

Decentralized Metering and Billing of energy on
Ethereum with respect to scalability and security

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Abstract

In 2009 Satoshi Nakamoto published the Bitcoin whitepaper [1] where he described ‘a purely peer-to-peer version of electronic cash’ which ‘would allow online payments to be sent directly from one party to another without going through a financial institution’.

Bitcoin was primarily used for fast and low-cost financial transactions which were routed without any bank interference. It was soon realized that its underlying technology, blockchain, could be used for more than transferring financial value. A blockchain is a database that can be shared between a group of non-trusting individuals, without needing a central party to maintain the state of the database. The data in a blockchain is transparent and secured via cryptography. As more advanced blockchain platforms were built on top of Bitcoin [2], in the end of 2014 a blockchain platform which was capable of executing smart contracts was released, called Ethereum [3]. A smart contract is software that is executed on a blockchain and can be used as a framework for secure and trustless computation.

We leverage the power of the Ethereum blockchain and smart contracts to create a system that can transparently and securely perform metering of energy as well as perform accounting for the consumed energy based on specific business logic. The advantages and disadvantages of smart contracts are explored. Due to the distributed nature of blockchains there are challenges towards achieving scalability and transaction throughput comparable to traditional centralized payment processors or server architectures. Smart contract security has been a pressing issue as large financial amounts have been stolen from smart contracts.

Past literature on current scalability and security issues of smart contracts is studied. Contributions are made on scalability by proposing a method to make data storage on smart contracts more efficient. On security we utilize and augment the functionality of an auditing tool in order to analyze and identify vulnerabilities in smart contracts. Finally, we apply the gained insight and techniques on the metering-billing use case in order to enhance its viability and robustness in production.

1 Introduction

1.1 Problem Statement

We aim to answer the following research questions in this thesis:

1. How can the scalability of smart contracts be improved?
2. How can the security of smart contracts be improved?
3. How can a system that is able to measure and bill the energy consumed by a set of energy meters be modeled? The system must be able to perform accounting on the measured energy based on a pre-specified accounting model. The system must be transparent, decentralized, and secure. Anyone in the network should be able to verify the validity transactions. Finally, the system needs to be scalable at reasonable cost.

1.2 Scope

The Master Thesis explores the fundamental terms needed to understand blockchain terminology. The contributions to scalability are limited to optimizing smart contracts. Other scalability solutions are mentioned but in-depth analysis is considered out of scope. On security we limit ourselves to the industry's best practices, as per the literature and utilize a tool provided by an auditing firm.

The technology used includes but is not limited to the Solidity programming language¹, the Truffle Framework for streamlining the compilation, testing and deployment process, Javascript for unit testing the smart contracts and the Python programming language for automating tasks, performing plotting and analyzing of data.

1.3 Relative Work

Techniques which illustrate more efficient smart contracts by storing less data on a blockchain are described in [4]. [5] makes it clear that compiler optimizations in smart contracts still need improvements in order to avoid unnecessary expenses. On network level scalability there are various approaches such as executing transactions 'off-chain'² [6, 7, 8] and use a blockchain only for the final settling of a series of

¹Ethereum's most popular language for writing smart contracts

²An exchange of cryptographically signed messages that does not happen on a blockchain.

transactions. Other approaches exist which involve creating ‘sidechains’ which can be used to offload the computational effort from the ‘mainchain’ [9, 10, 11, 12, 13]. Finally, another approach to achieving scalability is via permissioned blockchains which trade decentralization and transparency for efficiency [14, 15].

Extensive analyses have been performed on the security of blockchains as networks [16, 17] and specifically on the security of Ethereum smart contracts [18] which have proven to be insufficiently secure for the amounts of funds that they hold. As a result, tools that are able to analyze both source code and compiled bytecode for vulnerabilities have been developed [19, 20, 21, 22, 23, 24]. A recent study [25] illustrates how smart contracts that can freeze or cause loss of funds can be detected [26].

Utilizing blockchain for Internet of Things is explored in [27, 28], while a model for billing and accounting with smart contracts is proposed in [29]. Energy market use-cases are being piloted by [30, 31] and prototypes are being tested such as [32, 33]

1.4 Outline

In Chapter 2 introduces terminology required for understanding blockchain fundamentals. We then proceed to explain how Ethereum works at a lower level, along with the programming techniques and tooling necessary to author smart contracts.

In Chapter 3 we refer to the scalability issues that plague today’s blockchain systems and provide a brief description of the known possible solutions that can be implemented to solve these problems. We make a contribution on scaling smart contracts which allows for more optimized writes to the Ethereum blockchain.

In Chapter 4 we go over the most significant security issues found in Ethereum and its smart contracts. Having understood these, we evaluate and augment the auditing tool *Slither*’s ability to detect and identify vulnerabilities and compare it to taxonomy of tools described in [34]. Finally, we analyze smart contracts *honeypots* as a meta-hacking pattern.

In Chapter 5 we present ways in which smart contracts can address the energy market’s inefficiencies. We create a suite of smart contracts which is able to answer research question 3.1.1, while taking the lessons learned from 3 and 4 into account.

In Chapter 6 we evaluate the performance and the extent at which the smart contracts from 5 achieve their goal.

In Chapter 7 we reiterate on the findings from the previous chapters, summarize our findings and highlight future work that can be done to further improve both the design of the described smart contracts but also the security and scalability of Ethereum.

1.5 Writing Conventions

A glossary can be found at the end of the document for all terminology used (written in italics).

Limited code snippets can be found across the document when needed for explanatory reasons, full code with explanations can be found in the Appendices and in the accompanying GitHub URL.

2 Ethereum and Blockchain Basics

2.1 General Background

Before getting into the specifics of blockchains and Ethereum, the next section will be used to explain fundamental terms on cryptography (hash functions and public key cryptography) and blockchain.

In non technical terms, a blockchain is a database that can be shared by non-trusting individuals without having a central party that maintains the state of the database. Namely, it is a list of *blocks* that grows over time. Each block contains various metadata (called *block headers*) and a list of transactions. A block is linked to another block by referencing its *hash*. A blockchain gets formed when each existing block has a valid reference to the previous block. It is the case that as more blocks get added to a blockchain, older blocks and their contents are considered to be more secure.

Any future reference to blockchain terminology such as the contents of a block or a transaction will be specific to the implementations of the Ethereum Platform. The Ethereum Yellowpaper provides details on the formal definitions and contents of each term [35].

2.1.1 Cryptographic Hash Functions

A hash function is any function that maps data of arbitrary size to a fixed size string. The result of a hash function is often called the *hash* of its input. Hash functions used in cryptography must fulfil additional security properties and are called *cryptographic hash functions*.

More specifically, a secure cryptographic hash function should satisfy the following properties [36] ($H(x)$ refers to the hash of x):

1. **Collision Resistance:** It should be computationally infeasible to find x and y such that $H(x) = H(y)$.
2. **Pre-Image Resistance:** Given $H(x)$ it should be computationally infeasible to find x .
3. **Second Pre-Image Resistance:** Given $H(x)$ it should be computationally infeasible to find x' so that $H(x') = H(x)$. A second preimage attack on a hash function is significantly more difficult than a preimage attack due to the attacker being able to manipulate only one input of the problem.

Bitcoin uses the SHA-256 cryptographic hash function, while Ethereum uses KECCAK-256 [37, 38]. Ethereum’s KECCAK-256 is oftentimes mistakenly referred to as SHA-3 which is inaccurate since SHA3-256 has different padding and thus different values[39].

2.1.2 Public Key Cryptography

Also referred to as Asymmetric Cryptography, it is a system that uses a pair of keys to encrypt and decrypt data. The two keys are called *public* and *private*¹. The main advantage of Public Key Cryptography is that it establishes secure communication without the need for a secure channel for the initial exchange of keys between any communicating parties.

The security Public Key Cryptography is based on cryptographic algorithms which are not solvable efficiently due to certain mathematical problems, such as the factorization of large integer numbers for RSA[40] or calculating the discrete logarithm² for the Elliptic Curve Digital Signature Algorithm (ECDSA), being hard.

Public key cryptography allows for secure communications by achieving:

1. **Confidentiality - A message must not be readable by a third party:** By encrypting the plaintext with recipient’s public key, the only way to decrypt it is by using the recipient’s private key, which is only known to the recipient, thus achieving confidentiality of the message’s transmission. This has the disadvantage that it does not achieve authentication and thus anyone can impersonate the sender.
2. **Authentication - The receiver must be able to verify the sender’s identity:** By encrypting the plaintext with sender’s private key, the only valid decryption can be done with the sender’s public key. This authenticates the identity of the sender of the message. This has the disadvantage that the message can be read by any middle-man as the sender’s public key is known.
3. **Confidentiality and Authentication - The receiver must be able to verify the sender’s identity and verify that the message was not read by a third party:** The original message gets encrypted with the sender’s private key and encrypted again with the recipient’s public key. That way, a recipient decrypts the message firstly with their private key, achieving confidentiality, and then verifies the identity of the sender by decrypting with their private key.
4. **Integrity - The receiver must be able to verify that the message was not modified during transmission:** Digital signatures is a scheme which allows the recipient to both verify that the message was created by a sender and that the message has not been tampered with. The process is as follows:
 - (a) The sender calculates the hash of the message that they are transmitting and concatenates the message with the hash

¹The public key is a number which is derived by elliptic curve multiplication on the private key. The private key is usually a large number known only to its owner. The public key is in the public domain.

²The discrete logarithm $\log_b a$ is an integer k such that $b^k = a$

- (b) The sender encrypts the combined message with their private key and transmits the ciphertext to the receiver
- (c) The receiver decrypts the content of the message with the sender's public key, achieving authentication
- (d) The receiver hashes the plaintext and compares the result to the transmitted hash
- (e) If the result matches the transmitted hash then, given that the hashing function used is secure, the message has not been tampered with

If the sender wanted to also make sure of the confidentiality of the information, they would also encrypt with the receiver's public key after step 2, and similarly the receiver would decrypt with their private key after step 3. This process is often referred to as a sender broadcasting a *signed* message.

2.1.3 Advantages and disadvantages of Blockchains

A blockchain is a distributed immutable public ledger. It can be used to efficiently transfer value between multiple parties without using a trusted intermediary like a bank to settle the transaction.

Due to the public nature of the ledger, it provides transparency as every transaction can be inspected to verify its associated information. This can be utilized by companies to facilitate trust to their customers by providing them with access to otherwise private information. There are privacy implications with this however, since companies might not want to disclose all pieces of information to the public. Privacy enabled blockchains which use advanced cryptography to hide transaction information from non-transacting parties exist [41, 42, 43]. Bitcoin is *pseudonymous*, which means the identity of an individual is hidden behind a random address³, however research has shown that this is not always a reliable privacy measure [44, 45].

Due to the distributed nature of the ledger, it is impossible for a party to censor a transaction. This has very powerful political implications such as in the case of an authoritarian regime, there is no way for a transaction to be cancelled due to a court order. On the other hand, in the case of theft of private keys, there is no way to prevent an attacker from stealing a victim's funds. At current scale, transactions on a blockchain have very low costs to execute and very high confirmation speeds [46].

The ledger is secured by the used protocol's rules which utilize *consensus algorithms* to provide transaction finality and immutability. As a result, blockchains can be used to timestamp events in history [47] which can be utilized to tackle fraud. This feature contradicts the flexibility of centralized databases which allow for any past event to be rewritten, which allows for scenarios such as reverting the bank balance of a customer in the case of a mistaken transaction.

2.1.4 Blockchain Types

In order to tackle the disadvantages mentioned in 2.1.3, blockchains that make tradeoffs in decentralization for more Blockchains are inspectable and public. Any

³An individual can generate multiple addresses from the same private key.

entity can setup a node, download the full blockchain history and view all the transactions caused by anyone participating in that network. This is one of the main benefits of using a blockchain, transparency.

