SGXonerated: Finding (and Partially Fixing) Privacy Flaws in TEE-based Smart Contract Platforms Without Breaking the TEE

Nerla Jean-Louis
nerlaj2@illinois.edu
University of Illinois Urbana Champaign

Yunqi Li
yunqil3@illinois.edu
University of Illinois Urbana Champaign

Yan Ji
yj348@cornell.edu
Cornell University

Harjasleen Malvai
hmalvai2@illinois.edu
University of Illinois Urbana Champaign

Thomas Yurek
yurek2@illinois.edu
University of Illinois Urbana Champaign

Sylvain Bellemare
sbellemare@cornell.edu
IC3 (Cornell University)

Andrew Miller
soc1024@illinois.edu
University of Illinois Urbana Champaign, IC3

ABSTRACT

TEE-based smart contracts are an emerging blockchain architecture, offering fully programmable privacy with better performance than alternatives like secure multiparty computation. They can also support compatibility with existing smart contract languages, such that existing (plaintext) applications can be readily ported, picking up privacy enhancements automatically. While previous analysis of TEE-based smart contracts have focused on failures of TEE itself, we asked whether other aspects might be understudied. We focused on state consistency, a concern area highlighted by Li et al., as well as new concerns including access pattern leakage and software upgrade mechanisms. We carried out a code review of a cohort of four TEE-based smart contract platforms. These include Secret Network, the first to market with in-use applications, as well as Oasis, Phala, and Obscuro, which have at least released public test networks.

The first and most broadly applicable result is that access pattern leakage occurs when handling persistent contract storage. On Secret Network, its fine-grained access pattern is catastrophic for the transaction privacy of SNIP-20 tokens. If ERC-20 tokens were naively ported to Oasis they would be similarly vulnerable; the others in the cohort leak coarse-grained information at approximately the page level (4 kilobytes). Improving and characterizing this will require adopting techniques from ORAMs or encrypted databases.

Second, the importance of state consistency has been underappreciated, in part because exploiting such vulnerabilities is thought to be impractical. We show they are fully practical by building a proof-of-concept tool that breaks all advertised privacy properties of SNIP-20 tokens, able to query the balance of individual accounts and the token amount of each transfer. We additionally demonstrate MEV attacks against the Sienna Swap application. As a final consequence of lacking state consistency, the developers have inadvertently introduced a decryption backdoor through their software upgrade process. We have helped the Secret developers mitigate this through a coordinated vulnerability disclosure, after which their state consistency should be roughly on par with the rest.

1 INTRODUCTION

Ever since the very first projects in the blockchain space, achieving transaction privacy on a public blockchain has been a pivotal issue. Because the drawbacks of pseudonymity are well-known [28, 42, 54], many privacy-focused projects including Monero and Zcash have emerged with the goal of bringing true usable transaction privacy to end users. However, while these projects can handle basic anonymous payment functionality relatively well, the broader question of how to achieve general private computation through smart contracts remains unanswered. While enhanced privacy for more sophisticated decentralized finance applications is a worthwhile goal in its own right, it is also a promising solution to harmful forms of Miner Extractable Value (MEV) in which publically-visible market orders can be frontrun by block producers.

TEE-based smart contracts are an attractive solution. Compared with purely cryptographic approaches such as zero-knowledge proofs (ZKP) and secure multiparty computation (MPC), trusted execution environments (TEEs) — especially Intel SGX — are more efficient and are very expressive as well, capable of running existing smart contract applications from Ethereum and Cosmos. A line of research works has explored the design of secure TEE-based smart contracts [9, 14, 69, 72]. In this setting, the attacker model includes the untrusted host in possession of the TEE, where the TEE must rely on the host for all network access and to respond to queries about external data, such as clock times. In terms of real-world deployment, TEE-based smart contracts appear poised to grow. Secret Network (formerly known as Enigma [72]) launched the first public deployment of a TEE-based smart contract system in 2020. As of Feb 2023, it has a market cap of approximately $200M including native and bridged tokens.[1] Other TEE-based smart contract platforms, including Oasis [50], Obscuro [13], and Phala [52], are at varying stages of public launch - each of them has deployed at minimum a public test network with open-source code.

[1] https://secretanalytics.xyz/

Li, et al. [34] examined the research literature and pre-production industry whitepapers, pointing out several potential areas of concern. Looking at real-world implementations, the discussion of security issues in TEE-based smart contracts has focused largely on compromises of the TEE instantiation itself, specifically SGX, which has had to recover from a sequence of catastrophic vulnerabilities [7, 64, 66, 67]. The exposure of Secret Network to AepicLeak [7] highlighted the importance of compartmentalization and key rotation [68]. Although having systems in place to mitigate risks of TEE failures is crucial, focusing solely on this would miss the bigger picture of other forms of vulnerability.

In this paper, we ask the following: besides hardware vulnerabilities in the TEE itself, are TEE-based smart contracts implemented today vulnerable to non-TEE attacks? We analyze the codebases and documentation of Secret, Oasis, Obscuro, and Phala, especially focusing on the interface between untrusted and trusted code and the interaction between newly written code and software inherited from existing plaintext blockchains. We summarize the main lessons learned:

Access pattern leakage is a concern for all the systems we reviewed. This is especially a problem for fungible token applications ported from plaintext blockchains, such as ERC-20 tokens. These platforms support stateful contracts and are built around a high-performance key-value storage library that persists on disk, such as LevelDB. However, the patterns at which these databases are accessed when processing confidential transactions can themselves leak crucial information. In the worst case, this reveals to the untrusted operating system the sender and the recipient in every token transfer, violating the desired transaction privacy guarantees. This is the case for SNIP-20 tokens (privacy-enhanced fungible tokens based on the ERC-20 and CW-20 standards) on Secret Network, the only ones in use today. This leakage is also present in Oasis Sapphire and Cipher, suggesting that ERC-20 tokens that are naively ported would also fail to provide privacy. Obscuro and Phala mitigate this to some extent because their use of block-based paging means that the access pattern is only leaked to the nearest 4 kilobytes.

A comprehensive fix to access pattern leakage could make use of oblivious data structures (ORAM) or encrypted database techniques, found in other TEE-based distributed systems, but have not yet been adapted to smart contracts [4, 17, 24, 43, 61]. The MobileCoin [30] cryptocurrency (developed by Signal [1]) also uses ORAM with SGX to provide privacy-preserving transaction retrieval [39]. These solutions show the viability and scalability of a TEE solution that implements ORAM for interacting with untrusted storage.

State consistency and replay defenses are critical to privacy but do not apply intrinsically in L1 TEE-backed blockchains. The need for rollback protection for TEEs in general has been discussed in previous work [38], and has featured prominently in security research papers on TEE-based smart contracts [14, 29, 34]. This seems like a natural synergy for the two technologies — blockchains are good for committing to a sequential ordering of published transactions, and TEE-based smart contracts must rely on this. Li et al. suggested that state consistency and blockchain data confirmation come along as "intrinsic features" for a Layer 1 (L1) architecture, meaning that the consensus protocol to create new blocks is carried out by the same validator nodes that execute smart contracts using TEEs [34]. It turns out that even though Secret Network is considered an L1, Secret Network's design is incomplete in that it does not incorporate any defense against replay or rollback attacks. The untrusted host is therefore able to simulate or replay transactions in any order, regardless of what appears on-chain. Oasis and Phala have already implemented defenses against these, and it is on Obscuro's list of requirements prior to launch.

Design flaws in TEE-backed blockchains lead to practical attacks without compromising the TEE. Since Secret Network is the only TEE-based smart contract system with live running applications, we explore the impact of the above vulnerabilities. SNIP-20 tokens are believed to hide account balances, and the receiver and token amount involved in each transfer transaction [58]. Beyond just identifying vulnerabilities, we show how these can be exploited to break the advertised privacy guarantees. In fact, due to the fine-grained access pattern, just adding print statements to the debug log is enough to trace the senders and receivers in each token transfer.

We design new transaction simulation attacks that enable the forensic analysis of past and present SNIP-20 transfers, as well as query the balances of individual accounts. We also show how partial storage replay can amplify the attack, meaning attackers do not need capital deposits of their own to carry it out. Besides transaction privacy, we also show that replay defenses are critical for MEV prevention, one of the benefits of TEE-based smart contracts. Our attacks can be used by validator nodes to strategically frontrun automated market maker (AMM) swaps. All of our attacks can be performed by an unprivileged node (e.g., no stake deposits or developer keys are needed), without relying on any vulnerabilities of the underlying TEE, and without requiring any kernel patches. Given the threat, we have coordinated with Secret Network's development team on vulnerability disclosure and helped deploy mitigations.

The need for software updates creates a backdoor hazard. Every blockchain needs a software upgrade mechanism, though this is notoriously challenging [6] even before TEEs are involved. In order to update software, existing enclaves must transfer key material to enclaves running the new software. In Secret Network, the only policy enforced by the enclaves is code signing. Unfortunately this means that Secret developers have the ability to unilaterally apply updates to the software on their own machines, enabling them to decrypt every transaction - an unintentional backdoor. Oasis and Phala both implement not just a distributed code signing authority, but require proof of on-chain publication of the software binaries to hold them accountable. Obscuro has not implemented such a process but lists it on their requirements prior to mainnet launch.

To summarize our main contributions:

- We analyze the codebases of existing TEE-based smart contract systems that offer at least public test networks. Specifically we focus on issues involving the boundary between the trusted and the untrusted code, and especially the application storage.
- We provide evidence that access pattern leakage from the underlying key-value storage means that ordinary token contracts ported to any of the platforms today would fail to provide strong privacy. We discuss possible mitigations for the future including ORAM or decoys.
- For Secret Network in particular, we demonstrate new transaction simulation attacks, demonstrating that a lack of state consistency leads to breaking all the privacy guarantees of existing

```
1 storage balances: mapping { address => uint128 }
2 contract function send(sender, recipient, amount):
3     require balances[sender] >= amount
4     balances[recipient] += amount
5     balances[sender] -= amount
```

Figure 1: Contract pseudocode for sending fungible tokens.

