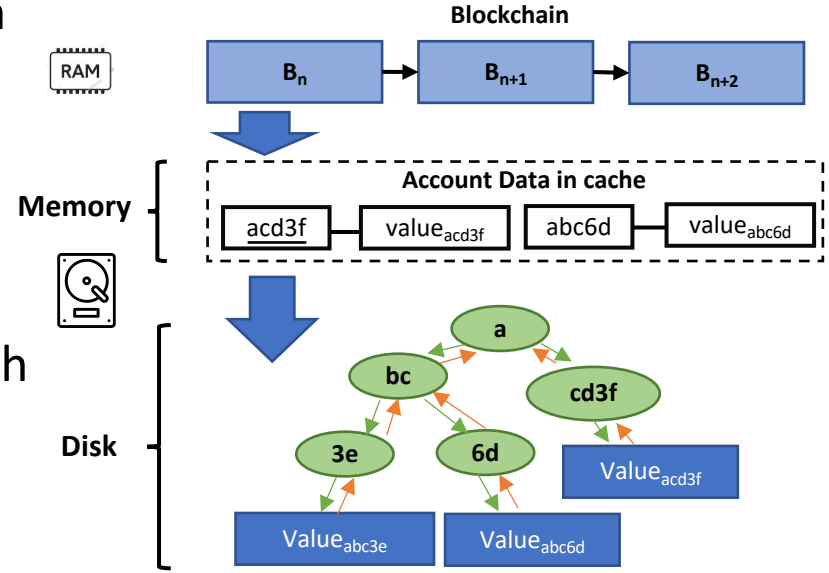
Blockchain and its world state

- Blockchain is a distributed ledger consisting of a chain of blocks, each containing transactions that interact with the blockchain world state.
- Blockchain world state
  - Blockchain world state contains all account and contract data, and is organized as Merkle Patricia Tries, with nodes stored on disk.
  - To improve efficiency, a partial blockchain world state is stored in memory caches shared by several adjacent blocks (max 128 blocks).



Read and write on world state

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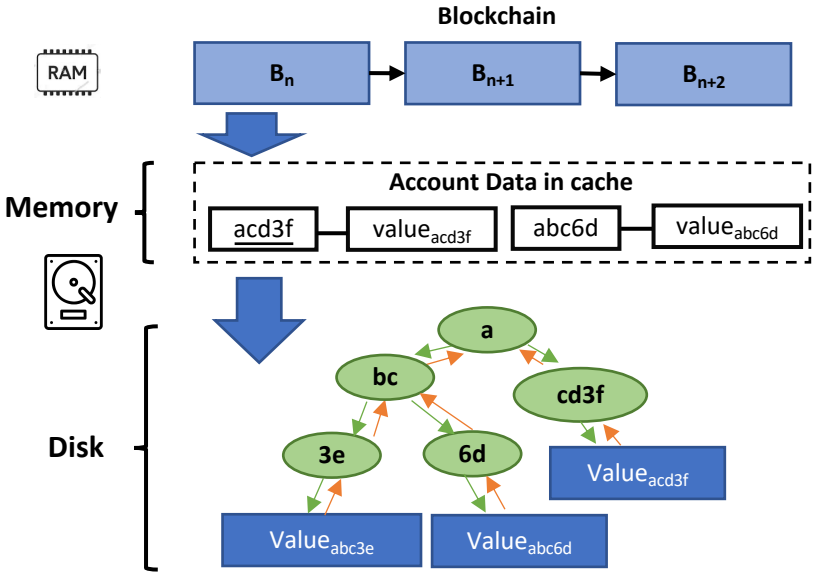
Read on world state:

Transactions first fetch data from the memory caches. If the caches miss, transactions will access the data stored on hard disk.

Write on world state:

Transactions first write the updated data to the memory caches. After the transactions in a block are finished, the updated data will be written to hard disk.