There are two blockchain categories:

1. Public or Permissionless: Low barrier to entry, transparent and immutable.
2. Private or Permissioned: Federated participation, can obscure certain pieces of data, ability to modify and revert past transactions if needed.

Vitalik Buterin goes indepth in the advantages and disadvantages between private and public blockchains in [48]. Due to the scalability and privacy restrictions of public blockchains, corporations can use permissioned blockchain frameworks [49, 14, 50] to include blockchain technology in their processes.

2.2 Ethereum Blockchain

The Ethereum blockchain acts as a transactional state machine. The first state is the *genesis* state referred to as the *genesis block*. After the execution of each transaction, the state changes. Transactions are collated together in *blocks*.

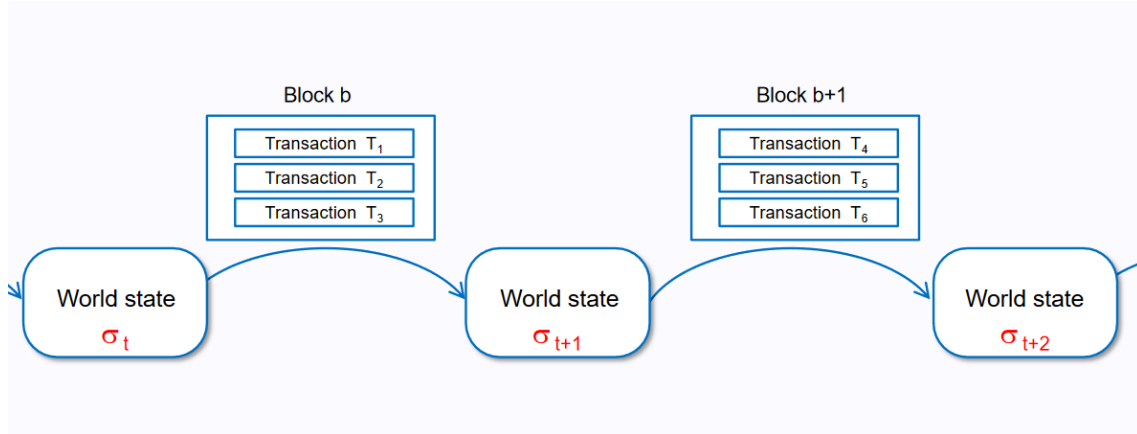


Figure 2.1: Ethereum can be seen as a chain of states, from [51]

A valid state transition requires the appending of a new block to the existing list of blocks. Each block contains transactions and a reference to the previous block, forming a chain. In Ethereum, the only way for a block to be validated and appended to the list is through a validation process called mining. Mining involves a group of computers, known as miners, expending their computational resources to find the solution to a puzzle. The first miner to find a solution to the puzzle is rewarded with Ether⁴ and is able to validate their block proposal. This is a process known as *Proof of Work* (PoW) [52].

Due to a large number of miners competing to solve the PoW puzzle, sometimes a miner might solve the PoW at the same time with another miner, but for different block contents. This results in a *fork* of the blockchain. Nodes will accept the first valid block that they receive⁵. Each blockchain protocol has a way to resolve forks

⁴The Ethereum network's native currency

⁵This depends on block propagation time based on bandwidth, block-size, connectivity etc.

and determine which chain is the valid chain. In Ethereum the longest chain is based on total difficulty⁶ which can be found in the *blockheader*. Ethereum is advertised to be using a modification of the GHOST Protocol[53] as its chain selection mechanism which uses *uncle blocks*⁷. This is contradictory since Ethereum's uncle blocks do not count towards difficulty and as a result, Ethereum does not actually use an adaptation of the GHOST protocol [16]; the uncle reward is just used to reduce miner centralization.

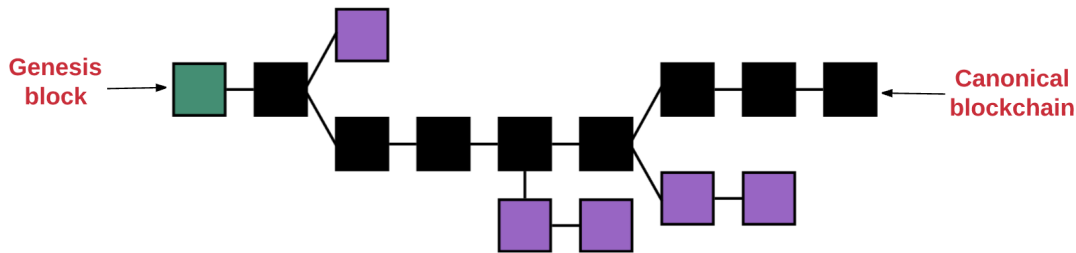


Figure 2.2: Blockchain forks: Ethereum's protocol chooses the canonical chain, from [54]

2.3 Inside the Ethereum Virtual Machine

The *Ethereum Virtual Machine* (EVM) is the runtime environment for Ethereum. It is a Turing Complete State machine, allowing arbitrarily complex computations to be executed on it. Ethereum nodes validate blocks and also run the EVM, which means executing the code that is triggered by the transactions. In this section we go over the internals of the EVM.

2.3.1 Accounts

2.3.1.1 World State

Ethereum's world state is a mapping between addresses of accounts and their states. Full nodes download the blockchain, execute and verify the full result of every transaction since the genesis block. Users should run a full node if they need to execute every transaction in the blockchain or if they need to swiftly query historical data.

⁶Difficulty is a measure of how much computational effort needs to be given on average by a miner to solve a PoW puzzle. Total Difficulty is the sum of the difficulties of all blocks until the examined block

⁷In Bitcoin a block with a valid PoW that arrived to a node after another valid block at the same height is called an orphan because it gets discarded by Bitcoin's algorithm. In Ethereum these blocks do not get discarded; instead they are added to the chain as *uncle blocks* and receive a reduced block reward

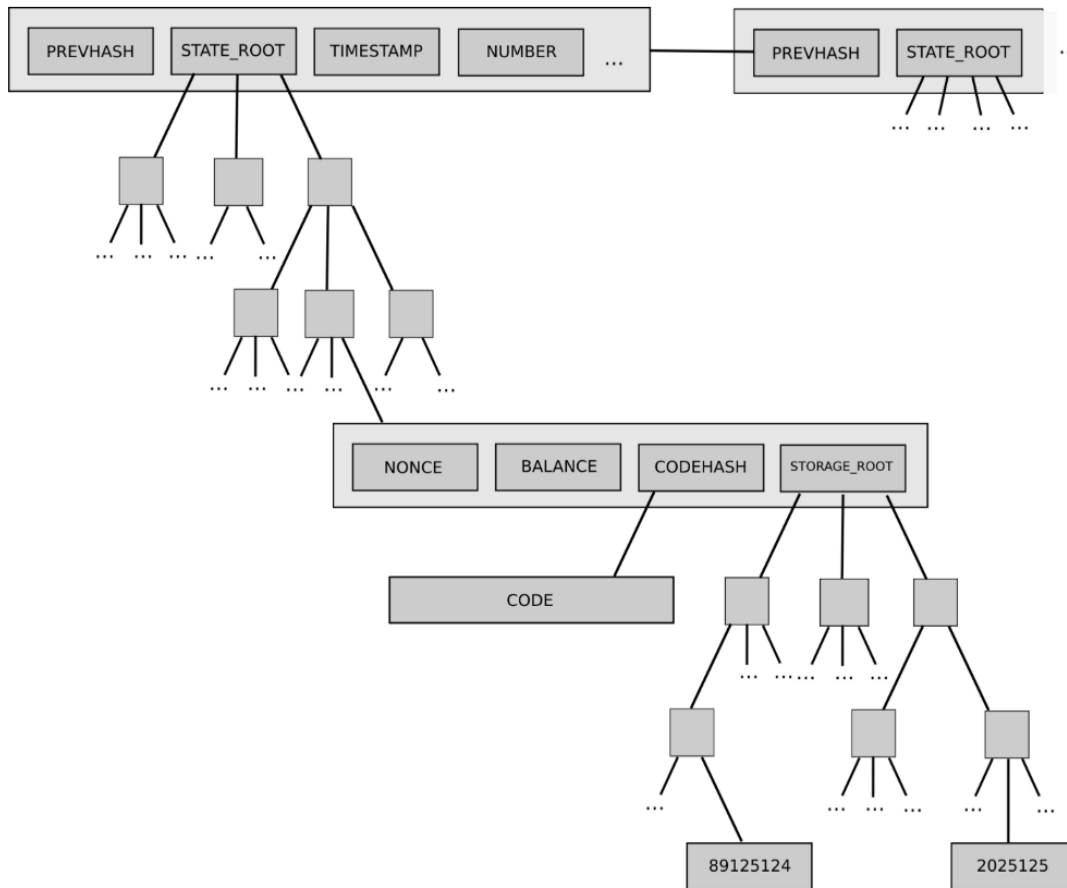


Figure 2.3: The world state of Ethereum, from [3]

A different kind of node called *light node* exists for cases where there is no need to store all the information. Instead, light nodes use efficient data structures called *Merkle Trees* which allow them to verify the validity of the data of a tree without storing the entire tree. A *Merkle Tree* is a binary tree where each parent node is the hash of its two child nodes⁸.

⁸Exception: Each leaf node represents the hash of a transaction in a block

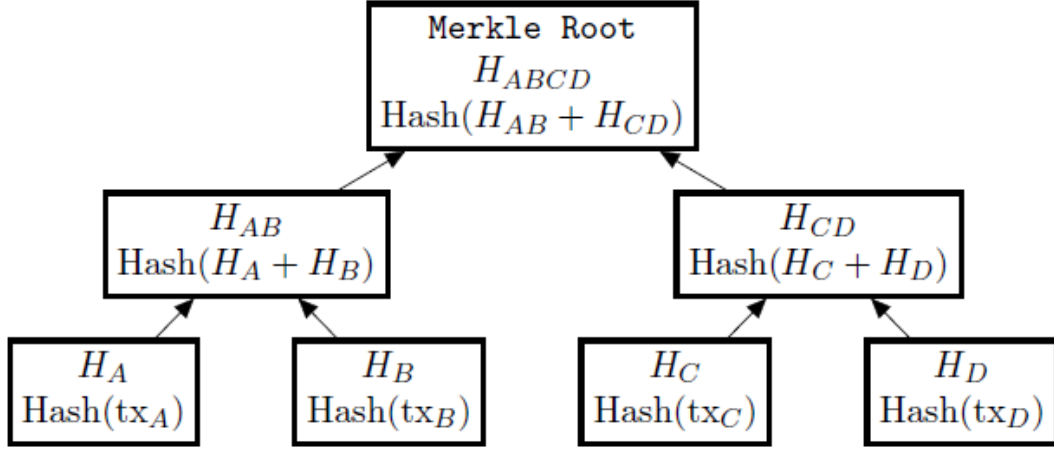
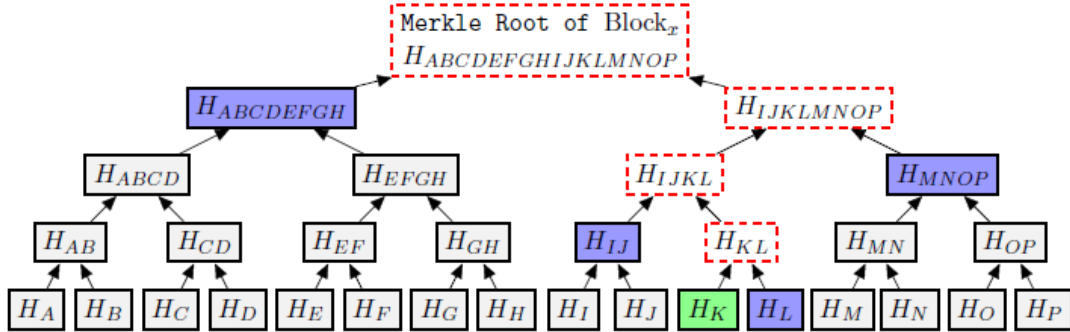


Figure 2.4: Node calculation in a Merkle Tree, from [55]

That way, instead of storing the whole tree of transactions, nodes can verify if a transaction was included in a block or not just by checking if the ‘merkle path’ to the merkle root is valid. This is efficient as there are only $O(\lg_2(n))$ comparisons needed to check the validity of a transaction, as shown in Figure 2.5

Figure 2.5: To prove that H_k was included in the merkle root of $Block_x$ only the blue elements are needed, from [55]

2.3.1.2 Account State

An ethereum account is a mapping between an address and an account state. There are two kinds of accounts, *Externally Owned Accounts* (EOA) and *Contract Accounts* (CA).