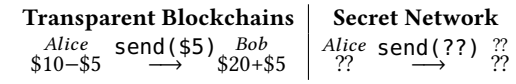


Figure 2: Privacy Goals for SNIP20 tokens versus Transparent tokens such as ERC-20.

tokens. We have conducted a coordinated vulnerability disclosure and helped developers with mitigations. They have now added replay defenses, although receiver privacy for SNIP-20 tokens is left currently unresolved.

2 BACKGROUND

Blockchains and smart contracts A blockchain is a decentralized ledger whose state is replicated and agreed upon by mutually untrusting nodes. A smart contract is a program whose execution is recorded on this ledger. Many blockchains, most notably Ethereum [23], support smart contracts. In Ethereum the state of all contracts on the chain is public, and identities are pseudonymous. Many works [42, 46, 53, 54] have shown that these pseudonyms are a weak form of privacy. The public nature of the Ethereum blockchain impedes many applications, though in particular we are interested in decentralized exchanges.

Decentralized finance. Decentralized finance facilitates manipulation of financial assets without relying on centralized authorities like banks, and its applications include payments, lending, auctions, and other financial derivatives. Tokens represent financial assets, and Automated Market Makers (AMM) facilitate token exchange by matching them with a liquidity pool. Liquidity providers contribute tokens to the pool and receive fees for facilitating transfers.

Fungible tokens. Fungible tokens serve as currency that can be owned and transferred using smart contracts in decentralized finance applications. The pseudocode for the `Send` function of a fungible token is shown in Fig. 1. These contracts can be customized for specific tokens while maintaining standardized interfaces such as ERC-20 on Ethereum and SNIP-20 on Secret.

Privacy expectations of fungible tokens. The appeal of Secret Network is that existing blockchain paradigms from the world of transparent blockchains, such as ERC-20 tokens in Ethereum, can be easily translated over to receive immediate privacy guarantees.

On a transparent blockchain all of the transaction data is viewable on chain. For Alice to send $5 to Bob, the network must know Alice's current balance of $10, Bobs's balance of $20, the value of the transaction $5, and Alice's and Bob's addresses. We summarize the possible privacy goals for transactions as: *sender privacy* and *receiver privacy* to hide the addresses involved in the transaction and *value privacy* and *balance privacy* to hide the amounts involved in the transaction.

For SNIP-20 tokens, the sender's address is automatically made public due to the nature of executing transactions on a public blockchain. Transaction fees in Secret are paid using the public native token Secret Token (SCRT), which must be checked for sufficient balance by running nodes. SCRT tokens are converted into the SNIP-20 token called Secret Secret Token (sSCRT) by wrapping it in a smart contract. SNIP-20 tokens like sSCRT are believed to hide receiver address, transaction value, and balances of involved parties. sSCRT is the most widely used smart contract on Secret, with approximately 36,000 token accounts and approximately 500,000 interactions[2], while other popular tokens include bridged versions of stablecoins like USDT and USDC, Bitcoin, Ethereum, and Monero.

Trusted execution environments. A *trusted execution environment* (TEE) or secure encalves are an isolated environment, often implemented with hardware, that provides privacy and integrity guarantees about the code it executes. Intel Software Guard Extensions (SGX) [2, 18, 26, 41] is the basis for Secret and other upcoming systems. It is a hardware TEE that supports remote attestation [56].

Hardware TEEs such as SGX are designed to defend against an attacker with OS kernel-level access. Due to the hardware isolation of these TEEs such an attacker should not be able to tamper with or observe the execution of a running TEE program. This model describes a malicious blockchain node operator running a cloud tenant with a dedicated instance. Because these guarantees only apply to a running TEE, any restart of the TEE will result in data being lost. SGX therefore makes use of sealed data to encrypt state on disk and securely load it into the TEE.

Remote attestation allows a node operator to prove to other network participants that they are running a legitimate TEE with the correct version of the software. At a high-level remote attestation is an interactive protocol where a measurement of the data and software running in the enclave is taken and signed using a secret key hidden in the hardware. This measurement and signature is checked and endorsed by the hardware manufacturer based on their secret knowledge of the hardware keys determined during the manufacturing process.

Following successful remote attestation, the operator's TEE can access confidential data, such as smart contract states, without requiring the network to trust individual node operators or cloud providers running the TEE. Even with physical access, breaching an Intel CPU is thought to be expensive and difficult [18]. The root of trust remains at the manufacturer (Intel in the case of SGX), responsible for correctly manufacturing hardware and issuing certificates only for appropriately manufactured TEE-enabled CPUs.

Even assuming this root of trust, however, the privacy and integrity guarantees provided by Intel SGX have been broken in practice. Papers such as [7, 11, 67] have identified vulnerabilities in the TEE implementation, resulting in memory and CPU register leaks, as well as the creation of fake attestation reports. Side channel attacks allow attackers to extract secrets from the enclave by observing resources such as caches [10, 15, 20, 25, 44, 57], branch predictions [21, 27, 33], and memory usage [45]. Tools such as SGX-Step [65] provide attackers with instruction level control and increase the efficiency of side-channel attacks.

[2] https://secretnodes.com/contracts

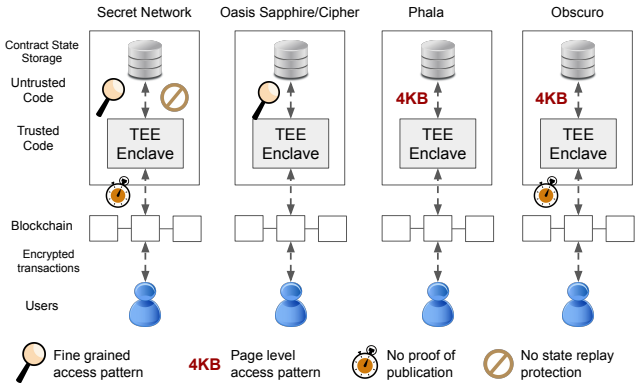


Figure 3: High-level architecture of TEE-based smart contracts, focusing on the interfaces between the TEE and external storage and between the TEE and the blockchain.

3 OVERVIEW OF TEE-BASED SMART CONTRACT PLATFORMS DESIGN

In this section, we review some general design patterns used to realize TEE-backed blockchains. We focus on explaining Secret Network, though the general design is applicable to others.

Structure of TEE-based blockchains. In TEE-based systems, the code is divided into trusted and untrusted portions. The trusted portion runs inside the TEE with integrity and privacy guarantees, while the untrusted portion runs on the host operating system and acts as an interface between 1) the TEE and clients, 2) TEE and the consensus layer, 3) TEE and persistent storage. Therefore, the main threat model for a TEE-based blockchain is that the attacker has full control of the untrusted portion of the nodes.

Clients need a way to encrypt their transactions such that only the enclave's trusted code can decrypt it. To enable this, a mechanism for clients to receive key material from trusted host hardware is necessary, which is then used to encrypt transactions to be sent to the network. Typically, the trusted portion passes a public encryption key to the untrusted portion so that encrypted messages can be sent directly to the enclave through a secure channel. The untrusted host code inputs these ciphertexts to the enclaves, which decrypts them, process them (and in the process possibly access some other encrypted state), encrypt the results, and feed these back to the untrusted code.

The relevant threat model for a TEE-based blockchain is that the attacker is in full control of the untrusted portion of the application running on its own nodes. An application using the TEE must assume that the host is malicious and will attempt to learn information about the confidential state using any queries it is permitted to make. The TEE can only help to enforce the policies that the enclave program explicitly writes.

In SGX the interface between the untrusted and the trusted portions of the application are known as `ecall`'s and `ocall`'s which make a function call from the untrusted process to the trusted (`ecall`), or vice versa (`ocall`). Since these are function calls, arguments and return values can be used to pass data between them.

Blockchains and proofs of publication. The separation of state machine replication (and execution) from a global consensus layer has been considered in prior work, notably [29] and [14]. [29] considers a more general model, where an untrusted host provides state and services that must be committed to a public ledger. They go on to provide a framework to achieve security against misbehaving hosts by introducing *proofs of publication* to the blockchain before clients accept any request responses from hosts. [14] specializes this model to a scenario similar to that of Secret Network, where a large number of TEE nodes can accept messages and requests, but only a small fraction of these nodes participate in consensus. They utilize proofs of publication to achieve what they call *atomic delivery*, that is, given any client transaction Tx, the output of this transaction is revealed to the client if and only if the consensus nodes have provided a valid proof of publication for Tx.

Secret Network, on the other hand, does not require these proofs of publication, breaking the atomic delivery requirement. Any Secret node can unilaterally execute a valid transaction and obtain an output (albeit in part encrypted). While an honest client may not accept this output, the untrusted host of the executing TEE can still glean important information from metadata or through its own transactions as we will soon demonstrate.

How to pass private outputs to individual users. Ordinary transparent smart contracts typically define "query" or "getter" methods in order to view the current application state (for example, to check a token account balance). User wallets typically use RPC servers to process these queries on their behalf. Private TEE smart contracts need a way to send query results from a remote enclave to the client, without revealing them to the untrusted host.

There are two main approaches that all of these networks follow: The first approach is based on encrypted log events. As a contract executes a transaction, it may write outputs to a log. This log is included in the public blockchain data. The contract encrypts by associating the intended recipient with a public encryption key. Since users are already identified by their address (a hash of a public key for digital signatures), it makes sense to extend the address format to include a public key for receiving outputs. Oasis and Obscuro support atomic delivery so that the outputs would not decrypt until the transaction is committed. An oracle could be used to determine the transaction confirmation.

The second approach uses off-chain queries. Nodes with enclaves are allowed to process "queries" executing the smart contract and retrieving the data from the local dastabase state of the TEE node. A viewing key is shared between the smart contract and a user. The viewing key is stored in the contract's application state, and the contract query results are encrypted using this key before they are passed on to the host. These off-chain queries are susceptible to access pattern leakage.

4 PRIVACY ANALYSIS OF REAL-WORLD TEE-BASED BLOCKCHAINS

We analyze the landscape of TEE-backed blockchain platforms in practice through the codebases of Secret Network, Oasis, Obscuro, and Phala. Table 1 and Figure 3 summarize the different privacy hazards relevant to TEE smart contracts detailed in this section.