Transaction fee mechanism

- To prevent unlimited access and modification on world states, blockchain charges users with some transaction fee based on the usage of on-chain resource, which is measured in gas units.
- Gas cost
  - Every transaction/contract operations (e.g., data access on disk) will be assigned a *gas cost.*
  - Gas cost is designed to reflect the actual resource consumption
    - Reading contract data from memory caches: 100 gas units
    - Reading contract data from disk: 2100 gas units

Table 2: Charges for opcodes on blockchain storage.

opcode	$g_{memload}$ (gas)	$g_{memstore}$ (gas)	$g_{diskload}$ (gas)	$g_{diskstore}$ (gas)
sload	100	N.A.	2,100	N.A.
balance	100	N.A.	2,600	N.A.
extcodesize	100	N.A.	2,600	N.A.
extcodehash	100	N.A.	2,600	N.A.
extcodecopy	100	N.A.	2,600	N.A.
call/callcode	100	N.A.	2,600	9,000
delegatecall	100	N.A.	2,600	N.A.
staticcall	100	N.A.	2,600	N.A.
$call_{external}$	N.A.	N.A.	N.A.	9,000
sstore	100	100	2,100	2,900
create/create2	N.A.	N.A.	N.A.	L_{code}*200

$call_{external}$ indicates external transactions (i.e., EOA to EOA), L_{code} indicates the length of the bytecode.

Our focus

In this work, we focus on *those storage related gas cost*

- Blockchain, like Ethereum, has been suffering from high transaction fees as a huge problem. For example, in 2023, users paid 2.4 billion USD in transaction fees on Ethereum.
- The storage related gas cost accounted for more than 70% of these transaction fees.

"High fees are a huge problem and the main thing that prevents the platform from being used for cool stuff today is just the fees." — Vitalik Buterin, Ethereum co-founder

Overcharge issues

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- Overcharge issues
  - By investigating the specifications and implementations of Ethereum clients, we uncover ***three overcharging issues***.
  - The gas cost for account/contract operations is higher than the actual resource usage

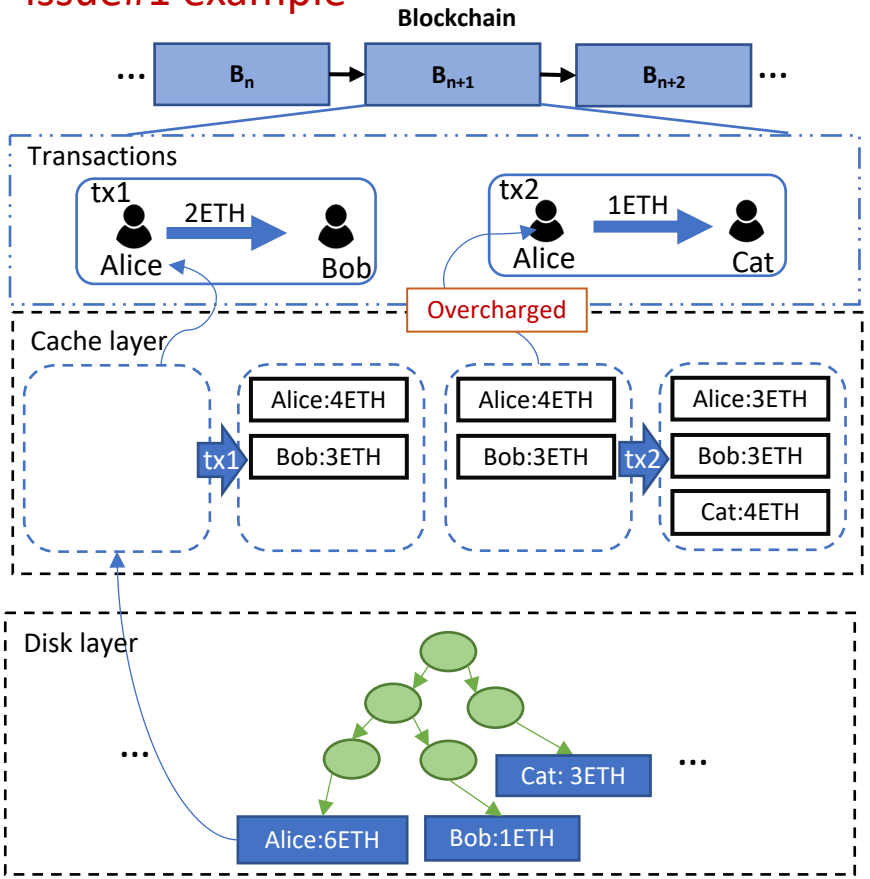
  E.g., charging a memory load operation as the fee of a disk load operation.

Overcharge issues

➢Issue#1

- Scenario: two transactions continuously read/write the same object in a block.
- Overcharged cases: Charging the gas cost of a disk read/write operation (2,100 gas) for a memory read/write operation on intra-block memory cache.