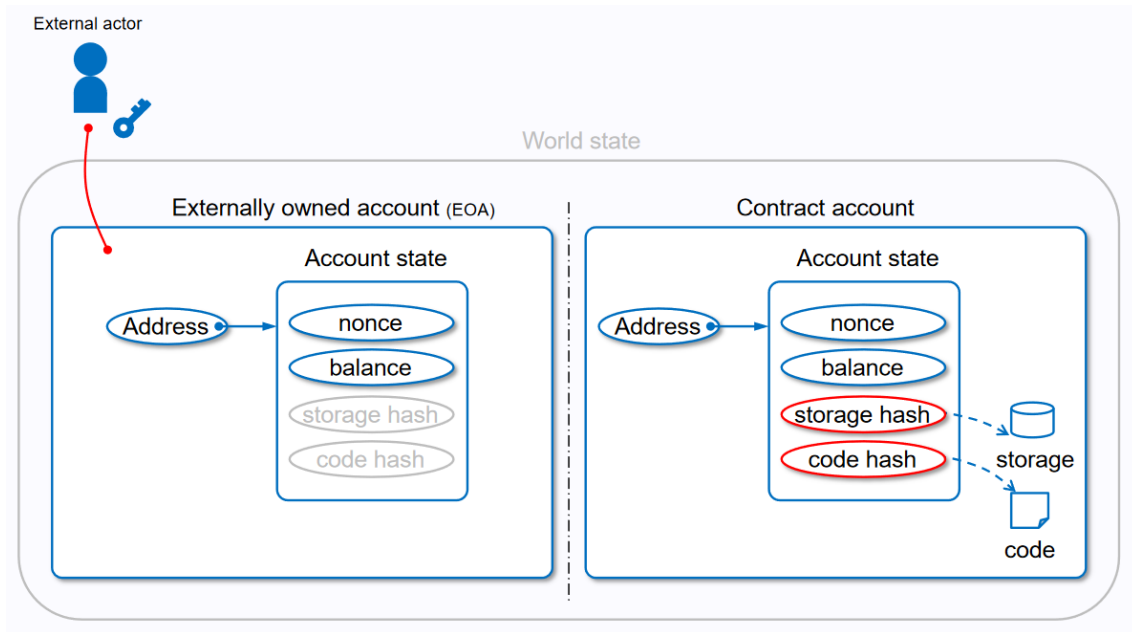


Figure 2.6: EOA is controlled by a Private Key and cannot contain EVM code. CAs contain EVM code and are controlled by the EVM code, from [51]

An EOA is able to send a message to another EOA by signing a transaction with their private key. CAs can make transactions in response to transactions they receive from EOAs.

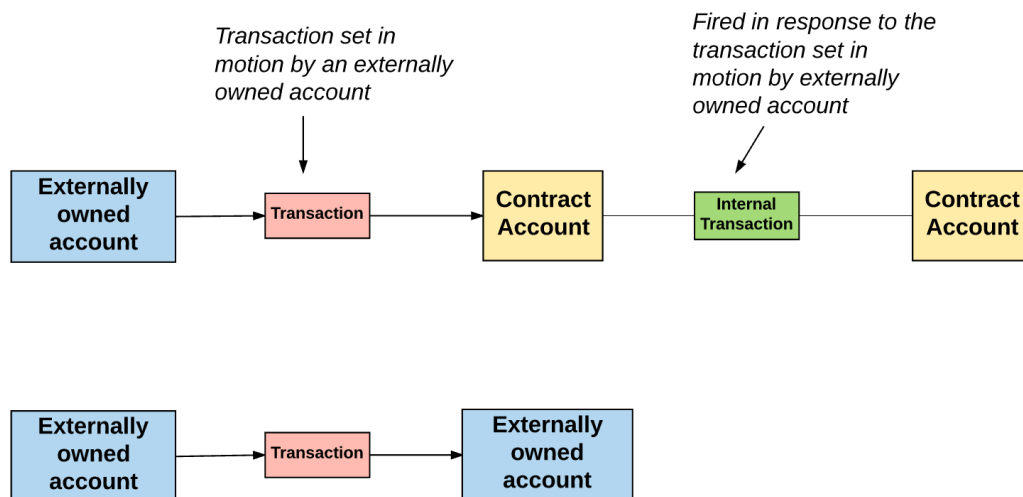


Figure 2.7: EOA can make a transaction to another EOA. A Contract fires a transaction after receiving a transaction from an EOA, from [54]

The public key of an EOA is derived from the private key through elliptic curve multiplication. The address of an EOA is calculated by calculating the KECCAK-256 hash of the public key and prefixing its last 20 bytes with '0x' [35]. The address of a CA is deterministically computed during contract creation from the sender EOA account's address and their transaction count⁹.

⁹Full explanation: <https://ethereum.stackexchange.com/a/761>

We describe the contents of the Account State shown in Figure 2.6 as follows:

1. **Nonce:** The number of transactions sent if it's an EOA, or the number of contracts created if it's a CA.
2. **Balance:** The account's balance denominated in 'wei'¹⁰
3. **Storage Hash:** The merkle root of the account's storage contents. This is empty for EOAs
4. **Code Hash:** The hash of the code of the account. For EOAs this field is the KECCAK-256 hash of '' while for CAs it is the KECCAK-256 of the bytecode that exists at the CAs address.

2.3.2 Transactions

A transaction is a specially formatted data structure that gets signed by an EOA¹¹ and gets broadcasted to an Ethereum node. Figure A.1 shows the contents of a transaction as seen after querying an Ethereum node for its contents.

Specifically:

1. **blockHash:** The hash of the block that included the transaction.
2. **blockNumber:** The number of the block that included the transaction.
3. **from:** The transaction's sender¹².
4. **gas:** The maximum amount of gas that the sender will supply for the execution of the transaction (see 2.3.4).
5. **gasLimit:** The amount of Wei paid by the sender per unit of gas.
6. **hash:** The transaction hash.
7. **input:** Contains the data which is given as input to a smart contract in order to execute a function. Can also be used to embed a message in the transaction. Contains the value '0x0' in the case of simple transactions of ether.
8. **nonce:** The number of transactions sent by the sender. It is used as a replay protection mechanism.
9. **v, r, s:** Outputs of the ECDSA signature.

¹⁰1 ether = 10^{18} wei

¹¹With the EOAs private key

¹²This field does not actually exist in a transaction however it is recovered from the v,r,s values of the signing algorithm (through *ecrecover*)

2.3.3 Blocks

A block contains the block header and a list of transaction hashes for all of the included transactions in that block. Figure A.2 shows the contents of a transaction as seen after querying an Ethereum node for its contents.

Specifically:

1. **difficulty:** The difficulty of the block.
2. **extraData:** Extra data relevant to the block. Miners use it to claim credit for mining a block. In Bitcoin fields with extra data are used to let miners vote on a debate.
3. **gasLimit:** The current maximum gas expenditure per block.
4. **gasUsed:** The cumulative amount of gas used by all transactions included in the block.
5. **hash:** The block's hash.
6. **logsBlom:** A bloom filter which is used for getting further information from the transactions included in the block.
7. **miner:** The address of the entity who mined the block.
8. **mixHash:** A hash used for proving that the block has enough PoW on it.
9. **nonce:** A number which when combined with the mixHash proves the validity of the block.
10. **number:** The block's number.
11. **parentHash:** The hash of the previous block's headers.
12. **receiptsRoot:** The hash of the root node of the Merkle Tree containing the receipts of all transactions in the block .
13. **sha3Uncles:** Hash of the uncles included in the block.
14. **size:** Block size.
15. **stateRoot:** The hash of the root node of the Merkle Tree containing the state (useful for light nodes).
16. **totalDifficulty:** The cumulative difficulty of all mined blocks until the current block.
17. **transactionsRoot:** The hash of the root node of the Merkle Tree containing all transactions in the block.

2.3.4 Gas

Since all nodes redundantly process all transactions and contract executions, an attacker would be able to maliciously flood the network with computationally intense transactions and cause nodes to perform costly operations for extended periods of time. Ethereum uses gas to introduce a cost on performing computations. Gas manifests itself as the fees to be paid by the sender for a transaction to complete successfully.

Every computational step on Ethereum costs gas. The simplest transaction which involves transferring Ether from one account to another costs 21000 gas. Calling functions of a contract involves additional operations where the costs can be estimated through the costs described in [56, 35].

When referring to blocks, the *gasLimit* is the maximum gas that can be included in a block. Since each transaction consumes a certain amount of gas, the cumulative gas used by all transactions in a block needs to be less than *gasLimit*. There is a similarity between the block *gasLimit* and the block size in Bitcoin in that they are both used to limit the amount of transactions that can be included in a block. The difference in Ethereum is that miners can ‘vote’ on the block *gasLimit*.

Every unit of gas costs a certain amount of *gasPrice* which is set by the sender of the transaction. The cost of a transaction in wei is calculated from the following formula:

$$totalTransactionCost = gasPrice * gasUsed \quad (2.1)$$

where *gasUsed* is the amount of gas consumed by the transaction

Miners are considered to be rational players who are looking to maximize their profit. As a result, they are expected to include transactions with transaction costs before transactions with low transaction costs. This effectively creates a ‘fee market’ where users are willing to pay more by increasing the *gasPrice* to have their transactions confirmed faster. In the times of network congestion such as popular Initial Coin Offerings¹³[57] or mass-driven games such as CryptoKitties¹⁴[58] transactions become very expensive and can take long times to confirm.

2.3.4.1 Successful Transaction

In the case of a successful transaction, the consumed gas from *gasLimit* (*gasUsed*) goes to miners, while the rest of the gas gets refunded to the sender. After the completion, the world state gets updated.

¹³Crowdfunding for cryptocurrency projects which allow investors to buy tokens in a platform

¹⁴<https://cryptokitties.co>

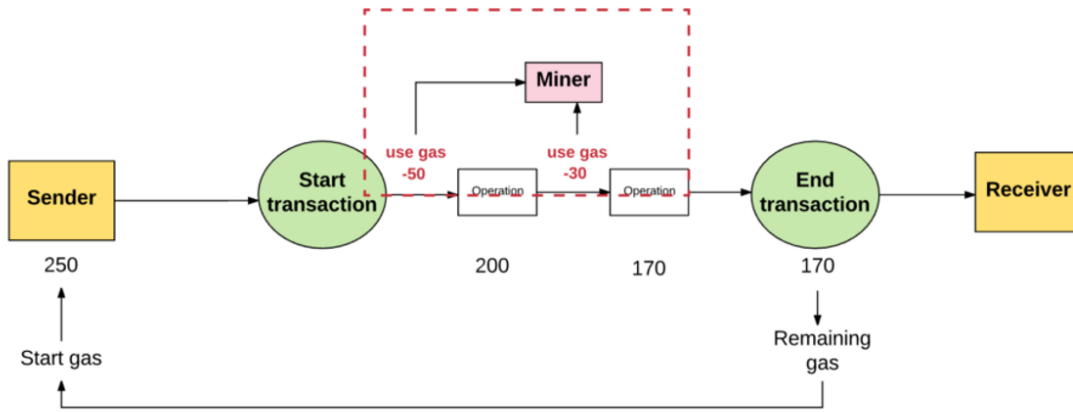


Figure 2.8: Successful transaction, from [54]

2.3.4.2 Failed Transaction

A transaction can fail for reasons such as not being given enough gas for its computations, or some exception occurring during its execution. In this case, any gas consumed goes to the miners and any state changes that would happen are reverted. This is similar to the SQL transaction commit-rollback pattern.