	Level of Access Pattern Leakage	Tx Replay Protection	Storage Replay Protection	Software Upgrade Transparency
Secret Network [a]	○ key	○ → ●	○ → ◌	○
Oasis [bc]	○ key	◒	●	●
Obscuro [d]	◒ page	○ → ◌	◒	○ → ◌
Phala [e]	◒ page	●	◒	●

[a] SecretNetwork fd2745 [b] oasis-sdk c82319 [c] oasis-core 5302f72 [d] go-obscuro b5a79e [e] phala-blockchain 55479c

Table 1: Analysis of security and privacy hazards in existing TEE-based smart contracts. This is a reflection of the current code bases for each project at the time of writing. An arrow and filled circle, → ●, indicates a fix as a result of our disclosure; → ◌ indicates a stated plan to add this mitigation in the future.

4.1 Integration with existing blockchain codebases and smart contract languages.

Secret Network. As we discussed in Sec. 3 Secret Network's code base, like other SGX applications, is divided into a trusted portion that is executed in the TEE and an untrusted portion that is run on the host operating system. The untrusted codebase for Secret Network is packaged into two binaries: (1) the `secretd` binary containing a command line interface client to interact with the network and to start a node server, and (2) the `libgo_cosmwasm.so` binary, which provides a programmatic API to `secretd` to interact with contract code and make calls to the TEE code. The code for either `libgo_cosmwasm.so` and `secretd` can be modified by a malicious host.

Much of Secret Network's codebase is inherited from the Cosmos Software Development Kit (Cosmos SDK) [59]. The Cosmos SDK code handles message authentication and processing of transactions and blocks. Secret Network uses Tendermint [60] to handle consensus and communication between nodes and clients. In order to use the Cosmos SDK and Tendermint frameworks Secret Network extends Cosmos SDK's default `Application` interface with functions and variables specific to their implementation. This includes the function `DeliverTx` that triggers the execution of a transaction after consensus. The Secret Network contract code is implemented using a Rust-based interface, called `CosmWasm`, which integrates with Cosmos SDK. `CosmWasm` contracts are compiled into binaries, which are eventually executed in the TEE.

Contract code storage occurs without the use of TEE and is stored unencrypted on disk. To initialize, execute, or query a contract the node server retrieves the stored contract code, a reference to the contract's key-value stores, and the encrypted message. Then pass these to the `libgo_cosmwasm.so` interface.

`libgo_cosmwasm.so` passes messages to the TEE using the `ecall` interface used for communication between the untrusted and trusted portions of SGX applications. `ecall_init` is used to initialize a contract, `ecall_handle` to execute a transaction on a contract, and `ecall_query` to query a contract. The trusted code is responsible for executing Rust contract code using Secret Network's `CosmWasm` interface.

`libgo_cosmwasm.so` also defines callback handlers for `ocalls` that are used for communication between the trusted and untrusted code bases. They include `ocall_read_db` and `ocall_write_db` to read and write values to the contract's key-value store that is stored on the untrusted host OS.

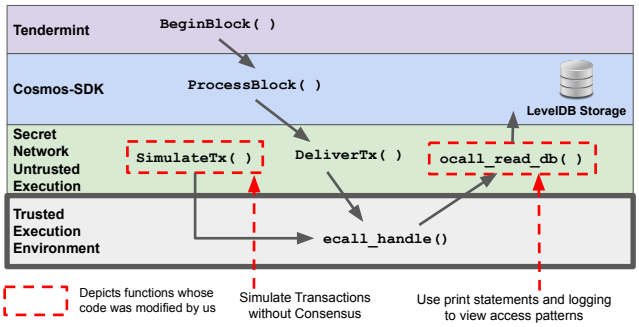


Figure 4: Illustration of the untrusted and trusted Secret Network codebase used to simulate transactions offline.

The execution flow for a transaction is shown in Figure 4. Once a transaction is committed, the transaction data itself, as well as the updated account balances of the sender and receiver are stored in an encrypted database or key-value store. The key-value store is accessible through a storage API but is stored in encrypted form on the untrusted host, due to the TEE's space constraints. To read or operate on a record, the TEE retrieves it from untrusted storage and decrypts it in the TEE.

Oasis. Oasis Network [50] is a Layer 1 (L1) blockchain in that it runs its own standalone consensus layer built on Tendermint (like Secret Network). On top of the consensus layer is an execution layer organized as independent "ParaTimes," which make use of the consensus layer. They are implemented using the `oasis-runtime-sdk` and are customized for different purposes.

There are two ParaTimes, Sapphire and Cipher, that provide confidential smart contracts. The main difference between the two is that Sapphire is EVM-compatible while Cipher runs Wasm-based contracts. Both do not further modify `oasis-runtime-sdk`. Emerald is an EVM-compatible ParaTime that does not aim to provide any privacy, which we ignored throughout our analysis.

Obscuro. Obscuro [13] is an L2 rollup network that aims to address privacy concerns in the transparent blockchain Ethereum. During each epoch aggregator nodes compete to become the leader and generate a new rollup transaction that is posted to the L1 Ethereum chain. This leader election is based on a random nonce that each aggregator generates in their TEE. All contract data is encrypted and added to the rollup. Because the data is replicated on chain they do not rely on the TEE for data integrity.

To participate in the next leader election, aggregator TEEs must validate the previous L1 blocks containing the previous rollup in the sequence. They are therefore reliant on the L1 for safety of the consensus mechanism.

Obscuro is designed to be EVM-compatible for easy porting of smart contracts. While it is the sole framework that encrypts contract bytecode, the degree to which this feature offers explicit privacy protection remains uncertain. In fact, it is possible for attackers to probe the contract code via side-channel attacks like SGX-Step [65].

Phala. Phala [52, 70] (Phat Contract) is an L1 blockchain implemented as a Polkadot parachain. Unlike the others, their focus is to act as middleware for other blockchains. Their goal is to enable serverless smart contracts called "Phat Contracts" similar to Amazon Lambda functions that can handle concurrent user requests and do not rely on fast updates to a global state.

They note their goal is not to replace existing smart contract infrastructure: "Instead of implementing an ERC-20 token with Phat Contract (whose balance has to be stored on-chain), we recommend deploying your ERC-20 contract on Ethereum and using a Phat Contract to operate it"[3]. Depending on the amount of stake held by the contract owner, a set of worker nodes are assigned to a contract. Although they encourage stateless smart contracts, they also support "vanilla on-chain states and transaction processing" for applications that need it, hence such contracts would be subject to the same state consistency hazards we consider.

Phat Contracts are written in Rust-based Ink! [4] language, compiled into Web Assembly and executed in TEE using Parity substrate[5]. The contract code and the initial parameters are public.

4.2 Storage access pattern leakage

All of these blockchains inherit a key-value storage programming model for their existing smart contract languages. This is backed by encrypted data stored locally on the node performing the execution. In the example of a private token, each account balance may be stored as a separate record.

None of the systems whose codebases we evaluate hides access pattern, and so an untrusted host OS can potentially learn private information (such as recipient addresses in the private token example) by monitoring accesses to the key-value storage. This is the most pronounced in Secret and Oasis, which leak the exact key that is being accessed. Obscuro uses a TEE-based database library called EdgelessDB, which reads and writes to the filesystem using 4KB blocks. Phala uses an entirely in-memory data structure for contract state, thus it would leak to the untrusted OS page fault handler which memory page is being accessed. To address this issue, it is crucial to employ effective obfuscation techniques such as the use of oblivious RAM/data structures or encrypted databases.

Secret Network. Each Secret Network contract has access to a key-value storage, where it implements an application-specific state. Each value is encrypted using an authenticated encryption mode, using the plaintext key as a tag. In this way, encrypted values cannot be replayed on different keys (important for Section Sec. 5.5).

A separate encryption key is derived for every contract. Each plaintext key-value store record is encrypted using the contract's encryption key and a fixed initialization vector (IV). The IV must be fixed, i.e., the encryption must be deterministic since the encrypted field name is used to retrieve the encrypted value.

Oasis. Oasis, like Secret, also uses an underlying database in the untrusted host, in this case BadgerDB. This similarly leaks the access pattern of each accessed record.

Obscuro/EdgelessDB. In addition to storing all contract data on chain Obscuro uses EdgelessDB to store and retrieve data during the execution of the smart contract. EdgelessDB runs in a separate TEE and uses a RocksDB backend. The data is accessed in 4KB blocks that are stored in sorted string table (SST) files.

Phala. While Phala encourages mainly stateless applications, persistent contract state is nonetheless supported. Since significant usage is not anticipated, they use an in-memory data structure, periodically saved in its entirety to disk as a "checkpoint." Compared with the alternatives like LevelDB, this incurs greater cost when saving and restoring from these checkpoints.

In addition to this contract state Phala allows contract owners to bring their own external database services that the contract can connect to via HTTP requests. This model requires contract owners to handle access patterns hiding themselves. They can choose to store and load data in blocks rather than fine-grained key-value pairs, but they are still subject 4KB limit for loading pages in a TEE. Contract owners must also ensure that the HTTP queries themselves do not uniquely leak the data block or key being accessed. Amazon S3 is one of the supported external database services in Phala. In order to perform a request to S3 the URL contains a unique identifier for the object and bucket being accessed. The access pattern could be inferred from logs viewable by the S3 bucket owner [6]. We use a half circle in Table 1 since Phala ensures storage replay protection for contract state but not external database accesses.

4.3 State consistency and blockchain data confirmation

The ability to perform transaction simulations can undermine privacy goals for TEE-based smart contracts. Even if transactions are encrypted and private their execution can have some side effects that change some public states, e.g. the public pool balance of a token will change depending on the amount of tokens traded in a private transaction. Under desired use, 1) the TEE only executes a transaction after it has already been committed/finalized by the validators' consensus, and 2) the execution permanently modifies the stored records on disk. However, these rules are not enforced by the TEE and are only expressed in the untrusted code. The result is that a validator can run *simulations* of a block prior to consensus, varying the subset of included transactions and their execution order to maximize profit.

Ensuring the validity and up-to-dateness of external storage data is crucial for secure TEE-based smart contract platform design. Failure to do so may result in storage replay attacks, which can lead to the exposure of private information.