Issue#1 example

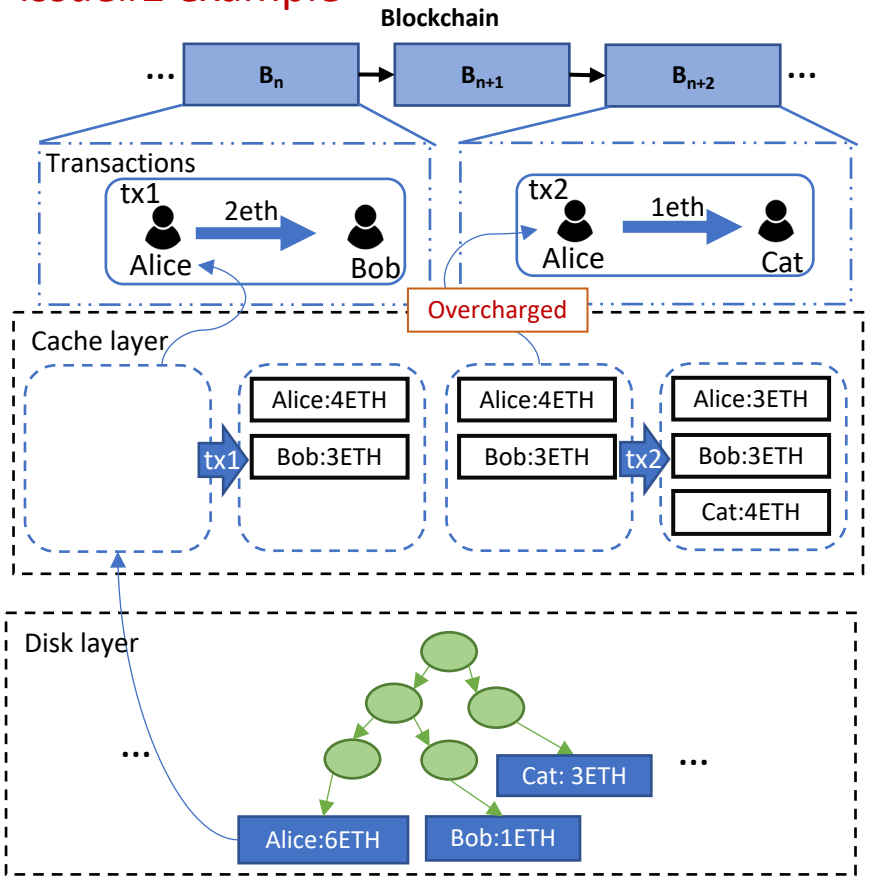


Overcharge issues

➢Issue#2

- Scenario: Two transactions continuously read the same object within 128 blocks.
- Overcharged cases: Charging the gas cost of a disk read operation (2,100 gas) for a memory read operation on cross-block memory cache.