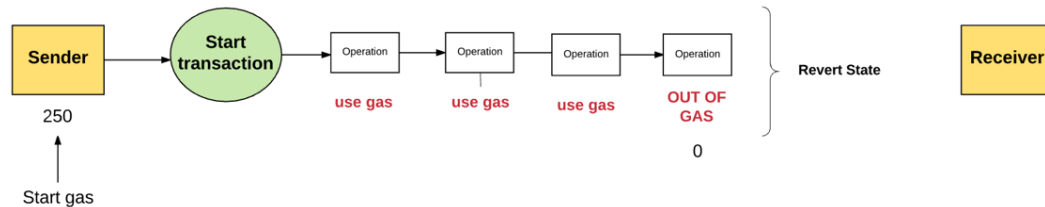


Figure 2.9: Failed transaction that ran out of gas, from [54]

2.3.5 Mining

The set of rules which allow an actor to add a valid block to the blockchain is called a *consensus algorithm*. In order to have consensus in distributed systems, all participating nodes must have the same version (often called history) of the system (blockchain). If there were no rules for block creation, a malicious node would be able to consistently censor transactions or double-spend [59]. In order to avoid that, consensus algorithms elect a network participant to decide on the contents of the next block.

Ethereum uses a consensus algorithm called ethash[38] which is a memory-hard¹⁵ consensus algorithm which requires a valid PoW in order to append a block to the Ethereum blockchain. PoW involves finding an input called *nonce* to the algorithm

¹⁵Requires a large amount of memory to execute it. This means that creating ASICs for ethash is harder, although not impossible [60]

so that the output number is less than a certain threshold¹⁶. PoW algorithms are designed so that the best strategy to find a valid nonce is by enumerating through all the possible options. Finding a valid PoW is a problem that requires a lot of computational power, however verifying a solution is a trivial process, given the nonce. In return, miners are rewarded with the *block reward* and with all the fees from the block's transactions.

This process is called 'mining'. In the future, Ethereum is planning to transition to another *consensus algorithm* called Proof of Stake (PoS), which deprecates the concept of 'mining' and replaces it with 'staking'. PoS is considered to be a catalyst for achieving scalability in blockchains and is briefly discussed in Chapter 3.

2.4 Programming in Ethereum

At a low level, the EVM has its own Turing Complete language called the EVM bytecode. Programmers write in higher-level languages and compile the code from them to EVM bytecode which gets executed by the EVM.

2.4.1 Programming Languages

Languages that compile to EVM code are Solidity, Serpent, LLL or Vyper.

Solidity is the most popular language in the ecosystem and although often comparable to Javascript, we argue that Solidity Smart Contracts remind more of C++ or Java, due to their object oriented design. The Solidity Compiler is called *solc*. In order to deploy a smart contract, its EVM Bytecode and its Application Binary Interface (ABI) are needed, which can be obtained from the compiler.

```
1  pragma solidity ^0.4.16;
2
3  contract TestContract {
4
5      string private myString = "foo";
6      uint private lastUpdated = now;
7
8      function getString() view external returns (string, uint) {
9          return (myString, lastUpdated);
10     }
11
12     function setString (string _string) public {
13         myString = _string;
14         lastUpdated = block.timestamp;
15     }
16 }
```

Figure 2.10: Basic Solidity Smart Contract

Due to the nascence of these languages and the security mistakes that have occurred due to them providing programmers with powerful state-changing functions, active research is being done towards safer languages [61].

¹⁶The threshold is also called difficulty and adjusts dynamically so that a valid PoW is found approximately every 12.5 seconds

2.4.2 Tooling

The following section describes tools and software that are often used by Ethereum users and developers to interact with the network.

2.4.2.1 Client (Node) Implementations and Testnets

Ethereum’s official implementations are Geth (golang) and cpp-ethereum (C++). Third party implementations such as Parity (Rust), Pyethereum (Python) and EthereumJ (Java) also exist. The most used kind of node implementations are Geth (compatible with Rinkeby testnet) and Parity (compatible with Kovan testnet).

Smart contracts are immutable once deployed which means that their deployed bytecode (and thus their functionality) cannot change. As a result, if a flaw is found on a deployed contract, the only way to fix it is by deploying a new contract. In addition, the deployment costs can be expensive, so development and iterative testing can be costly. For that, public test networks (testnets) exist which allow for testing free of charge. Kovan and Rinkeby are functioning with the Proof of Authority [62] consensus algorithm, while Ropsten is running Ethash [38] with less difficulty.

We provide a comparison between test networks:

1. Kovan: Proof of Authority consensus supported by Parity nodes only
2. Rinkeby: Proof of Authority consensus supported by Geth nodes only
3. Ropsten: Proof of Work consensus, supported by all node implementations, provides best simulation to the main network

In addition, before deploying to a testnet, developers are encouraged to run their own local testnets. Geth and Parity allow for setting up private testnets. Third-party tools also exist that allow for setting up a blockchain with instant confirmation times and prefunded accounts, such as ganache¹⁷ (User Interface at A.3, formerly known as testrpc).

2.4.2.2 Web3

Web3 is the library used for interacting with an Ethereum node. The most feature-rich implementation is Web3.js¹⁸ which is also used for building web interfaces for Ethereum Decentralized Applications (DApps). Implementations for other programming languages are being worked on such as Web3.py¹⁹. We illustrate an example of connecting and fetching the latest block from Ropsten and Mainnet using Web3.js in A.4 and Web3.py in A.5. The full specifications of each library’s API can be found in their respective documentation^{20,21}

¹⁷<http://truffleframework.com/ganache>

¹⁸<https://github.com/ethereum/web3.js>

¹⁹<https://github.com/ethereum/web3.py>

²⁰<https://github.com/ethereum/wiki/wiki/JavaScript-API>

²¹<https://web3py.readthedocs.io/en/stable/>

2.4.2.3 Truffle Framework

The Truffle Framework is a development framework for smart contract development written in NodeJS. It is currently the industry standard for developers. It allows for automating the smart contract deployment pipeline through *migration* scripts and scripting test suites for scenarios using the Mocha Testing suite. Finally, it includes a debugger for stepping through transaction execution and can internally launch a ganache testnet.

3 Blockchain Scalability

3.1 Bottlenecks in Scalability

A blockchain's ability to scale is often measured by the amount of transactions it can verify per second. A block gets appended to the Ethereum blockchain every 12.5 seconds on average, and can contain only a finite amount of transactions. As a result, transaction throughput is bound by the frequency of new blocks and by the number of transactions in them.

We argue that there are two levels of scalability, scalability on contract and on network level. Better contract design can result in transactions which require less gas to execute, and thus allow for more transactions to fit in a block while also making it cheaper for the end user. It should be noted that as Ethereum's current `blockGasLimit` is set by the miners at 8003916; if all transactions in Ethereum were simple financial transactions¹, each block would be able to verify 381 transactions - 25 transactions per second (tps) - which is still not comparable to traditional payment operators.

3.2 Network Level Scalability

Scale should not be confused with scalability. While scale describes the size of a system and the amount of data being processed, scalability describes how the cost of running the system changes as scale increases. Existing blockchains scale poorly due to the costs associated with them increase faster than the rate at which data can be processed.

First of all, transactions per second as a metric is inaccurate. Solving scalability does not imply just increasing the transaction throughput. It is a constraint-satisfaction-problem; the goal is to maximize throughput while maintaining the network's decentralization and security.

¹Not calls to smart contracts. Transactions without any extra data cost 21000 gas

This sounds like there's some kind of scalability trilemma at play. What is this trilemma and can we break through it?

The trilemma claims that blockchain systems can only at most have two of the following three properties:

- Decentralization (defined as the system being able to run in a scenario where each participant only has access to $O(c)$ resources, ie. a regular laptop or small VPS)
- Scalability (defined as being able to process $O(n) > O(c)$ transactions)
- Security (defined as being secure against attackers with up to $O(n)$ resources)

Figure 3.1: The Scalability Trilemma, from Ethereum's Sharding documentation [63]

As an example that trades decentralization for more transactions is the increase of block size. Increasing the size of each block, implies more disk space for storing the blockchain, better bandwidth for propagating the blocks and more processing power on a node to verify any performed computations. This eventually requires computers with datacenter-level network connections and processing power which are not accessible to the average consumer, thus damaging decentralization which is the core value proposition of blockchain.

As described in [64], Proof of Work is a consensus algorithm optimized for censorship-resistance while (in theory) maintain a low barrier to entry. In reality, due to economies of scale, PoW blockchains end up being centralized around small numbers of miners [65].

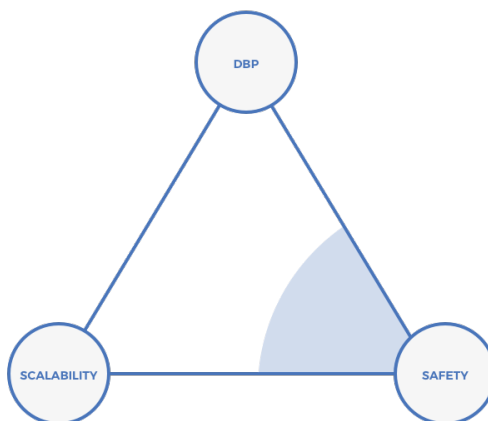


Figure 3.2: Bitcoin and Ethereum's PoW networks have slow probabilistic time to finality and do not scale well. Mining capacity has high concentration in a small amount of entities, from [64]

We proceed to discuss some network level solutions that can improve Ethereum’s scalability.

3.2.0.1 Proof-of-Stake

Proof-of-Stake (PoS) is an alternative consensus algorithm where in the place of miners, there are validators who instead of expending computational resources to ‘mine’ a valid block, they stake² their ether and the probability for them to be elected to validate the next block is proportional to their stake. Designing a secure PoS protocol is still under heavy research. The Ethereum Foundation is working on ‘Casper the Friendly Finality Gadget’[66] which is a hybrid PoW/PoS consensus algorithm that provides block finality³ which combined with the ‘correct-by-construction Casper the Friendly GHOST’⁴ [67] will enable a full transition to Proof of Stake.

3.2.0.2 Sidechains

A sidechain [9] is a blockchain defined by a custom ‘rule-set’ and can be used to offload computations from another chain. Individual sidechains can follow different sets of rules from the mainchain, which means they can optimize for applications that require high speeds or heavy computation, while still relying on the mainchain for issues requiring the highest levels of security. Ethereum’s sidechain solution is called ‘Plasma’ [13] and involves creating ‘child-chains’ that run their own consensus algorithm with a two-way peg as described in [9]. *Plasma chains* can have more adjustable parameters such as be less decentralized, however the protocol does not allow for the child-chain operator to abuse their power. A more recent Plasma construct is called ‘Plasma-Cash’ [12] and describes a more efficient way of executing fraud proofs, in the case of a malicious actor in a *Plasma chain*.

3.2.0.3 Sharding

Due to the architecture of the EVM all transactions are executed sequentially on all ethereum nodes. Sharding refers to splitting the process across nodes, so that each full node is responsible only for a shard⁵ and acts as a light client to the other shards. Sharding is the most complex scaling solution and is still at research stages. It also requires a stable Proof of Stake consensus algorithm to function properly.

3.2.0.4 State channels

Contrary to the previous solutions which still record messages on a blockchain, state channels involves exchange of information ‘off-chain’. The primary use-case for state channels is micro-transactions between two or more parties. This technique involves exchanging signed messages through a secure communications channel and perform a transaction on the blockchain only when the process is done⁶.

²Lock up for an amount of time

³A block that is finalized cannot be reverted. This is different to traditional PoW which achieves *probabilistic finality*; a block is considered harder to revert the older it is

⁴Uses the GHOST protocol to choose a chain in the case of a fork.