[3] https://wiki.phala.network/en-us/build/general/intro/
[4] https://paritytech.github.io/ink/
[5] https://www.parity.io/technologies/substrate/
[6] https://github.com/Phala-Network/phala-blockchain/blob/a6b6c7f/crates/pink-libs/s3/src/lib.rs#L123

Secret Network. In Secret Network, there is no Proof of Publication mechanism, so uncommitted transactions can be run against the local TEE. To carry out a simulation attack, the untrusted code is modified so that a) the `ecall_handle` can be invoked directly to execute a transaction without waiting for network consensus, and b) the `ocall_read_db` and `ocall_write_db` handlers provide a "snapshot"/"restore" mechanism to reset the simulated contract state. The potential for transaction replay is acknowledged in Secret Network developer documentation as Theoretical Attacks but is not considered a practical concern [22].

As mentioned, Secret Network stores records with encrypted field names and encrypted values. In more detail:
$(\text{Enc}_{\text{key}}(\texttt{field\_name, Tag=""}),$
$\text{Enc}_{\text{key}}(\texttt{value, Tag = } \text{Enc}_{\text{key}}(\texttt{field\_name, Tag=""})))$.
While each record has an authentication tag (specifically `AES-SIV` authenticated encryption), such that values cannot be replayed across different records, this does not prevent the replay of previous values for the same record.

Oasis. Oasis uses a Proof of Publication similar to that described in Ekiden, in which the enclave verifies that a transaction is committed before executing. A slight difference is that in Oasis [50], transactions are executed before confirmation, however the decryption key to their results and events is not released until they are committed on-chain.

Oasis comes with a Merklized Key-Value Store (MKVS). All data provided to the enclave is authenticated by the current root hash of the state Merkle tree stored inside the enclave.

Obscuro. As of writing this paper, Obscuro does not implement any method to prevent simulation attacks, but they propose strategies to defend against these attacks in their design documentation [7]. Obscuro uses Sequencer nodes to order transactions before they are included in a rollup transaction. In order for the Sequencer to simulate different orderings of transactions it would have to be restarted using an old state. They plan to require the sequencer to be delayed or re-register to the network after restarting so they cannot execute multiple simulations in the same epoch before proposing a block.

As mentioned in Section 4.2, Obscuro makes use of EdgelessDb which uses sorted string table (SST) files. These SST files consist of 4KB blocks and are append-only (meaning blocks are not modified after being written). EdgelessDB notably aims to provide integrity guarantees but does not aim to prevent rewinding the entire database to a previous state. The position in the block and a file-specific key is used as a parameter for encryption to get position-dependent authenticated encryption. This prevents fine-grained replays because blocks cannot be swapped between files and values cannot be changed in a block [16].

Phala. The contract state in the Phala blockchain is determined by a sequence of transactions executed in order in a TEE. TEE also validates the blocks containing these transactions before writing the expected outputs back to the blockchains in "checkpoints" [70]. The transaction order is determined before execution.

Replay attacks to contract state are not possible in Phala. As described in Section 4.3 transaction ordering occurs before execution and this ordering is validated in the TEE. If a contract makes use of an additional external database it falls to the contract owner to ensure that a malicious worker node cannot replay old database values when the contract makes an HTTP request to the server. This can be done by including a random nonce in the requests that are signed by the server in the response.

4.4 Software update transparency

Software upgrades are notoriously challenging for blockchains [40], even before we consider privacy and TEEs. In short, to avoid partitioning the network, it is important that all nodes participating in the network can apply updates simultaneously. Additionally, developers should not have the ability to unilaterally change the rules, e.g., to print more coins.

The standard process involves several steps. First developers publish a proposed software update. The upgraded software initially behaves the same as existing software so that node operators can gradually update without risk of partition. An on-chain vote is collected, such as through miners or validators signaling support for/against the blocks they produce, and with enough votes it is approved. The upgraded software includes a "flag day" timestamp (or block number), after which the software switches to the new behavior; at this point, any nodes that have not yet updated will find themselves partitioned from the network.

The additional challenge in TEE-based smart contracts is that enclaves running the old software must somehow transfer key material to enclaves running the upgraded software, but only after the update has been approved on-chain. In Secret Network, although software updates follow the on-chain approval process outlined above, the enclaves do not enforce this policy. Instead, key material is transferred between versions through the use of SGX-sealed data.

As mentioned in Section 2, TEEs use sealing to survive power resets and to make use of on-disk storage. Sealing in SGX takes one of two modes: MRENCLAVE, which means that only the exact same TEE that created the sealed file can unseal it; and MRSIGNER, which means that any enclave code signed by the developers can load the sealed file. Although using MRSIGNER simplifies the upgrade process, it means that the developers have the unilateral authority to secretly decrypt every transaction on the network, simply by code-signing a TEE that outputs the master key in plaintext and running that on their own node. In other words, the upgrade process has introduced an unwanted backdoor. Furthermore, as this could be carried out offline, there is no way for developers to provide evidence they have not exploited this.

Obscuro similarly uses MRSIGNER to seal enclave data on their public testnet. As a result of our disclosure, they have committed to transition to MRENCLAVE prior to their mainnet launch. [8]. They propose to do these updates by creating a transaction on the network to propose the upgrade and allow for disputes/objections to the update. After the upgrade is accepted all enclaves will be required to use the new version. Secret keys are transferred between versions of the enclave via an RPC call. [9]

Phala and Oasis already use MRENCLAVE sealing. For upgrades, their enclaves check that an update has been approved on-chain.

[7] https://github.com/obscuronet/go-obscuro/blob/e626db/design/fast_finality.md#possible-designs-for-preventing-value-extraction

[8] https://github.com/obscuronet/go-obscuro/pull/1065

[9] https://github.com/obscuronet/go-obscuro/blob/bacb60/design/security/Upgrade_Design.md

As this relies on proof of publication, Obscuro and Secret will need to fix this first before changing their update process.

5 FLESHING OUT THE ATTACKS ON SNIP-20 TOKENS IN SECRET.

It is clear that the vulnerabilities noted in the previous section may have some effect on the privacy properties of the systems in which they are present. But are they real-world issues?

To evaluate this, we analyzed Secret Network, since it is the only of the TEE-based systems advertising strong privacy guarantees with currently in-production-use applications. Especially popular are its fungible privacy tokens, known as SNIP-20. SNIP-20 tokens have nearly identical functionality to the ERC-20 tokens from plaintext blockchains, following the pseudocode mentioned in Sec. 2. The balances are stored as smart contract application states in the encrypted key-value storage. Users can transfer a token balance by including a "send" message in the transaction payload. In order to query the account balance, users need to set a viewing key through an on-chain transaction, but afterward they can query their balance with the help of any network node. At the time of writing, while the market cap of circulating SCRT (i.e., the native asset that is not "staked" in the consensus protocol) is $169 million, of that a fraction $5.87 million is wrapped in sSCRT[10]. As explained in Section 2 the sender address in SNIP 20 tokens are public, therefore we can query the number of unique addresses that have interacted with the token contracts as well as the number of transactions sent to each contract in Appendix Table 2. The most popular SNIP-20 tokens we investigated have a combined market cap of $20.2 million[11], over 1 million successful transactions, and 44.9 thousand unique senders.

5.1 Tracing attacks on SNIP-20 Transfers

Before getting to transaction simulation attacks, we start by simply adding logging statements to the untrusted software with to observe the storage access patterns. This is enough to invalidate the Receiver Privacy guarantees of the SNIP-20 tokens. In particular, the `recipient` and the `amount` are both intended to be confidential.

The combination of encrypted transaction requests and encrypted storage is the basis for expecting receiver privacy and value privacy for transactions. As discussed in Section 4.2, however, users' balances are maintained by a key-value store and the encrypted key for each account remains the same. By logging the keys fetched from the storage, we can infer the recipient of a SNIP-20 transfer.

We modified the untrusted code, specifically `ocall_read_db`, to simply print the **`get`** traces of encrypted keys fetched while executing a contract program. For instance, an abridged trace resulting from executing a SNIP-20 transfer is illustrated in Figure 5. We carried out experiments on the public testnet by sending transactions between our own addresses to confirm our hypothesis.

As the above discussion implies, the balances of the parties (sender/receiver) involved in a transaction are accessed using fixed keys for each address. By correlating two transactions, `Tx1` and `Tx2`, such that the sender of `Tx1` is the receiver of `Tx2`, we were able to deanonymize the *supposedly private* receiver of `Tx2`.

[10] https://secretnodes.com/

[11] https://secretanalytics.xyz/bridge, https://www.coingecko.com

```
get 0x6592ff[...] // contract status
get 0x9e82b0[...] // sender balance
get 0x3d4982[...] // receiver balance
get 0x4155b8[...] // config constants
get 0x888eb5[...] // tx count
... // additional accesses
```

Figure 5: The log of `get` traces in a SNIP-20 transfer.

5.2 Implementing transaction simulation

We now describe how we modified (the untrusted portion of) the existing Secret Network codebase, to build a forensic analysis node capable of carrying out offline simulation attacks.

We focus on adding a wrapper around the `ecall_handle` function described in Section 4.1. Secret's untrusted codebase includes `DeliverTx` and `SimulateTx`, two high level wrappers that call this function. `DeliverTx` is intended to used after a transaction has been committed in a block — though lacking a Proof of Publication, the enclave cannot ensure this. `SimulateTx` is used to estimate gas costs. While either could be used, we found `SimulateTx` to be the easiest code to modify. We then added the following new RPC calls to support transaction simulation:

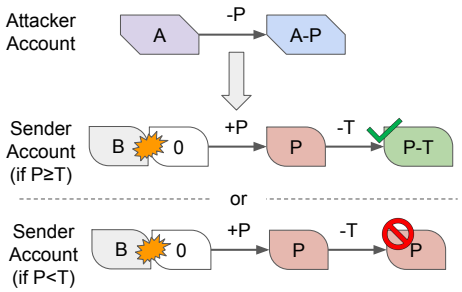
- **Fork()**: (Re-)Initializes a new in-memory cache, `SimState`, for persisting state changes between transaction simulations.
- **Simulate**(Tx) → `[ck=cv,...]`: Simulates one transaction, modifying only `SimState`. During contract execution, interactions with key-value storage (through `ocall_get`, `ocall_set`) are diverted to `SimState`. Returns a transcript `[ck=cv,...]` resulting from interacting with key-value storage.
- **Replay**`(ck=cv,...)`: Replays previously stored mappings from encrypted keys `ck` to encrypted values `cv`. Since the empty string is a default value, this can be replayed for any key regardless of whether it has been previously observed.