Issue#2 example

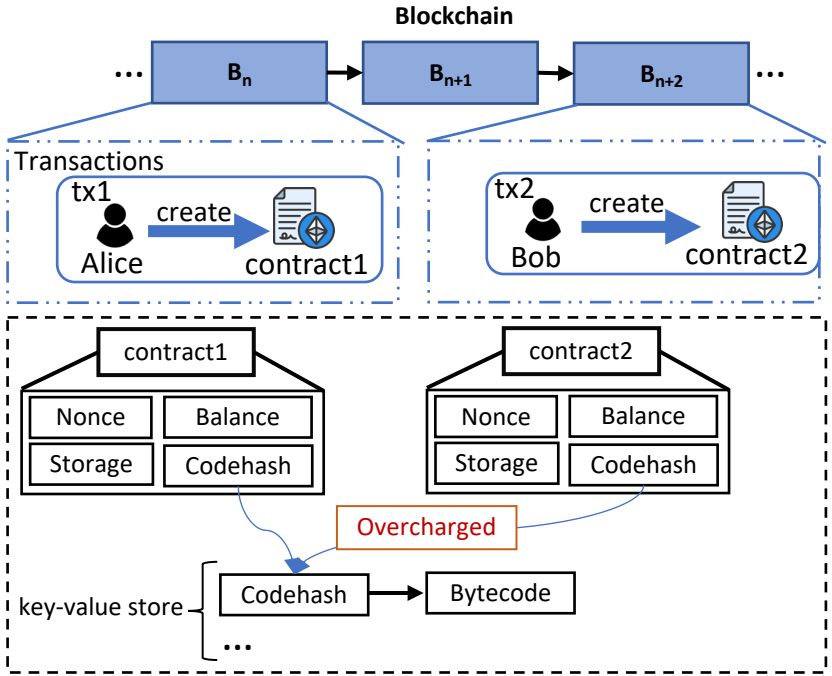


Overcharge issues

➢Issue#3

- Scenario: two transactions deploy contracts with duplicated bytecode.
- Overcharged cases: Charging an unnecessary disk write fee for storing the duplicated bytecode on disk (200 gas per byte).

Issue#3 example



Impact of three overcharging issues

- We measure the overcharging issues on Ethereum and BSC within the block range from #18M (Aug 26, 2023) to #19M (Jan 13, 2024) and the block range from #34.15M (Dec 07, 2023) to #35.15M (Jan 11, 2024)

	Ethereum	BSC
Transactions (Issue#1)	43.7% (69M)	63.1% (106M)
Fees (Issue#1)	25.6% (90M USD)	23.7% (6M USD)
Transactions (Issue#2)	42.4% (67M)	62.0% (104M)
Fees (Issue#2)	12.9% (45M USD)	15.3% (4M USD)
Transactions (Issue#3)	0.5% (1M)	0.3% (0.5M)
Fees (Issue#3)	3.5% (12M USD)	2.7% (1M USD)
Transactions (Total)	70.4% (117M)	92.8% (156M)
Fraction of fees (Total)	42.0% (147M USD)	41.7% (11M USD)

Maat Overview

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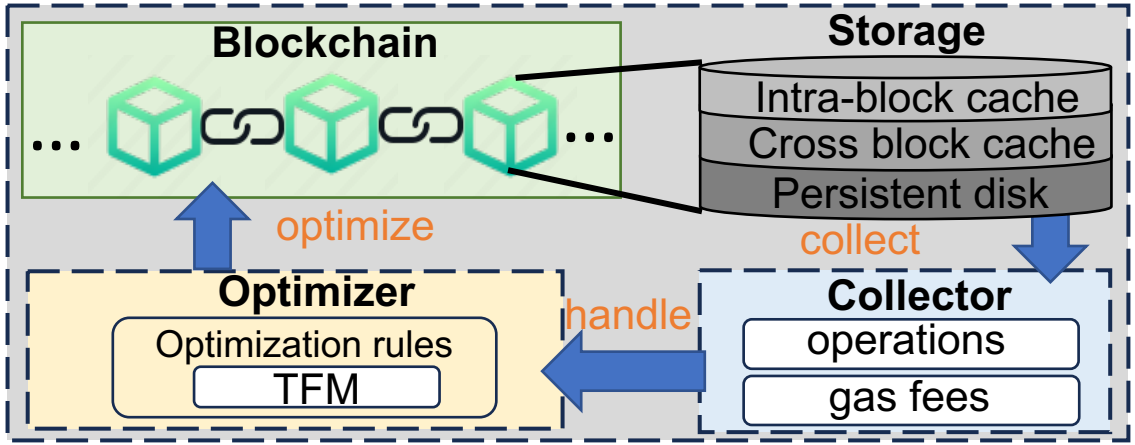
✓Target: Optimize the identified overcharging issues in blockchains

➢Methodology: Align the actual workloads of storage operations with gas fees.

- Collector: Gather storage operations and the fine-grained gas fees of the storage operations from the block and transaction execution in clients.
- Optimizer: Apply four optimization rules to optimize the gas fees in the actual cases of overcharging issues collected by Collector.



Four optimization rules

- O1/O2 target Issue#1, i.e., repeated memory reads/writes are incorrectly charged as disk reads/writes within the intra-block cache.
  - Replacing the incorrect charges of disk read/write with the fee of memory read/write.
- O3 addresses Issue#2, i.e., repeated memory reads are mistakenly charged as disk reads in the cross-block cache.
  - Replacing the incorrect charges of disk read as the fee of memory read.
- O4 mitigates Issue#3, i.e., deploying contracts with duplicated bytecode, where redundant disk fees are charged.
  - Eliminating the charges of deploying contracts with duplicated bytecode.