⁵A shard is a part of the blockchain’s state

⁶Example: Instead of making 10 transactions worth 0.1 ether each, a transaction is made to open the channel, participants exchange off-chain messages transferring value, and settle or dispute

3.3 Contract Level Scalability

In a recent study [5], after evaluating 4240 smart contracts, it is found that over 70% of them are under-optimized with respect to gas from the compiler. In this section we explore how gas gets computed in smart contracts and ways we can save on gas and transaction costs.

3.3.1 Gas Costs

An Ethereum transaction's gas costs are split in:

1. **Transaction Costs:** The cost of sending data to the blockchain. There are 4 items which make up the full transaction cost:
 - (a) The base cost of a transaction (21000 gas)
 - (b) The cost of a contract deployment (32000 gas)
 - (c) The cost for every zero byte of data in a transaction's input (4 gas per zero byte).
 - (d) The cost of every non-zero byte of data in a transaction's input (68 gas per zero byte)
2. **Execution Costs:** The cost of computational operations which are executed as a result of the the transaction, as described in detail in [35, 56]

Gas costs get translated to transaction fees. As a result, a contract should be designed to minimize its operational gas costs in order to minimize its transaction fees. In addition, as gas is a unit for computational costs, less gas consumed results in less burden on the nodes validating the smart contracts which can lead to better scalability.

Table 3.1: Gas cost of different operations, a complete list can be found in Ethereum's yellow paper [56], from [5]

Operation	Gas	Description
ADD/SUB	3	Arithmetic operation
MUL/DIV	5	
ADDMOD/MULMOD	8	
AND/OR/XOR	3	Bitwise logic operation
LT/GT/SLT/SGT/EQ	3	Comparison operation
POP	2	Stack operation
PUSH/DUP/SWAP	3	
MLOAD/MSTORE	3	
JUMP	8	Unconditional jump
JUMPI	10	Conditional jump
SLOAD	200	Storage operation
SSTORE	5,000/20,000	
BALANCE	400	Get balance of an account
CREATE	32,000	Create a new account using CREATE
CALL	25,000	Create a new account using CALL

As seen in Table 3.1, the most expensive operations involve CREATE⁷ and SSTORE operations. The focus of this section will be to explore ways to decrease

the channel with one more transaction at the end.

⁷Used to create a new contract.

gas costs on Smart Contracts, either through better practices or by handcrafting optimizations for specific use cases.

It should be noted, that non-standard methods have been proposed for reducing fees incurred by gas costs. A recent construction [68] describes a method of buying gas at low cost periods and saving it in order to spend it when gas prices are higher⁸. The economic implications of gas arbitrage are outside the scope of this Master Thesis.

General rules that should be followed for saving gas costs:

1. Enable compiler optimizations (although can lead to unexpected scenarios [69]).
2. Reuse code through libraries [70].
3. Setting a variable back to zero refunds 15000 gas through SSTORE, so if a variable is going to be unused it is considered good practice to call ‘delete’ on it.
4. Use ‘bytes32’ instead of ‘string’ for strings that are of known size. ‘bytes32’ always fit in an EVM word, while ‘string’ types can be arbitrarily long and thus require more gas for saving their length.
5. Do not store large amounts of data on a blockchain. It is more efficient to store a hash which can be either proof of the existence of the data at a point in time, or it can be a hash pointing to the full data⁹

As described in [5] there is a lot of room for further compiler optimizations. Future Solidity compiler versions are addressing some already¹⁰¹¹¹²

The EVM operates on 32 byte (256 bit) words. The compiler is able to ‘tightly pack’ data together, which means that 2 128 bit storage variables can be efficiently stored with 1 SSTORE command. The *optimize* flag of the Solidity compiler needs to be activated to access this feature when programming in Solidity.

3.3.2 Gas Savings Case Study

In order to illustrate our findings and compare across different scenarios, we will perform a Solidity benchmarking test based on a use-case of a Solidity Smart Contract which describes a game. The contract-design requirements are:

- A user must be able to register.
- A user must be able to create a character with certain traits as function arguments.
- A user must be able to retrieve the traits of a character.

⁸When the network is congested

⁹This pattern has been used in combination with IPFS, <https://ipfs.io>

¹⁰<https://github.com/ethereum/solidity/issues/3760>

¹¹<https://github.com/ethereum/solidity/issues/3716>

¹²<https://github.com/ethereum/solidity/issues/3691>

Name	Type	Comment
playerID	uint16	Game supports up to 65535 players
creationTime	uint32	Game supports timestamps up to $2^{32} = 02/07/2106$ @ 6:28am (UTC)
class	uint4	Game supports up to 16 classes
race	uint4	Game supports up to 16 classes
strength	uint16	Stats can be up to 65535
agility	uint16	Stats can be up to 65535
wisdom	uint16	Stats can be up to 65535
metadata	bytes18	Utilize the rest of the word for metadata

Table 3.2: Required variables and size. Sizes add up to 248 bits which can be efficiently stored in a 256 bit word.

The size of the variables is selected so that all the information required to describe a ‘Character’ can fit in a 256 bit word. The interface that satisfies the requirements is shown in B.2

For each of the following implementations we will examine the deployment gas costs, as well as the gas costs for calling the ‘CreateCharacter’ function:

1. Tightly packed structures for setting data
2. Bit masking encoding for setting data
3. Bit masking encoding utilizing libraries, influenced by [71].

The full contracts of each contract can be found in the Appendix. In this section we describe the implementation and in section we go over the results and caveats of each method.

3.3.2.1 Method 1: Tight packing of variables through structs

We’re using a solidity ‘struct’¹³ as a means to group all traits of a character as described in 3.2. This allows for easy code readability since every variable of a struct object can be accessed by its name as seen in B.3c, like the property of an object.

In this case, assignment and retrieval of the variables is done in a very straightforward way. By utilizing Solidity’s built-in structures and arrays, we can create an array of ‘Character’ type structures and access their traits by their indexes, as done in B.3c

The gas costs per function call with this method are:

Optimizer Runs	Register	CreateCharacter	Deployment
0	70003	104205	903173.0
1	69943	104202	529979.0
100	69811	103402	561342.0
500	69604	103207	586867.0
500000	69598	103183	651665.0

Table 3.3: Gas costs for deployment and for each function using Solidity’s built-in structs

3.3.2.2 Method 2: Manually pack variables in a 256 bit uint with masking and shifting

In 3.3.2.1 we let the compiler perform optimizations in order to make storing the data more efficient. It turns out¹⁴ that even with the optimizer, a lot of redundant

¹³<http://solidity.readthedocs.io/en/v0.4.21/types.html>

¹⁴<https://github.com/figs999/Ethereum/blob/master/Solc.aComedyInOneAct>

operations are done. In order to get better results, we create a ‘virtual struct’ by encoding all the information needed in a ‘uint’ variable. Here we create a new character by shifting variables. Essentially, instead of creating a ‘struct’ as Solidity expects it and let the compiler do the parsing, we do it ourselves. That way, we achieve gas costs which are substantially lower.

The encoding is done by shifting each of the described variables and then performing bitwise OR operations so that the data gets embedded in the uint variable, as shown in 3.3. This is implemented in B.4

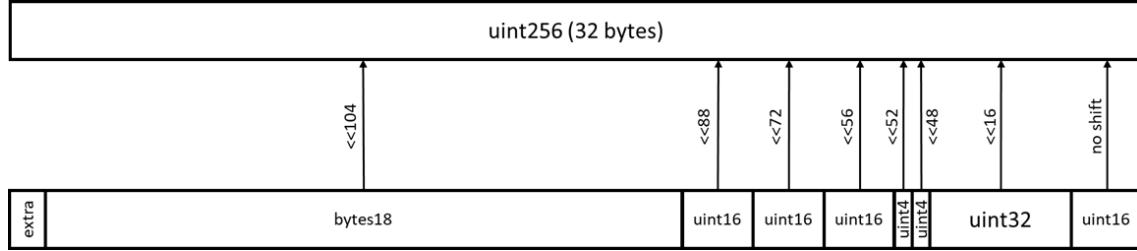


Figure 3.3: Setting data requires shifting left N times and performing bitwise OR with the target variable, where N is the number of bits of the previous variable.

Retrieving the data requires shifting the ‘Character’ uint and performing bitwise ‘AND’ operations in order to mask out the higher bits of the variable that are unused, as shown in 3.4, implementation in B.5.

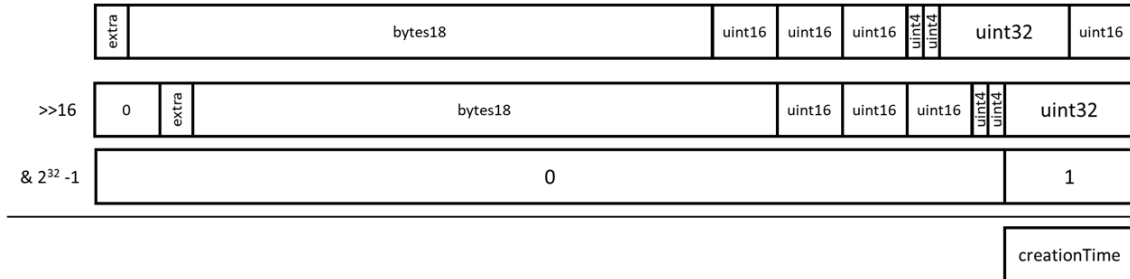


Figure 3.4: Decoding shift and

The gas costs per function call with this method are:

Optimizer Runs	Register	CreateCharacter	Deployment
0	70003	66620	551800.0
1	69943	66365	378022.0
100	69811	65924	402120.0
500	69604	65855	419559.0
500000	69598	65855	432409.0

Table 3.4: Gas costs for deployment and for each function using the masking method on a uint.

3.3.2.3 Method 3: Manually pack variables in a 32 byte variable with masking and shifting, utilizing Solidity Libraries

Code reusability and readability should always be given high priority. In the previous method, although the data packing is very efficient compared to the ‘struct’ method, the code is hardly readable and it is impossible to reuse parts of it. It would be

possible to extract the logic into functions, however the overheads introduced by the additional operations made it inferior to the technique we describe in this section.

We utilize Solidity's 'Library' feature which allows us to define a set of methods which are possible to be applied on a datatype using the 'using X for Y' syntax¹⁵

There are two ways to implement functions in a Library:

1. Internal: The library's bytecode is inlined to the main contract's code. This results in larger bytecode during deployment, however each of the contract's function are immediately jumping and returning to the Library's code, like any function. In this case, only the main contract gets deployed.
2. Public:
 - (a) The library contract gets compiled and deployed
 - (b) The main contract gets compiled and has placeholder slots in the bytecode.
 - (c) The placeholder gets replaced by the deployed library's address
 - (d) Any function call that requires the library utilizes the 'delegatecall' opcode.

We provide a minimal code snippet which illustrates the syntax to use libraries.

```
1  pragma solidity ^0.4.21;
2
3  library L {
4      function add(uint a, uint b) public pure returns(uint) {
5          return (a+b);
6      }
7  }
8
9  contract C {
10     using L for uint;
11     uint public x = 1;
12     uint public y = 2;
13
14     function add() {
15         x = x.add(y);
16     }
17
18 }
```

Figure 3.5: Example of 'using X for Y' syntax to enhance operations done on datatypes

Libraries with public functions are deployed as standalone contracts to be used by contracts made by other developers. They often include generic functionality such as math operations¹⁶. Depending on the complexity of the contracts, this can be more efficient compared to using *internal* functions. When *public* is used,

¹⁵This is similar to calling functions on struct's in Golang

¹⁶A popular Solidity Library is SafeMath which contains error-checked math operations

the DELEGATECALL opcode is used¹⁷. When *internal* is used, a function call is interpreted as a jump and thus is more efficient than the DELEGATECALL.