5.3 Inferring SNIP-20 Transfer Amounts

As our first transaction simulation attack, we can infer the amount of tokens transferred in a SNIP-20 transaction. While access pattern leakage from Sec. 5 enabled us to determine the receiver's address, the number of tokens transferred remains encrypted.

Assume that our goal is to infer the transfer amount T of a victim transaction $\mathsf{Tx}_{\mathsf{victim}}$. For now, let us assume the attacker has an account with balance A that we know is greater than T. We'll design a simulation attack that probes the victim transaction by constructing a comparison oracle, i.e., for each choice of a probe value P, we learn whether $T < P$.

In Fig. 6 we give a schematic for our approach along with a pseudocode description. The legend in Fig. 7 should help for following the schematic. We start by **Replay**ing balance[sender]=0, where the encrypted field name corresponding to balance[sender] can be inferred from the access pattern analysis. Next we generate and **Simulate** the execution of a transaction that transfers the probe amount P from the attacker's balance to the sender's balance. Finally, we **Simulate** the victim's transaction $\mathsf{Tx}_{\mathsf{victim}}$. As a result of transaction simulation, we learn whether or not the transaction succeeds. If it succeeds, we've learned that $P \geq T$, and if it fails




```
function TransferAmountInferenceAttack(Tx_victim)
    sender := Tx_victim.sender
    # assume balance[attacker] > T
    low := 0, high := A := balance[attacker]
    while low < high do # start bisection search
        P := (low+high)/2
        Fork()
        # replay 0 for the sender's account balance
        Replay(balance[sender] = 0)
        # transfer amount = P to sender's account
        Simulate(Transfer(attacker, sender, P))
        if Simulate(Tx_victim) succeeds then
            low = P+1 # try larger
        else
            high = P # failed, try smaller
        end if
    end while
    return low # return the probed amount low = T
```

Figure 6: Schematic and Pseudocode for Transaction Simulation Attack to Infer SNIP-20 Transfer Amount

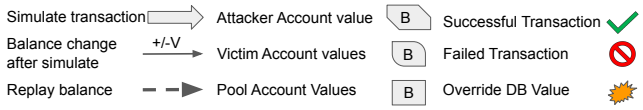
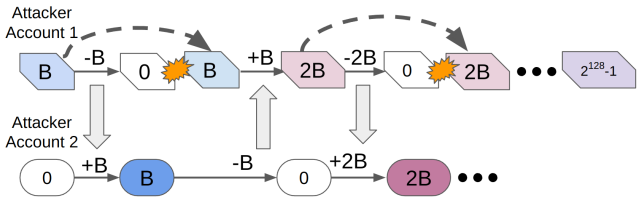


Figure 7: Legend for transaction simulation schematics. Elements with the same shape have the same key and can be replaced with one another. Elements with the same color have the same representation as encrypted values.

then $P < T$. We can simply rewind the simulation to the beginning by calling **Fork**, choosing a different probe value via binary search.

5.4 Surveillance without having to buy tokens

We previously assumed that the attacker's balance A at the beginning of the attack was larger than the transaction they sought to analyze, meaning that the attack had an upfront investment requirement. We now explain how to get around this assumption by *simulating the inflation of the attacker's account*. Pseudocode and a schematic are given in Fig. 8. The main idea is that the attacker simulates transferring a balance between two of her own accounts, replenishing each empty account with a replayed value. Since this algorithm doubles the balance of an adversarial account at each




```
function BalanceInflationAttack(addr_1,addr_2)
    # both accounts are controlled by the attacker
    # start with balance[addr1]>0 & balance[addr2]=0
    Fork()
    while balance[addr_1] < (2^128 − 1) do
        # store the current balance B of addr1
        B := balance[addr_1]
        Simulate(Transfer(addr_1,addr_2,balance[addr_1]))
        # now balance[addr1]=0
        # replay the balance of addr1 back to B
        Replay(balance[addr_1]=B)
        amt := B if 2B≤(2^128 − 1) else (2^128 − 1)−B
        Simulate(Transfer(addr_2, addr_1, amt))
        # now balance[addr1]=min((2^128−1), 2B)
    end while
```

Figure 8: Schematic and pseudocode for a transaction simulation attack that inflates the attacker's (simulated) balance.

step, it takes 128 iterations to reach the maximum representable value. This only needs to be carried out once per token type since the resulting encrypted value can be stored for later use.

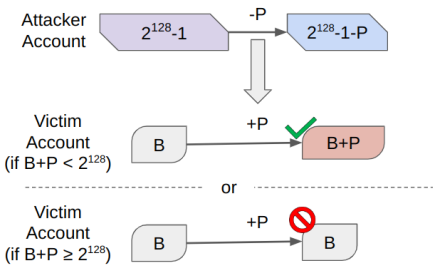
Note that this inflation is only occurring within the attacker's local simulation and does not in any way imply that the *integrity* of the overall blockchain is at risk. The reason for this is that even if there were no enclaves at all, the integrity of the blockchain would still be ensured by the *consensus* among validator nodes, just as in any transparent blockchain.

5.5 Querying SNIP-20 account balances

We now present an attack that allows us to probe the account balance of an arbitrary victim, just given their address. We assume the attacker begins with a maximal account balance of $2^{128} - 1$ (obtained in Section 5.4). SNIP-20 tokens throw an exception when adding two `u128` elements that overflow. We use this as our next oracle to probe whether a victim's account with balance B is less than a parameter $2^{128} - 1 - P$. Following along with the illustration in Fig. 6, we simulate a transaction that transfers P from the attacker's account to the victim's account. This transaction succeeds if $B + P < 2^{128}$, and fails otherwise. Using rewinding and a binary search we can recover the exact value after 128 iterations.

5.6 Forensic analysis of past SNIP-20 transfers

For reasons involving details of the Secret Network's implementation, it is difficult to obtain a snapshot of the blockchain state from very far back. State snapshots are cycled on a rolling basis, and while archive nodes provide most old blocks, we found we were unable to sync a node by replaying blocks from "genesis." So, how




```
function BalanceInferenceAttack(victim)
    # begin with inflated balance[attacker]=2^128−1
    low = 0, high = 2^128 − 1
    while low<high do
        P := (low+high)/2
        Fork()
        if Simulate(Transfer(attacker, victim, P))
        succeeds then
            low = P+1 # try larger
        else
            high = P # failed, try smaller
        end if
    end while
    return (2^128 − 1)−low # return the probed balance[victim]
```

Figure 9: Schematic and Pseudocode for Transaction Simulation Attack to Probe the Balance of Arbitrary Address.

would we break receiver privacy for transactions prior to the last available state checkpoint?

The first challenge is that the Secret, like most blockchains, implements a form of replay prevention based on "sequence numbers." Transactions are rejected unless they have a sequence number that matches a counter associated with each account. The counter for an account is incremented each time a transaction from that account is committed. However, this mechanism is implemented only within the untrusted codebase, so we simply disable the checks on the sequence number of a transaction before `ecall_handle`.

Next, the sender's balance at the snapshot time may be lower than it was when the past transaction of interest was committed. However, the techniques we described earlier enable us to control the sender's simulated balance, as we make use of when inferring the transaction amounts. Therefore, forensic analysis of prior transactions does not require syncing a node to old application state.

6 MINER EXTRACTIBLE VALUE ON TEE-BASED NETWORKS

Though the privacy of SNIP-20 tokens is by far the most important issue for Secret Network, it is not the only application at risk. We also explain how transaction simulation attacks can undermine defenses against front-running.

```
contract function UniswapTrade(amtA, slippage_limit)
    amtB = calcB(PoolAmtA, PoolAmtB, amtA)
    if amtB < slippage_limit then
        # no state change but the transaction is committed.
    else
        # changes to caller account balances as well as the
        # contract's variables are committed to chain.
        PoolAmtB −= amtB
        PoolAmtA += amtA
    end if
contract function calcB(PoolAmtA, PoolAmtB, amtA)
    amtB = PoolAmtB − (PoolAmtB * PoolAmtA) / (PoolAmtA + amtA).
```

Figure 10: Contract Pseudocode for Uniswap Trade.

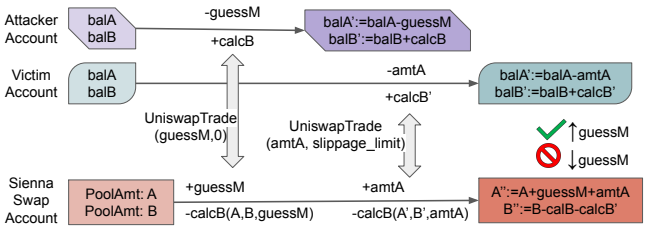
6.1 Background on MEV

Constant Product Automated Market Makers. The most well-known AMM model (and the one we use for our demonstration) is called a Constant Product AMM and was pioneered by the Uniswap contract [32]. A Uniswap contract is meant to help trade any number of token pairs, which we will generalize to calling `tokenA`and `tokenB`. The contact has the following variables: `PoolAmtA`, `PoolAmtB`, `PriceA = PoolAmtB/PoolAmtA`, `PriceB = 1/PriceA`, `Product = PoolAmtA*PoolAmtB`, with the invariants (1) Withdrawing and depositing do not change the price, i.e. the ratio, and (2) Trade doesn't change `Product`. Pseudocode for this contract is provided in Figure 10.

MEV and Frontrunning attacks. Any operations that clients want to be executed on the blockchain must be committed in a block by the validator nodes running a consensus protocol. Since the validators must collect pending transactions before assembling them into a block, they have the opportunity to use this knowledge to insert their own transactions and reorder the pending ones in whatever order they see fit. This is known as *frontrunning*. See [62] for a more detailed discussion about frontrunning. In blockchains, the notion of validators benefiting economically from the ability to determine transaction order is called *miner extractable value* (MEV).

Returning to the Uniswap example, upon seeing that a client wants to buy `tokenB` using `tokenA`, the miner generates a transaction buying `tokenB`, ahead of the clients, artificially inflating the demand for `tokenB`. This means the client would end up getting less `tokenB` for the same amount of `tokenA`. Subsequently, the price of `tokenB` would inflate even more and the adversarial miner could now "sell" `tokenB` to get more of `tokenA` than it originally spent buying it.Thus, the miner benefits from sandwiching the client transaction. For a more detailed discussion of MEV and the other perils to the blockchain introduced by it, see [19].