Design consideration

- Q1: How does Maat ensure that optimized gas charges are consistent across all clients?
  - We harness the inherent data structures of the blockchain to formalize the conditions for the four optimization rules.
  - The inherent data structures include block, transaction, account, contract variables, and contract opcodes. The execution over these structures is deterministic across clients, as guaranteed by blockchain consensus.

Table 3: Optimization rules against overcharging issues.

Optimization rules	Issues
$O1: \dfrac{^{1}\left(tx_i, tx_j \in B\right) \wedge ^{2}\left(ins.load\left(loc_i\right) \in tx_i\right) \wedge ^{3}\left(ins.load\left(loc_j\right) \in tx_j\right) \wedge ^{4}\left(loc_i == loc_j\right)}{^{5}G\left[ins.load\left(loc_j\right)\right] := G_{memload}}$	Issue#1

Design consideration

- Q2: How does Maat guarantee the storage operations are consistent across all clients?
  - ? O1-3 depend on the intra-block and cross-block caches to conduct optimization. However, the different configurations and clients may vary the contents in caches.
  - We propose a resource pre-allocation technique to cache the data accessed in previous 128 blocks to assign the cache contents across clients in advance.

Table 3: Optimization rules against overcharging issues.

Optimization rules	Issues
$O1: \frac{{}^{1}(tx_i, tx_j \in B) \wedge {}^{2}(ins.load(loc_i) \in tx_i) \wedge {}^{3}(ins.load(loc_j) \in tx_j) \wedge {}^{4}(loc_i == loc_j)}{{}^{5}G[ins.load(loc_j)] := G_{memload}}$	Issue#1

Account: $\frac{30M}{2.6K\ gas} \times 164\ bytes = 1.8\ MiB$

$1.8MiB \times 128\ blocks =$ 230 MiB

Slot: $\frac{30M}{2.1K\ gas} \times 96\ bytes = 1.3\ MiB$

$1.3MiB \times 128\ blocks =$ 167 MiB

Evaluation

- Baseline: EIP-2929, which is designed to address overcharging issues, where repeated memory read is incorrectly charged as disk read in the intra-block cache (partial Issue#1).
- We conduct the evaluation on 1M blocks on Ethereum and BSC blockchains.
- Ethereum: Maat achieves a significant optimization of 112M USD in transaction fee, and outperforms baseline about $3\times$.
- BSC: Maat makes optimization of 7.71M USD in transaction fee, and outperforms baseline about $3\times$.

Table 4: Optimization effect on Ethereum overcharging issues.

Metrics	Optimized gas (gas)	Optimized ether (ETH)	Optimized fee (USD)
1M blocks (Maat)	2.01×10^{12}	58,358.52	1.12×10^{8}
1M blocks (Baseline)	0.67×10^{12}	21,221.28	0.39×10^{8}
Per block (Maat)	2.01×10^{6}	0.058	112.09
Per block (Baseline)	0.67×10^{6}	0.021	39.02
Per transaction (Maat)	12,730	3.69×10^{-4}	0.71
Per transaction (Baseline)	4,247	1.34×10^{-4}	0.25
Per opcode (Maat)	463.08	1.34×10^{-5}	0.026
Per opcode (Baseline)	155.54	4.93×10^{-5}	0.009
Per operation (Maat)	342.67	9.95×10^{-6}	0.019
Per operation (Baseline)	113.66	3.60×10^{-6}	0.006
Optimized rate (Maat)	33%	32%	32%
Optimized rate (Baseline)	11%	12%	11%

1M blocks represents Ethereum block #18M (Aug-26-2023) to #19M (Jan-13-2024)

Takeaways

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- We identify three overcharging issues in blockchain implementations, which affect more than 70% of transactions and 40% of transaction fees.
- We propose a novel tool, Maat, to address the three overcharging issues.
- We assess the effectiveness of Maat on Ethereum and BSC, and it achieves 5.6M USD fees in weekly savings, and outperforms the baseline by 3×.
- **What's more?**
  - ✓ Effect of distinct optimization rules and their combinations.
  - ✓ Overhead of Maat at space overhead (5.6%) and time overhead (1.4%).
  - ✓ Scalability of Maat on 50 blockchains in Ethereum ecosystems.

About me: https://zzzihao-li.github.io/

Thank you!