That way, instead of having to deploy a new contract, developers can use an already deployed one. Due to the usage of DELEGATECALL, there is a tradeoff between the deployment cost of the contract and the extra costs when making function calls. We opt for the *internal* approach because it requires less gas and since this is a specialized use-case it is not expected to be used by third-parties.

The final version is split in two files, the library which includes the API for setting and retrieving the character's traits, and the main contract which uses the library's high-level functions.

By utilizing the 'using CharacterLib for bytes32' syntax we are able to write and retrieve the character's traits in a user-friendly manner.

The gas costs per function call with this method are:

Optimizer Runs	Register	CreateCharacter	Deployment
0	70003	67581	754613.0
1	69943	67414	508014.0
100	69811	66904	538621.0
500	69604	66835	556054.0
500000	69598	66835	569032.0

Table 3.5: Gas costs for deployment and for each function using the masking method on bytes32 utilizing Libraries.

3.3.3 Results

It can be seen that in all cases the optimizer's first iteration creates significant gas savings. However, the more optimizer-runs were done, the more gas was spent during deployment. On the other hand, the cost of calling functions went down. Code in Solidity is either optimized for size, and thus costs less to deploy, or for runtime costs[72]. We proceed to compare the gas costs from each implementation while considering the advantages and disadvantages of each method.

In Method 1 (3.3) the optimizer is able to cut down deployment costs by 42%, due to being able to pack all variables in a storage slot. In Method 2 (3.4), the optimization is done manually and has significant results both in deployment and in function costs. In Method 3 (3.5), although we follow the same pattern as in Method 2, we introduce a more verbose API which results in more complex operations being done at a lower level. This introduces slightly bigger deployment costs, and a negligible difference in gas costs for function calls. We consider this overhead to be worth it, since we export an API that is usable.

Deciding how many times to run the optimizer requires estimating the expected usage of the smart contracts. Comparing the results from running the optimizer 1 and 500 times in Method 2, it can be seen that the deployment costs can increase by as much as 10% while the savings for each function call are in the range of 0.7%. When quantifying these percentages in gas, we conclude that if a function is going to be called *enough*¹⁸ times, then the contract which was compiled with more optimizer runs is more efficient in the long run. In addition, this shifts the costs towards the contract deployer rather than the users. Given the tradeoffs described above and

¹⁷Relays the message to the library while allowing it to execute in the sender's state

¹⁸Enough is not quantifiable and depends on the implementation. A developer should perform a similar analysis to the one we do in order to set their breakeven points.

the improved code readability and maintainability, we opt to use Method 3 in our implementations.

4 Ethereum and Security

The Ethereum platform itself has proven to be robust and reliable as a blockchain as it has been resistant to both censorship and double-spend attacks. In this chapter we discuss vulnerabilities that have been found in the network’s implementation which resulted in Denial of Service-like attacks and the blockchain’s state being bloated with junk data. Afterwards, we discuss the security of smart contracts and the best practices that need to be applied in order to have a proper workflow. We contribute to the existing literature by evaluating the usage of the tool ‘Slither’ towards finding smart contract vulnerabilities and edge cases. We also improved ‘Slither’ by augmenting the scope of vulnerabilities it was able to detect.

4.1 Past Attacks

4.1.1 Network Level Attacks

October 2016 Spam Attacks During the period of September-October 2016, an attacker was able to spam the Ethereum network’s state by creating 19 million ‘dead’ accounts. The attack was made possible by a mispricing in the SUICIDE opcode of smart contracts, allowing an attacker to submit transactions that created new accounts at a low cost. The creation of these accounts filled the blockchain’s state with useless data which resulted in clients being unable to synchronize in time, effectively causing a *Denial of Service* attack to the network [73]. As a response, two hard-forks¹ were proposed [74, 75]. Tangerine Whistle² solved the gas pricing issue and at a later point, Spurious Dragon³ cleared the world state from the accounts created by the attack.

Eclipse Attacks on Ethereum [17] describes *Eclipse* attacks on Ethereum, a type of attack which by flooding a node’s TCP connections is able to make them see a different blockchain history than the network’s actual one. This was an attack which was known on Bitcoin which was considered to be harder to perform on Ethereum nodes. The researchers communicated the potential effects of the attack and the vulnerabilities were fixed in geth v1.8⁴. This vulnerability was not abused in the wild, and as a result there was no need for a hard-fork. It should be noted, that other client implementations such as parity or cpp-ethereum were not found to be

¹A non-backwards compatible upgrade mechanism that creates new rules for a blockchain, usually to improve the system

²EIP608

³EIP607

⁴Most popular implementation of Ethereum in go lang

vulnerable, which shows that having a diverse set of implementations of a protocol can contribute to the network's security.

4.1.2 Smart Contract Attacks

Contrary to the network itself, Smart Contracts have proven to be quite vulnerable in the past. We proceed to give a brief description and explanation of the three biggest hacks in Ethereum's Smart Contracts, involving the TheDAO and a multisignature wallet implementation by Parity Technologies⁵.

4.1.2.1 TheDAO

TheDAO is an acronym for The Decentralized Autonomous Organization. The goal of TheDAO was to create a decentralized business where token holders would vote on projects to get funded. TheDAO was initially crowdfunded with approximately \$150.000.000, the largest crowdfunding in history, to date. In July 2016 it was proven that the smart contract governing TheDAO was vulnerable to a software exploit which enabled an attacker to steal approximately 3.600.000 ether, worth more than \$50.000.000 at the time.

If a user did not agree with a funding proposal they were able to get their investment back through a *splitDAO* function in the smart contract. The function was vulnerable to a *reentrancy*⁶ attack which allowed an attacker to make unlimited withdrawals from TheDAO contract [76, 77].

What made TheDAO hack very significant was that as a response, part of the Ethereum community decided to perform a hard-fork to negate the mass theft of funds. This was not accepted by the whole community, and as a result, nodes which did not decide to follow the hard-fork, stayed on the original unforked chain which is still maintained and is called 'Ethereum Classic' [78].

4.1.2.2 Parity Multisig 1

In July 2017 a vulnerability was found in the Parity Multisig Wallet⁷ which allowed an attacker to steal over 150.000 ether [79]. The attack involved a library contract, which contrary to using Solidity's 'Library' pattern discussed in 3.3.2.3, it involves using the *proxy libraries* pattern [80] to extract the functionality of a smart contract and let it be usable by other contracts, in order to reuse code, and reduce gas costs, as best practices dictate.

The vulnerability in this was that the Library contract involved a *initWallet* function which was being called through the Parity Multisig Wallet. The function was called when the contract was initially deployed in order to set up the owners of the multisig wallet, however due to it being unprotected⁸ it was callable by any

⁵<https://www.parity.io/>

⁶Essentially because an account's balance was not reduced before performing a withdrawal it was possible for a malicious user to perform multiple withdrawals and withdraw bigger amounts than their balance allowed.

⁷A cryptocurrency wallet, in this case a smart contract, which requires more than one cryptographic signatures to perform a transaction. It is generally used in organizations and to decrease the chances of funds being stolen.

⁸Public or External visibility without any access control.

user of the wallet⁹. As a result, a malicious user could reinitialize any multisig with their address as the contract's owner and drain its funds.

This was observed by a group of hackers called the 'White-Hat Group' who proceeded to drain vulnerable wallets before the attacker could, saving more than \$85.000.000 worth of ether at the time. The unrestricted usage of *delegatecall* as well as the lack of proper access control on the *initWallet* function was the root of this hack.

4.1.2.3 Parity Multisig 2

After the first Parity hack, a new multisig wallet library was deployed, with the visibility in the *initWallet* function initialized. This provided the expected functionality to all Parity Multisig implementations which were using the library. The fix in *initWallet* involved adding *only_uninitialized* modifier which would only allow modification of the linked multisig's wallet owners during initialization. However, the library itself was not ever initialized. As a result, any user could call the *initWallet* function and set themselves as the owner of the library contract. This alone would not have been dangerous, had there not been a *kill* function in the smart contract, which when called deletes the contract's bytecode, and effectively renders it useless.

The attacker first¹⁰ became owner of the library by calling *initWallet* with their address as argument, and then proceeded to kill the library. This resulted in **all** contracts that were using the library's logic to be rendered useless, effectively *freezing* 513774 Ether, as well as tokens [81].

A number of proposals were made [82] in order to recover the locked funds. All of these would require an 'irregular state change' similar to what happened with the DAO¹¹ which was eventually dismissed.

4.2 Evaluating Smart Contract Security

Due to the high financial amounts often involved with smart contracts, security audits from internal and external parties are considered a needed step before deployment to production. It is also being practiced that companies with public smart contracts also engage in bug-bounties, where they encourage users to interact with versions of their contracts deployed on a testnet, in order to identify any other vulnerabilities. Comprehensive studies on identifying the security, privacy and scalability of smart contracts [84] as well as taxonomies aiming to organize past smart contract vulnerabilities have been done [18, 34] have been done, however due to the rapid evolution of the field they get outdated very soon.

There is a need for auditors and developers to use automated auditing tools on their smart contracts and also use the latest version of the Solidity Compiler. As an example, none of the tools mentioned in [34] were able to detect the 'Uninitialized

⁹<https://github.com/paritytech/parity/blob/4d08e7b0aec46443bf26547b17d10cb302672835/js/src/contracts/snippets/enhanced-wallet.sol>

¹⁰Although claiming they were not aware of their actions' consequences

¹¹ 12 million ETH were moved from the "Dark DAO" and "Whitehat DAO" contracts into the WithdrawDAO recovery contract[83]

Storage Pointer’ vulnerability¹², however the Solidity Compiler was later updated to throw a Warning if this vulnerability exists.

4.2.1 Automated Tools

Auditing smart contracts significantly more effective when the source code is available. Taking into account the tools which have not been examined in our literature, we came in contact with TrailOfBits, a security auditing firm, and used their suite of tools to extend the already built taxonomies.

We utilized the tool Slither¹³ to audit smart contracts which had their source code available. As our concern is primarily in auditing and ensuring smart contracts that have yet to be deployed, we process all the smart contracts with the latest version of the Solidity compiler, v0.4.21, which provides verbose warnings and errors.

As Slither is a static analyzer and works on the source code, its modules (called ‘detectors’) are to find certain coding patterns which can be considered harmful to the smart contract. This includes detecting popular past contract vulnerabilities such as Reentrancy or the ‘Parity bugs’, however it’s not limited to that. New functionalities can be added through its scriptable API. We describe its modules:

Constant/View functions that write to state: It is planned to make constant and view functions unable to modify state variables by default in the next Solidity compiler versions, however until that happens, it should be enforced manually by developers. It ensures that the code functions as advertised.

Misnamed constructors that allow modification of ‘owner’-like variables: A constructor in a smart contract is run once at contract creation and usually sets an ‘owner’ variable which allows the contract’s deployer to have some extra functionality on the contract. In past cases, constructors were not named properly and were callable by adversaries, leading to smart contracts being drained of funds [18]

Reentrancy bugs: After TheDAO brought reentrancy and race-to-empty¹⁴ to the spotlight, all vulnerability scanners for Ethereum smart contracts are able to detect this vulnerability.

Deletion of struct with mapping: Deleting a struct with a mapping inside resets the contents of the struct, however it does not clear the contents of a mapping. This has not been reported as an exploit in the wild¹⁵, however it can be critical in the case of a banking DApp that keeps tracks of balances. A full Proof of Concept is given Appendix A.

Variable Shadowing: This is a unique feature of Slither that has not been implemented in other scanners (has been used in honeypot contracts).

Similar Naming between Variables: Warns users in the case two variables with same length have very similar names. This is used to have more clear variable naming in order to avoid misconceptions and typos.

Unimplemented Function Detection: This ensures that the implementation of an interface stays compliant and does not diverge from the intended specification.

¹²<https://github.com/ethereum/solidity/issues/2628>. This particular vulnerability has been exploited in Smart Contract honeypots as discussed in Section X

¹³Currently not open-sourced. TrailOfBits shared it with us to use it in the thesis.