Note that to know the frontrun amount, the adversarial miner needs to see the amounts in the client's transaction. This is because if the miner raises `PriceB` too little it will not profit, and if it raises it too much, the `slippage_limit` parameter of the client causes the target transaction to fail altogether. Thus, if the miner were unable to access the amounts input by the target transaction caller, they would not be able to mount any effective MEV attacks.




```
1  function FindMaxFrontrunAmt(Tx_victim)
2      low := 0, high := balA
3      while low < high do
4          guessM := (low+high)/2
5          Fork( )
6          Simulate(Trade_attacker(mid, 0))
7          if Simulate(Tx_victim) succeeded then
8              low := guessM+1 # try larger
9          else
10             high := guessM # failed, try smaller
11         end if
12     end while
13     return low # the maximal frontrun amount
```

Figure 11: Schematic and Pseudocode for Transaction Simulation Attack to Determine the Maximal Frontrun Amount.

6.2 Sandwich attacking a private swap

Recall from Figure 10, the `Trade` function of a DEX contract, which takes as inputs parameters `amtA` and `slippage_limit` where `amtA` is the total amount of token `A` that the caller of this transaction would like to give, in exchange for receiving token `B`. In this notation, `slippage_limit` is the minimum amount of token `B` they would exchange for the amount of token `A` i.e. `amtA`.

We demonstrate the power of our sandwich attack on a victim transaction `Tx = Trade(amtA, slippage_limit)`. The public pool balances are `PoolAmtA` and `PoolAmtB`, and the value of `amtA` can be inferred from the change in `PoolAmtA`, but `slippage_limit` here would be secret. The main parameter of a sandwich attack is how large the frontrun transaction should be. The attacker's profit is maximized when the victim transaction succeeds but just barely within the slippage limit. Optimizing a sandwich attack thus requires determining the victim's slippage limit, which can be done through a "bisection" search, as shown in Figure 11.

Note that the attacker's ability to front run is limited by their available capital. Thus while the attacker could use simulated balance inflation as described earlier to infer the slippage limit even for larger trades, this would not help them to front run.

6.3 Validating our implementation and artifact

There are two main ways we validate our implementation. The first is through the use of container-based local networks, which is used by Secret Network for integration tests. This requires us to compile both the Secret enclave as well as the smart contracts from the SSCRT implementationfrom source code. This is ideal for reproducing our demonstrations, so we plan to publish an artifact based on this. The second is through the use of Secret's public test network, `pulsar-2`. The test network runs an enclave binary that was signed by the developers, so it is ideal for demonstrating that the vulnerabilities we rely on were not introduced by our own modifications. The production versions of Secret Swap and Sienna Swap also provide development versions on the test network.

7 MITIGATIONS

7.1 Coordinated vulnerability disclosure

We discussed our preliminary findings with Secret Network developers and have been coordinating with them on our public disclosure and helping them to deploy mitigations. Ultimately these attacks are much more concerning than the prior disclosures related to AepicLeak [68] as they do not require running an unpatched TEE exploit. Even cloud tenants could easily carry out this offline analysis without even needing kernel access, let alone hardware access. Regardless, despite the much larger attack surface, several principles for deploying mitigations are the same.

7.2 Mitigating retroactive SNIP-20 privacy leaks

The most immediate intervention the developer have at their disposal is to disable remote attestation by revoking the API key associated with their IAS account, which we refer to as a "registration freeze." We can divide the threats into *new nodes* that attempt to join the network after the registration freeze, and *existing nodes* that have already registered on the network prior to it. A registration freeze conclusively blocks the threat from new nodes, since they would be unable to complete the IAS attestation process. Once developers have updated their software with mitigations (e.g., proofs of publication and storage replay defense), they can also reenable registration by generating a new API key through their account with IAS. By incrementing the Security Version Number (SVN), new nodes will only be able to complete attestation if they are running the updated software. In response to our disclosure, developers expedited a proof-of-publication feature that had been partially written, and that now serves as a defense against transaction replay. We coordinated our public disclosure to follow this upgrade.

Despite the successful deployment of a mitigations, there remains a lingering threat to past transactions and balances. Any node with a disk backup from prior to the upgrade would still be able to carry out the described attacks.

7.3 Preventing future SNIP-20 leaks

As mentioned, the response to our disclosure has been to mitigate transaction replay attacks by implementing proof of publication. Essentially the mechanism incorporates a Tendermint verifier in the trusted enclave code. Storage replay attacks have not yet been addressed, so whether this can be exploited in practice remains a question for future work. Additionally, hiding access patterns is still very important, if challenging. We discuss two possible approaches.

Transparent use of ORAM. The most straightforward way to integrate ORAM would be to automatically use it for every get/set instruction. This would require no change to existing contracts, which would automatically gain these benefits. Since the overhead associated with ORAM might be unwanted for application features that don't actually need privacy, it would be desirable to allow applications to opt-in. We may want to take cues from prior research on

```
contract function send(address[] recips,
                       address real, uint amount)
    # Suppose the client has selected ~10 decoy indexes
    for each address a in recips do
        bal := balances[a]
        bal := bal + (amount * (a == real))
        balances[a] += bal
    end for
```

Figure 12: A decoy-based mitigation for access pattern leakage inspired by Monero

oblivious programming, which suggests partitioning an application into small ORAMs according to the desired leakage model [36].

Another approach is to leave the task of hardening up to the application developers. In principle, the ORAM client could be implemented within the contract language, the existing key-value interface sufficing as the ORAM server. To get this benefit, existing SNIP-20 tokens would need to be patched and migrated to the new version. We speculate that the performance of a smart contract with ORAM would be an order of magnitude worse than one without.

Access pattern decoys. The proposed approach based on ORAM might be described as Zcash-like, in that it aims to leak no information about which account is being accessed. We might ask whether there is a Monero-like alternative, that settles for limited anonymity by using obfuscation or "decoys." We provide pseudocode for a SNIP-20-like transfer method that makes several decoy accesses along with the actual access in Figure 12.

However, a limitation of this approach is that frequently used accounts that receive lots of transactions would still be identifiable since they would appear in more `recips` sets. The leakage would be worse than Monero, which derives new accounts (i.e., "stealth addresses") for each use. Overall, moving more complexity to the smart contract, and especially having to redesign existing cryptography, seems to trade away much of the appeal of TEE-based smart contracts in the first place.

7.4 Ethical principles

Beyond coordinating our vulnerability disclosure with developers, our main concern has been to avoid contributing to the data breach hazard created by this vulnerability. We did not collect a dataset or carry out a measurement study by probing balances and transactions on the production network.

The setting of TEE-based smart contracts creates some unique issues worth discussing. Previous blockchain deanonymization and tracing attacks [28, 42, 48] have only required the public dataset as input, i.e., the blocks and transactions, which are widely replicated. They publish their tracing analysis concept along with a measurement study. While the Secret blockchain itself is a public dataset, executing transactions requires a sealed copy of the master key, which can only be obtained through remote attestation. Freezing registration or incrementing the SVN means that no new nodes with vulnerable software can register. Thus while we may retain the ability to carry out measurements, having our authority "grandfathered in," other researchers would be unable to obtain this authority for themselves.

We have reset our authority to baseline by erasing our node's sealed key, such that we have to upgrade and re-register our node like anyone else. However, as part of our public disclosure, we plan to provide an "access pattern dashboard" service that displays the access pattern logs that remain leaked to the untrusted host by an ordinary node post-mitigation.

8 RELATED WORK

Security issues in TEE-based smart contracts. Our work is most closely related to Li et al. [34] in aiming to systematize privacy hazards in TEE-based smart contracts. Whereas they consider frameworks including research proposals, we focus on running systems and design choices manifest in code. While they point out potential hazards, our goal is to demonstrate how these hazards translate into real world application failures. Previous real world attacks have also been demonstrated, again using Secret Network as the concrete example due to its in-use applications. Specifically Van Schaik et al. [68] showed that Secret Network was vulnerable to AepicLeak [7] (the most recent in a long line of SGX vulnerabilities [11, 64, 67]). Although TEE breaks threaten any system that relies on it, Phala and Obscuro limit access to the key material to nodes who are trusted or at least have committed financial stakes; in contrast, Secret Network, as well as Obscuro, allow anyone with a compatible processor to register and obtain the ability to execute contract transactions in an enclave. Our attacks are different in that they do not involve a failure of the TEE itself, but rather the integration of the TEEs within a blockchain architecture.

Smart contract security and privacy. While smart contracts have enabled many innovative decentralized applications, their history could easily be characterized by the many high-profile hacks and losses of funds that have taken place over the years. Consequently, much research effort has been devoted to surveying these risks [3, 51] and creating tools to reduce them [37, 47, 63, 71]. At the same time, researchers have begun to explore the intersection of private computation and public blockchains. For example, Zether [12] proposes an Ethereum-compatable confidential payments contract, Hawk [31] creates a framework for private smart contract development, and Zexe [8] extends this idea to also obfuscate which functions are being executed. Relative to these works, however, TEE-backed chains offer high performance along with the features developers expect from transparent smart contracts.

Secure systems based on TEEs. The need for defense against replay attacks and rollback attacks is well understood in the security literature. Systems such as Rote [38] and Microsoft Confidential Consortium Framework [55] create a distributed network of TEEs such that an honest subset remains online. Since today's TEE platforms cannot offer a reliable non-volatile monotonic counters, such a distributed network can be used as a monotonic counter service. This network of nodes keeps track of the most recent version of the seal data output by the enclave and signs the input along with a hash of the sealed data. On restart, the TEE must verify that signature ensuring that it can only execute one input using that sealed data. Narrator [49] similarly uses a distributed system of TEEs but application enclaves send a state update message to the system before revealing the output of the computation. Our work reinforces

these efforts by demonstrating the consequences of foregoing these defenses.

Besides the blockchain itself, TEEs have also been proposed for blockchain-adjacent services; here too rollback prevention is a central focus. Bite [39] implements a privacy preserving light client for Bitcoin that can receive payments and construct transactions requests without running a full Bitcoin node. It uses ORAM to hide data access patterns and Rote [38] to prevent rollback attacks. TEEChain [35] uses TEEs to create a private payment channel system and requires hardware monotonic counters to protect against rollback attacks. Tesseract [5] implements a private real-time cryptocurrency exchange using TEEs and requires an honest subset of nodes participating in the protocol to be online to prevent rollback attacks.

9 CONCLUSION

The usage of TEEs is a promising way to realize practical, performant, and private general computation on blockchains. While it is well-known that TEE compromises are a possibility, this is just one of the attack surfaces to contend with. Previous discussions on replay and access pattern hazards have been somewhat abstract, making them easy to underestimate when transitioning research to practice. In this work we bring clarity to this issue by demonstrating the first replay and access pattern attacks on in-use TEE-based smart contract systems. The impact of our vulnerability disclosure has already led to rapid deployment of mitigations for Secret Network's in-use SNIP-20 tokens, as well as to influence the development plans of others their mainnet launches.

REFERENCES

[1] 2017. Technology preview: Private contact discovery for Signal. https://signal.org/blog/private-contact-discovery/.

[2] Ittai Anati, Shay Gueron, Simon Johnson, and Vincent Scarlata. 2013. Innovative technology for CPU based attestation and sealing. In *Proceedings of the 2nd international workshop on hardware and architectural support for security and privacy*, Vol. 13. Intel, ACM New York, NY, USA, 7 pages.

[3] Nicola Atzei, Massimo Bartoletti, and Tiziana Cimoli. 2017. A survey of attacks on ethereum smart contracts (sok). In *Principles of Security and Trust: 6th International Conference, POST 2017, Held as Part of the European Joint Conferences on Theory and Practice of Software, ETAPS 2017, Uppsala, Sweden, April 22-29, 2017, Proceedings 6*. Springer, 164–186.

[4] Pierre-Louis Aublin, Florian Kelbert, Dan O'Keeffe, Divya Muthukumaran, Christian Priebe, Joshua Lind, Robert Krahn, Christof Fetzer, David Eyers, and Peter Pietzuch. 2018. LibSEAL: Revealing Service Integrity Violations Using Trusted Execution. In *Proceedings of the Thirteenth EuroSys Conference* (Porto, Portugal) *(EuroSys '18)*. Association for Computing Machinery, New York, NY, USA, Article 24, 15 pages. https://doi.org/10.1145/3190508.3190547

[5] Iddo Bentov, Yan Ji, Fan Zhang, Lorenz Breidenbach, Philip Daian, and Ari Juels. 2019. Tesseract: Real-Time Cryptocurrency Exchange Using Trusted Hardware. In *Proceedings of the 2019 ACM SIGSAC Conference on Computer and Communications Security* (London, United Kingdom) *(CCS '19)*. Association for Computing Machinery, New York, NY, USA, 1521–1538. https://doi.org/10.1145/3319535.3363221

[6] Joseph Bonneau, Andrew Miller, Jeremy Clark, Arvind Narayanan, Joshua A. Kroll, and Edward W. Felten. 2015. SoK: Research Perspectives and Challenges for Bitcoin and Cryptocurrencies. In *2015 IEEE Symposium on Security and Privacy*. IEEE, San Jose, CA, USA, 104–121. https://doi.org/10.1109/SP.2015.14

[7] Pietro Borrello, Andreas Kogler, Martin Schwarzl, Moritz Lipp, Daniel Gruss, and Michael Schwarz. 2022. {ÆPIC} Leak: Architecturally Leaking Uninitialized Data from the Microarchitecture. In *31st USENIX Security Symposium (USENIX Security 22)*. USENIX Association, BOSTON, MA, USA, 3917–3934.

[8] Sean Bowe, Alessandro Chiesa, Matthew Green, Ian Miers, Pratyush Mishra, and Howard Wu. 2020. Zexe: Enabling decentralized private computation. In *2020 IEEE Symposium on Security and Privacy (SP)*. IEEE, 947–964.

[9] Marcus Brandenburger, Christian Cachin, Rüdiger Kapitza, and Alessandro Sorniotti. 2018. Blockchain and Trusted Computing: Problems, Pitfalls, and a Solution for Hyperledger Fabric. https://doi.org/10.48550/ARXIV.1805.08541

[10] Ferdinand Brasser, Urs Müller, Alexandra Dmitrienko, Kari Kostiainen, Srdjan Capkun, and Ahmad-Reza Sadeghi. 2017. Software Grand Exposure: SGX Cache Attacks Are Practical.. In *WOOT*. USENIX Association, VANCOUVER, BC, CANADA, 11–11.

[11] Jo Van Bulck, Marina Minkin, Ofir Weisse, Daniel Genkin, Baris Kasikci, Frank Piessens, Mark Silberstein, Thomas F. Wenisch, Yuval Yarom, and Raoul Strackx. 2018. Foreshadow: Extracting the Keys to the Intel SGX Kingdom with Transient Out-of-Order Execution. In *27th USENIX Security Symposium (USENIX Security 18)*. USENIX Association, Baltimore, MD, 991–1008. https://www.usenix.org/conference/usenixsecurity18/presentation/bulck

[12] Benedikt Bünz, Shashank Agrawal, Mahdi Zamani, and Dan Boneh. 2020. Zether: Towards privacy in a smart contract world. In *Financial Cryptography and Data Security: 24th International Conference, FC 2020, Kota Kinabalu, Malaysia, February 10–14, 2020 Revised Selected Papers*. Springer, 423–443.

[13] James Carlyle, Tudor Malene, Cais Manai, Neal Shah, Gavin Thomas, and Roger Willi. 2021. Obscuro White Paper. hhttps://whitepaper.obscu.ro/assets/images/obscuro-whitepaper-0-10-0.pdf

[14] Raymond Cheng, Fan Zhang, Jernej Kos, Warren He, Nicholas Hynes, Noah Johnson, Ari Juels, Andrew Miller, and Dawn Song. 2019. Ekiden: A Platform for Confidentiality-Preserving, Trustworthy, and Performant Smart Contracts. In *2019 IEEE European Symposium on Security and Privacy (EuroS&P)*. IEEE, Stockholm, Sweden, 185–200. https://doi.org/10.1109/EuroSP.2019.00023

[15] Chitchanok Chuengsatiansup, Daniel Genkin, Yuval Yarom, and Zhiyuan Zhang. 2022. Side-channeling the Kalyna key expansion. In *Topics in Cryptology–CT-RSA 2022: Cryptographers' Track at the RSA Conference 2022, Virtual Event, March 1–2, 2022, Proceedings*. Springer, Springer, San Francisco, CA, USA, 272–296.

[16] Jenny Cook. 2021. Introducing EdgelessDB: A Database Designed for Confidential Computing. https://techcommunity.microsoft.com/t5/azure-confidential-computing/introducing-edgelessdb-a-database-designed-for-confidential/ba-p/2813631

[17] Manuel Costa, Lawrence Esswood, Olga Ohrimenko, Felix Schuster, and Sameer Wagh. 2017. The Pyramid Scheme: Oblivious RAM for Trusted Processors. https://doi.org/10.48550/ARXIV.1712.07882

[18] Victor Costan and Srinivas Devadas. 2016. Intel SGX Explained. Cryptology ePrint Archive, Paper 2016/086. https://eprint.iacr.org/2016/086 https://eprint.iacr.org/2016/086.

[19] Philip Daian, Steven Goldfeder, Tyler Kell, Yunqi Li, Xueyuan Zhao, Iddo Bentov, Lorenz Breidenbach, and Ari Juels. 2020. Flash Boys 2.0: Frontrunning in Decentralized Exchanges, Miner Extractable Value, and Consensus Instability. In *2020 IEEE Symposium on Security and Privacy (SP)*. IEEE, San Francisco, CA, USA, 910–927. https://doi.org/10.1109/SP40000.2020.00040

[20] Fergus Dall, Gabrielle De Micheli, Thomas Eisenbarth, Daniel Genkin, Nadia Heninger, Ahmad Moghimi, and Yuval Yarom. 2018. CacheQuote: Efficiently Recovering Long-term Secrets of SGX EPID via Cache Attacks. *IACR Transactions on Cryptographic Hardware and Embedded Systems* 2018, 2 (May 2018), 171–191. https://doi.org/10.13154/tches.v2018.i2.171-191

[21] Dmitry Evtyushkin, Ryan Riley, Nael CSE Abu-Ghazaleh, ECE, and Dmitry Ponomarev. 2018. BranchScope: A New Side-Channel Attack on Directional Branch Predictor. In *Proceedings of the Twenty-Third International Conference on Architectural Support for Programming Languages and Operating Systems* (Williamsburg, VA, USA) *(ASPLOS '18)*. Association for Computing Machinery, New York, NY, USA, 693–707. https://doi.org/10.1145/3173162.3173204

[22] Leor Fishman. 2020. Secret Network documentation: Theoretical Attacks. https://github.com/scrtlabs/SecretNetwork/blob/61cfc4/docs/protocol/encryption-specs.md.

[23] Ethereum Foundation. 2023. Ethereum: Blockchain App Platform. https://ethereum.org/. Accessed: 2023-01-22.

[24] Daniel Gruss, Julian Lettner, Felix Schuster, Olya Ohrimenko, Istvan Haller, and Manuel Costa. 2017. Strong and Efficient Cache {Side-Channel} Protection using Hardware Transactional Memory. In *26th USENIX Security Symposium (USENIX Security 17)*. USENIX Association, Vancouver, BC, Canada, 217–233.

[25] Marcus Hähnel, Weidong Cui, and Marcus Peinado. 2017. High-Resolution Side Channels for Untrusted Operating Systems. In *2017 USENIX Annual Technical Conference (USENIX ATC 17)*. USENIX Association, Santa Clara, CA, 299–312. https://www.usenix.org/conference/atc17/technical-sessions/presentation/hahnel

[26] Matthew Hoekstra, Reshma Lal, Pradeep Pappachan, Vinay Phegade, and Juan Del Cuvillo. 2013. Using innovative instructions to create trustworthy software solutions. *HASP@ ISCA* 11, 10.1145 (2013), 2487726–2488370.