¹⁴<http://vessenes.com/more-ethereum-attacks-race-to-empty-is-the-real-deal/>

¹⁵TrailOfBits have found this bug in audits

Unused State Variables: Detects state variables that are not used in any operations and suggests their removal.

Unprotected Function Detection: Detects public functions which have no modifiers and do not perform any assertions on state variables. The current implementation can impose false positives, however it does not have false negatives. This is able to find the Parity Wallet hack.

Wrong Event Prefix: As per the best practices, the names of ‘events’ should be capitalized. After a discussion on Github¹⁶, using ‘emit’ for events is going to be a mandatory for Solidity 0.5.0 and onwards.

It is seen that Slither can be used both for finding known vulnerabilities, but also to avoid common coding anti-patterns and mistakes. Due to its highly scriptable API we can extend it to include more rules. We contributed to the Slither repository by adding support for detecting *tx.origin* and *block.blockhash* usage. The usage of *tx.origin* should be avoided unless necessary, and as stated in the Solidity documentation can incur in loss of funds¹⁷. *block.blockhash* has been misused in smart contracts and ended up in 400 ETH being stolen from a company called SmartBillions [85]. We also contributed to the improvement of the accuracy of the modules ‘UnimplementedFunctionDetection’. Figure X shows a comparison of Slither after our contributions to the other analysis tools from [34].

[CREATE GRAPH WITH SLITHER FINDING VULNS SAME AS OTHER TOOLS]

4.2.2 Honeypot Smart Contracts

Since the second Parity bug and as of March 2018, no novel critical vulnerabilities have been identified in smart contracts. However, smart contracts that are architected to look vulnerable to known exploits started surfacing, when their true purpose is stealing the funds of aspiring hackers. These contract honeypots are funded with an initial small amount of ether (0.5 to 2 ether). Hackers who attempt to exploit them need to first deposit some amount (depending on the honeypot’s implementation) before trying to drain the contract. Each honeypot has a well-hidden mechanism to prevent the attacker from draining the funds, essentially locking up any funds that get deposited by individuals other than the contracts deployer.

¹⁶<https://github.com/ethereum/solidity/issues/2877>

¹⁷<http://solidity.readthedocs.io/en/v0.4.21/security-considerations.html>

```

1 // contract address: 0xd8993F49F372BB014fB088eaBec95cfDC795CBF6
2 pragma solidity ^0.4.17;
3
4 contract Gift_1_ETH
5 {
6
7     bool passHasBeenSet = false;
8
9     function() payable{}
10
11     function GetHash(bytes pass) constant returns (bytes32) {return
        sha3(pass);}
12
13     bytes32 public hashPass;
14
15     function SetPass(bytes32 hash)
16     payable
17     {
18         if(!passHasBeenSet && (msg.value >= 1 ether))
19         {
20             hashPass = hash;
21         }
22     }
23
24     function GetGift(bytes pass) returns (bytes32)
25     {
26
27         if( hashPass == sha3(pass))
28         {
29             msg.sender.transfer(this.balance);
30         }
31         return sha3(pass);
32     }
33
34     function PassHasBeenSet(bytes32 hash)
35     {
36         if(hash==hashPass)
37         {
38             passHasBeenSet=true;
39         }
40     }
41 }

```

Figure 4.1: Example honeypot

The above contract was initialized with 1 ether at its balance. An attack can drain the contract by calling the *GetGift* function with the correct password. Due to the attacker not knowing the password, they proceed to change it, using the *SetPass* function, which requires at least a 1 ether deposit, which is acceptable since the attacker will get that back. This also requires that the ‘passHasBeenSet’ variable is false, or that the PassHasBeenSet function has not been called yet.

A naive attacker would inspect the contract’s transactions in Etherscan¹⁸ and after notice that no transaction referring to ‘PassHasBeenSet’ has been made, and thus proceed to attack the contract and change the password, only to find that

¹⁸<https://etherscan.io/address/0xd8993f49f372bb014fb088eabec95cfdc795cbf6>

the password did not get changed. A transaction where a contract calls another contract's function is called a 'Message Call'. Etherscan shows this kind of calls as 'Internal Transactions', only when they include values of more than 0 ether. In this case, 'PassHasBeenSet' does not accept Ether and thus cannot be detected in Etherscan. The contract's owner called 'PassHasBeenSet' from another contract and as a result the password is not changeable. Detecting that the 'passHasBeenSet' variable had been set to true can be done by inspecting the storage of the smart contract, which is always public as shown in C.1

An extensive analysis of smart contracts as honeypots is made in [86] which was released to accompany the research of this Master Thesis.

4.2.3 Towards more secure smart contracts

It is apparent that since smart contracts being unmodifiable after deployment, there is no way of patching any vulnerabilities. Testing platforms have been setup so that developers can practice and test their skills. A developer should keep their code as simple as possible, while providing test coverage for as many scenarios as possible. Using audited and tested code for parts of contracts that have already been implemented (eg. an *ERC20* token contract) ensures that these parts of the code are going to be secured. Following the best practices as described by the industry's most sophisticated auditors¹⁹. Finally, developers should be looking for confluence between the results of different automated analyzers in order to filter out false-positives and find false-negatives.

¹⁹https://consensys.github.io/smart-contract-best-practices/known_attacks/

5 Metering and Billing of Energy on Ethereum

5.1 Energy Market inefficiencies

Having discussed how Ethereum works, and explained techniques to improve smart contracts' scalability and security, we proceed to discuss the topic of making energy markets more transparent and efficient by utilizing smart contracts. The use-case we describe can be used as a starting point for better tracking of energy usage inside a company, allowing better prediction of future needs. The world is gradually shifting from nuclear and fossil fuels to Renewable Energy Sources (RES). RES have been taking a larger share of Germany's gross energy production and this has created a Germany is on a rollout plan of installing smart meters in every household which incorporates RES.

The barrier to entry to become an energy producer¹

In its current state, most consumers do not know what they are paying Business level take long time and are

Price of energy, consumer does not know always what they pay, or what they gain from their renewables

5.2 Advantages of an Energy-based Blockchain application

5.2.1 Peer 2 Peer

In the most general cases, blockchains have the ability to provide transparency and immutability. When talking about energy and transparency, full history of meter readings, price calculation, billing of inhouse energy departments. This can be extended for EV car payment microtransactions and so on.

5.2.2 User Owned Data

5.3 Business Logic

In collaboration with Honda R&D Germany, we create a pilot suite of smart contracts for in-house use in order to track and bill the consumed energy of the com-

¹By installing solar panels for example

pany's headquarters as measured by a set of smart meters.

Describe meters, billing and so on. The purpose is to serve as a means of tracking the energy consumed by the company's smart meters and ensuring the data's validity and existence in a smart contract. In addition, due to the complex structure of the company, every smart meter's consumption can contribute with different coefficients to the total energy consumption of the rooms in a building. As a result, the developed smart contract are able to track the energy consumption of each room and assign it to a higher-order. We proceed to discuss the business logic of the use-case and then implement it. We utilize the technique from 3.3.2.3 to optimize our smart contracts for gas efficiency and utilize Slither from 4.2.1 and the learned best-practices to ensure that the developed smart contracts are robust. Due to the intellectual property of Honda R&D, all testing and verification of the contracts' functionality was done in a private in-house testnet.

5.3.1 Smart Meters and Rooms

A smart meter must be able to keep track of the current reading and timestamp of the reading as well as the last reading and timestamp in order to calculate the difference of the two. It also has a unique identifier which is used to retrieve it in the smart contract.

A company building is split into rooms. Each smart meter contributes to a room's consumption with a real coefficient, according to Equation 5.1

$$R = C * M \quad (5.1)$$

where

$$C = \begin{bmatrix} c_{11} & \cdots & c_{1M} \\ \vdots & \ddots & \vdots \\ \vdots & \ddots & \vdots \\ c_{N1} & \cdots & c_{NM} \end{bmatrix}$$

(c_{ij} is the coefficient of the j th meter for the i th room)

and

$$M = [m_1 \quad \cdots \quad m_M]^T$$

(m_i is the kilowatthour reading of the i th meter)

The coefficients are calculated through an internal partner, INSERT DETAILS ON EASD.

5.3.2 Cost Centers and Billing

Rooms are grouped together in a structure called *Cost Center* which does X. A room can belong only to one cost center. During the accounting stage, the accountant can retrieve the difference in energy consumption since the last clearing period and thus

5.4 Smart Contracts

In this section we go over the implementation and the rationale of each developed smart contract. We explain the inner workings and provide tests of their functionality. A thorough walkthrough on how they interact with each other can be found in 6.1

5.4.1 Contract Registry

Upgradable logic, call smart contract by name.

5.4.2 Meter Management

Meter manager utilizes 3.3.2.3. Each meter has its own ID. We use the pattern. Deleting a meter sets the active status to false. We iterate over the array of meters. There are software engineering patterns [87] that allow more proper usage, however they cost a lot more gas.

5.4.3 Cost - Profit Management

We follow the same pattern as with meters for storing cost centers. We define Follow busienss logic

5.4.4 Access Control

Defining a proper access control policy is very important as discussed in Section ?? . It is common to find Access Control Lists (ACL) in enterprise environments which allow access to resources only to selected participants. This does not exist by default in smart contracts. The Aragon Project² provides an ACL contract, however it was not used in the final version due to the complexity it introduced to our code³. Instead, the DSAUTH pattern is used.

5.5 Monitoring Server

Could be implemented without monitoring server if each meter was smarter. Explain monitoring server

5.5.1 REST API

Explain rest api usage

5.5.2 Python Client

Explain python implementation of rest api

²Project aimed at creating DAOs

³Aragon's contracts are architected towards creating fully upgradable DAOs, which would introduce considerable overheads and complexity to our code

5.5.3 web3.py interaction

Explain how web3.py interacts with monitoring server and sends data to Smart Contracts

6 Results

6.1 leResults

We are able to create blabla

7 Conclusion

7.1 Future Work

The main issue with our current implementation is that instead of having a direct push from each meter (or any IoT device) to the blockchain, we need to pull the data from the aforementioned monitoring server, and then push it again. This introduces latencies and single points of failure, however, this was done due to our corporate setup. An improvement would be to setup a microcontroller on each that would be executing a binary that pings readings to the blockchain. even better, run a node on each IoT device, however requires too much power, maybe in the far future. We explore Ethereum platform due to its abundance in developers and stay in it. There are other smart contract platforms however they lack developer tools, are not battle tested and are potentially centralized. As there is a bigger issue with scaling, the whole infrastructure could be transferred to a permissioned in-house blockchain, however we wanted to stay within the scope of keeping it as transparent as possible.

FIN.

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Appendices

[illegible]

```

1 > web3.eth.getBlock(5284738)
2 { difficulty: BigNumber { s: 1, e: 15, c: [
3     32,
4     85319757566868
5   ]
6 },
7   extraData: '0x7869786978697869',
8   gasLimit: 7995219,
9   gasUsed: 1547361,
10  hash: '0
      x61ff0118470fdda14815bdc26f6e4fb29effc55369f3d6985e1433f782686403
      ',
11  logsBloom: '0
      x0002080000020400020004000000000000010040000000000800020000000084000800400
      ',
12  miner: '0xf3b9d2c81f2b24b0fa0acaaa865b7d9ced5fc2fb',
13  mixHash: '0
      x29b6efa55ad0298b0c90f21e9e23d572977ffb3c5064a9816a69bb2bf2a9effd
      ',
14  nonce: '0xabad128000fed25e',
15  number: 5284738,
16  parentHash: '0
      xb7063b9c7b05c95c35a329717e44875829cc740b2e0749e03d54806dcf34b520
      ',
17  receiptsRoot: '0
      xe5e176557b9f40394917191095b706a2a331742f0dc93a10e1d59b5e297ee0b5
      ',
18  sha3Uncles: '0
      x1dcc4de8dec75d7aab85b567b6ccd41ad312451b948a7413f0a142fd40d49347
      ',
19  size: 7789,
20  stateRoot: '0
      x1c62917ac72a2b76e00053efbb7af0d6949e86cafb3f983812d763715c6c9905
      ',
21  timestamp: 1521484243,
22  totalDifficulty: BigNumber { s: 1, e: 21, c: [
23     31406307,
24     78318927526632
25   ]
26 },
27  transactions: [ '0
      x6a5d9e470bbff3eb476e20647fbe66e0cec7795291efd6301e6028865d0d4201
      ',
28    '0
      xbe1c3e767e34d5d668ea50d3400b2e11a663479f931c225eda5e1d314e012589
      ', ...
29  ],
30  transactionsRoot: '0
      xb0a066469d74fe1f450c5fa8a1f59c5b7305feb6336d0d59f347a2b2c7a8c579
      ',
31  uncles: []
32 }

```

Figure A.2: Contents of an Ethereum block when querying a node

Ganache UI:

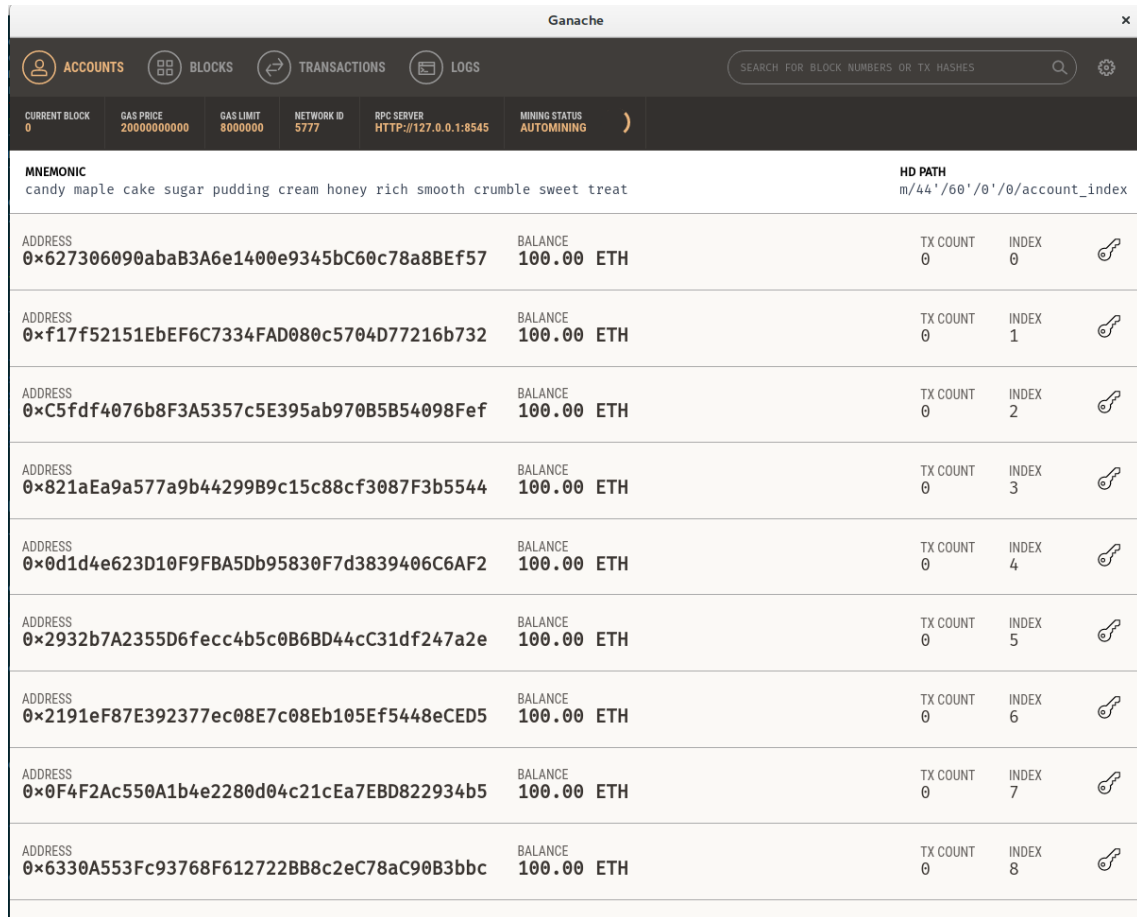


Figure A.3: Ganache testnet User Interface

Web3js example:

```

1 node
2   > Web3 = require('web3');
3 > INFURA_API = process.env.INFURA_API; // Infura is a third party
    service that allows us to connect to their Ethereum node without
    setting up our own. > web3 = new Web3(new Web3.providers.
    HttpProvider("https://mainnet.infura.io/" + INFURA_API));
4 > web3.eth.blockNumber;
5 5289236

```

Figure A.4: Interacting with a node in Javascript

Web3py example:


```
1 $ ipython
2 In [1]: from web3 import Web3, HTTPProvider
3 In [2]: import os
4 In [3]: INFURA_API = os.environ['INFURA_API']
5 In [4]: w3 = Web3(HTTPProvider('https://ropsten.infura.io/'+
    INFURA_API))
6 In [5]: w3.eth.blockNumber
7 Out[5]: 2872088
```

Figure A.5: Interacting with a node in Python

B Scalability through Gas Saving masks

```
1 pragma solidity ^0.4.21;
2
3 contract Packing {
4
5     uint64 a;
6     uint64 b;
7     uint64 c;
8     uint64 d;
9     uint128 e;
10    uint128 f;
11
12    function set() public {
13        a = 1;
14        b = 2;
15        c = 3;
16        d = 4;
17        e = 5;
18        f = 6;
19    }
20 }
```

```
1 $ solc --optimize --asm Packing.sol | grep sstore | wc -l
2 2
3 $ solc --asm Packing.sol | grep sstore | wc -l
4 6
```

Figure B.1: Running the optimizer in storage variables less than 256 bytes results in 2 SSTORE commands instead of 6 which results in significant savings in gas costs

Game interface:

```
1 pragma solidity ^0.4.21;
2
3 interface Game {
4     event PlayerRegistered(uint16 playerID, address player);
5
6     function Register() public returns (uint16 playerID);
7     function CreateCharacter(uint256 creationTime, uint256 class,
8         uint256 race, uint256 strength, uint256 agility, uint256
9         wisdom, uint256 metadata) external;
10    function GetCharacterStats(uint256 index) external view returns
        (uint16 playerID, uint32 creationTime, uint8 class, uint8
        race, uint16 strength, uint16 agility, uint16 wisdom,
        bytes18 metadata);
11 }
```

Figure B.2: Interface for described use-case

Tightly packed code:

```

1  struct Character {
2      uint16 playerId;
3      uint32 creationTime;
4      uint8 class;
5      uint8 race;
6      uint16 strength;
7      uint16 agility;
8      uint16 wisdom;
9      bytes18 metadata;
10 }

```

(a) Character structure definition

```

1  function CreateCharacter(
2      uint256 creationTime,
3      uint256 class,
4      uint256 race,
5      uint256 strength,
6      uint256 agility,
7      uint256 wisdom,
8      uint256 metadata)
9      external
10 {
11     uint16 playerId = player2ID[msg.sender];
12     require(playerID != 0);
13
14     Character memory c;
15     // Overhead from converting, in order to match interface
16     c.playerID = uint16(playerID);
17     c.creationTime = uint32(creationTime);
18     c.class = uint8(class);
19     c.race = uint8(race);
20     c.strength = uint16(strength);
21     c.agility = uint16(agility);
22     c.wisdom = uint16(wisdom);
23     c.metadata = bytes18(metadata);
24
25     uint CharacterId = Characters.length;
26     emit CharacterCreated(c, CharacterId);
27
28     Characters.push(c);
29 }

```

(b) Create character simply sets values to each struct variable

```
1  function GetCharacterStats(uint256 index)
2      external view
3      returns (
4          uint16 playerId,
5          uint32 creationTime,
6          uint8 class,
7          uint8 race,
8          uint16 strength,
9          uint16 agility,
10         uint16 wisdom,
11         bytes18 metadata
12     )
13 {
14     Character memory c = Characters[index];
15     return (
16         c.playerID,
17         c.creationTime,
18         c.class,
19         c.race,
20         c.strength,
21         c.agility,
22         c.wisdom,
23         c.metadata
24     );
25 }
```

(c) Retrieve the character and save it in memory, then return all values.

Figure B.3: Implementation requires a Solidity ‘struct’ to pack all the variables together. CreateCharacter and GetCharacterStats

Method 2 code:

```
1  function CreateCharacter(  
2      uint256 creationTime,  
3      uint256 class,  
4      uint256 race,  
5      uint256 strength,  
6      uint256 agility,  
7      uint256 wisdom,  
8      uint256 metadata)  
9      external  
10     {  
11         uint16 playerId = player2ID[msg.sender];  
12         require(playerID != 0);  
13  
14         uint c = uint256(playerID);  
15         c |= creationTime << 16;  
16         c |= class << 48;  
17         c |= race << 52;  
18         c |= strength << 56;  
19         c |= agility << 72;  
20         c |= wisdom << 88;  
21         c |= metadata << 104;  
22  
23         uint CharacterId = Characters.length;  
24         emit CharacterCreated(c, CharacterId);  
25  
26         Characters.push(c);  
27     }
```

Figure B.4: Create Character by shifting variables

```
1  function GetCharacterStats(uint256 index)
2      external view
3      returns (
4          uint16 playerID,
5          uint32 creationTime,
6          uint8 race,
7          uint8 class,
8          uint16 strength,
9          uint16 agility,
10         uint16 wisdom,
11         bytes18 metadata)
12     {
13         uint c = Characters[index];
14         return (
15             uint16(c),
16             uint32(c >> 16),
17             uint8((c >> 48) & uint256(2**4-1)),
18             uint8((c >> 52) & uint256(2**4-1)),
19             uint16(c >> 56),
20             uint16(c >> 72),
21             uint16(c >> 88),
22             bytes18(c >> 104)
23         );
24     }
```

Figure B.5: Get the traits of a character by shifting and masking appropriately. Typecasting is the same as applying a mask of N bits.

Method 3 code:

```

1  function GetProperty(bytes32 Character, uint mask, uint shift)
    private pure returns (uint property) {
2      property = mask & (uint(Character) / shift);
3  }
4
5  function SetProperty(bytes32 Character, uint mask, uint shift,
    uint value) private pure returns (bytes32 updated) {
6      updated = bytes32((~(mask * shift) & uint(Character)) | ((
        value & mask) * shift));
7  }

```

(a) Getting and setting a property

```

1  uint private constant mask32          = (1 << 32) - 1;
2  uint private constant _CreationTime = 1 << 16;

```

(b) Mask and shift offsets for CreationTime

```

1  function SetCreationTime(bytes32 Character, uint256 value)
    internal pure returns (bytes32) { return SetProperty(
    Character, mask32, _CreationTime, value); }
2  function GetCreationTime(bytes32 Character) internal pure
    returns (uint32) { return uint32(GetProperty(Character,
    mask32, _CreationTime)); }

```

(c) Getting and Setting creation time API

Figure B.6: Parts of the Library API for Character Creation

<pre> 1 bytes32 c = c.SetPlayerID(playerId); 2 c = c.SetCreationTime(creationTime); 3 c = c.SetClass(class); 4 c = c.SetRace(race); 5 c = c.SetStrength(strength); 6 c = c.SetAgility(agility); 7 c = c.SetWisdom(wisdom); 8 c = c.SetMetadata(metadata); </pre>	<pre> 1 bytes32 c = Characters[index]; 2 return (3 c.GetPlayerID(), 4 c.GetCreationTime(), 5 c.GetClass(), 6 c.GetRace(), 7 c.GetStrength(), 8 c.GetAgility(), 9 c.GetWisdom(), 10 c.GetMetadata() 11); </pre>
--	---

(a) Create Character by shifting variables

(b) get character variables

Figure B.7

[illegible]

Figure C.1: Inspecting the first storage slot of a contract

D Code for Smart Meters