[27] Tianlin Huo, Xiaoni Meng, Wenhao Wang, Chunliang Hao, Pei Zhao, Jian Zhai, and Mingshu Li. 2019. Bluethunder: A 2-level Directional Predictor Based Side-Channel Attack against SGX. *IACR Transactions on Cryptographic Hardware and Embedded Systems* 2020, 1 (Nov. 2019), 321–347. https://doi.org/10.13154/tches.v2020.i1.321-347

[28] George Kappos, Haaroon Yousaf, Rainer Stütz, Sofia Rollet, Bernhard Haslhofer, and Sarah Meiklejohn. 2022. How to Peel a Million: Validating and Expanding Bitcoin Clusters. In *31st USENIX Security Symposium (USENIX Security 22)*. Usenix

Association, Boston, MA, 2207–2223.

[29] Gabriel Kaptchuk, Ian Miers, and Matthew Green. 2017. Giving State to the Stateless: Augmenting Trustworthy Computation with Ledgers. Cryptology ePrint Archive, Paper 2017/201. https://eprint.iacr.org/2017/201 https://eprint.iacr.org/2017/201.

[30] koe. 2022. Mechanics of MobileCoin. https://mobilecoin.com/files-uploads/2022/09/Mechanics-of-MobileCoin-v0-0-39-preview-10-11.pdf.

[31] Ahmed Kosba, Andrew Miller, Elaine Shi, Zikai Wen, and Charalampos Papamanthou. 2016. Hawk: The blockchain model of cryptography and privacy-preserving smart contracts. In *2016 IEEE symposium on security and privacy (SP)*. IEEE, 839–858.

[32] Uniswap Labs. 2023. The Uniswap Protocol. https://docs.uniswap.org/concepts/uniswap-protocol. Accessed: 2023-01-23.

[33] Sangho Lee, Ming-Wei Shih, Prasun Gera, Taesoo Kim, Hyesoon Kim, and Marcus Peinado. 2017. Inferring Fine-grained Control Flow Inside SGX Enclaves with Branch Shadowing. In *26th USENIX Security Symposium (USENIX Security 17)*. USENIX Association, Vancouver, BC, 557–574. https://www.usenix.org/conference/usenixsecurity17/technical-sessions/presentation/lee-sangho

[34] Rujia Li, Qin Wang, Qi Wang, David Galindo, and Mark Ryan. 2022. SoK: TEE-Assisted Confidential Smart Contract. *Proceedings on Privacy Enhancing Technologies* 3 (2022), 711–731.

[35] Joshua Lind, Oded Naor, Ittay Eyal, Florian Kelbert, Emin Gün Sirer, and Peter Pietzuch. 2019. Teechain: A Secure Payment Network with Asynchronous Blockchain Access. In *Proceedings of the 27th ACM Symposium on Operating Systems Principles* (Huntsville, Ontario, Canada) *(SOSP '19)*. Association for Computing Machinery, New York, NY, USA, 63–79. https://doi.org/10.1145/3341301.3359627

[36] Chang Liu, Xiao Shaun Wang, Kartik Nayak, Yan Huang, and Elaine Shi. 2015. ObliVM: A Programming Framework for Secure Computation. In *2015 IEEE Symposium on Security and Privacy*. IEEE, San Jose, CA, USA, 359–376. https://doi.org/10.1109/SP.2015.29

[37] Loi Luu, Duc-Hiep Chu, Hrishi Olickel, Prateek Saxena, and Aquinas Hobor. 2016. Making smart contracts smarter. In *Proceedings of the 2016 ACM SIGSAC conference on computer and communications security*. 254–269.

[38] Sinisa Matetic, Mansoor Ahmed, Kari Kostiainen, Aritra Dhar, David Sommer, Arthur Gervais, Ari Juels, and Srdjan Capkun. 2017. ROTE: Rollback Protection for Trusted Execution. In *Proceedings of the 26th USENIX Conference on Security Symposium* (Vancouver, BC, Canada) *(SEC'17)*. USENIX Association, USA, 1289–1306.

[39] Sinisa Matetic, Karl Wüst, Moritz Schneider, Kari Kostiainen, Ghassan Karame, and Srdjan Capkun. 2019. BITE: Bitcoin Lightweight Client Privacy Using Trusted Execution. In *Proceedings of the 28th USENIX Conference on Security Symposium* (Santa Clara, CA, USA) *(SEC'19)*. USENIX Association, USA, 783–800.

[40] Patrick McCorry, Ethan Heilman, and Andrew Miller. 2017. Atomically Trading with Roger: Gambling on the Success of a Hardfork. In *Data Privacy Management, Cryptocurrencies and Blockchain Technology*, Joaquin Garcia-Alfaro, Guillermo Navarro-Arribas, Hannes Hartenstein, and Jordi Herrera-Joancomartí (Eds.). Springer International Publishing, Cham, 334–353.

[41] Frank McKeen, Ilya Alexandrovich, Alex Berenzon, Carlos V. Rozas, Hisham Shafi, Vedvyas Shanbhogue, and Uday R. Savagaonkar. 2013. Innovative Instructions and Software Model for Isolated Execution. In *Proceedings of the 2nd International Workshop on Hardware and Architectural Support for Security and Privacy* (Tel-Aviv, Israel) *(HASP '13)*. Association for Computing Machinery, New York, NY, USA, Article 10, 1 pages. https://doi.org/10.1145/2487726.2488368

[42] Sarah Meiklejohn, Marjori Pomarole, Grant Jordan, Kirill Levchenko, Damon McCoy, Geoffrey M. Voelker, and Stefan Savage. 2016. A Fistful of Bitcoins: Characterizing Payments among Men with No Names. *Commun. ACM* 59, 4 (mar 2016), 86–93. https://doi.org/10.1145/2896384

[43] Pratyush Mishra, Rishabh Poddar, Jerry Chen, Alessandro Chiesa, and Raluca Ada Popa. 2018. Oblix: An Efficient Oblivious Search Index. In *2018 IEEE Symposium on Security and Privacy (SP)*. IEEE, San Francisco, CA, USA, 279–296. https://doi.org/10.1109/SP.2018.00045

[44] Ahmad Moghimi, Gorka Irazoqui, and Thomas Eisenbarth. 2017. CacheZoom: How SGX Amplifies The Power of Cache Attacks. *CoRR* abs/1703.06986 (2017), 69–90. arXiv:1703.06986 http://arxiv.org/abs/1703.06986

[45] Ahmad Moghimi, Jan Wichelmann, Thomas Eisenbarth, and Berk Sunar. 2017. MemJam: A False Dependency Attack Against Constant-Time Crypto Implementations. *International Journal of Parallel Programming* 47 (2017), 538–570.

[46] Malte Möser and Rainer Böhme. 2017. The price of anonymity: empirical evidence from a market for Bitcoin anonymization. *Journal of Cybersecurity* 3, 2 (2017), 127–135.

[47] Bernhard Mueller. 2018. Smashing ethereum smart contracts for fun and real profit. *HITB SECCONF Amsterdam* 9 (2018), 54.

[48] Malte Möser, Kyle Soska, Ethan Heilman, Kevin Lee, Henry Heffan, Shashvat Srivastava, Kyle Hogan, Jason Hennessey, Andrew Miller, Arvind Narayanan, and Nicolas Christin. 2017. An Empirical Analysis of Traceability in the Monero Blockchain. https://doi.org/10.48550/ARXIV.1704.04299

[49] Jianyu Niu, Wei Peng, Xiaokuan Zhang, and Yinqian Zhang. 2022. NARRATOR: Secure and Practical State Continuity for Trusted Execution in the Cloud. In *Proceedings of the 2022 ACM SIGSAC Conference on Computer and Communications Security* (Los Angeles, CA, USA) *(CCS '22)*. Association for Computing Machinery, New York, NY, USA, 2385–2399. https://doi.org/10.1145/3548606.3560620

[50] Oasis Labs. 2020. The Oasis Blockchain Platform. Whitepaper. https://assets.website-files.com/5f59478e350b91447863f593/628ba74a9aee37587419cf65_20200623TheOasisBlockchainPlatform.pdf. Accessed: 2023-01-22.

[51] Daniel Perez and Benjamin Livshits. 2021. Smart Contract Vulnerabilities: Vulnerable Does Not Imply Exploited.. In *USENIX Security Symposium*. 1325–1341.

[52] Phala. 2020. Phala Wiki. Wiki. https://wiki.phala.network/en-us/general/phala-network/intro/. Accessed: 2023-01-22.

[53] Ashay Rane, Calvin Lin, and Mohit Tiwari. 2015. Raccoon: Closing Digital {Side-Channels} through Obfuscated Execution. In *24th USENIX Security Symposium (USENIX Security 15)*. Usenix Association, Santa Clara, CA, 431–446.

[54] Fergal Reid and Martin Harrigan. 2013. *An Analysis of Anonymity in the Bitcoin System*. Springer New York, New York, NY, 197–223. https://doi.org/10.1007/978-1-4614-4139-7_10

[55] Mark Russinovich, Edward Ashton, Christine Avanessians, Miguel Castro, Amaury Chamayou, Sylvan Clebsch, Manuel Costa, Cédric Fournet, Matthew Kerner, Sid Krishna, Julien Maffre, Thomas Moscibroda, Kartik Nayak, Olya Ohrimenko, Felix Schuster, Roy Schwartz, Alex Shamis, Olga Vrousgou, and Christoph M. Wintersteiger. 2019. *CCF: A Framework for Building Confidential Verifiable Replicated Services*. Technical Report MSR-TR-2019-16. Microsoft. https://www.microsoft.com/en-us/research/publication/ccf-a-framework-for-building-confidential-verifiable-replicated-services/

[56] Moritz Schneider, Ramya Jayaram Masti, Shweta Shinde, Srdjan Capkun, and Ronald Perez. 2022. SoK: Hardware-supported Trusted Execution Environments. https://arxiv.org/abs/2205.12742. https://doi.org/10.48550/ARXIV.2205.12742

[57] Michael Schwarz, Samuel Weiser, Daniel Gruss, Clémentine Maurice, and Stefan Mangard. 2017. Malware Guard Extension: Using SGX to Conceal Cache Attacks. In *Detection of Intrusions and Malware, and Vulnerability Assessment*, Michalis Polychronakis and Michael Meier (Eds.). Springer International Publishing, Cham, 3–24.

[58] scrtlabs. 2023. Snip-20 Reference Implementation. https://github.com/scrtlabs/snip20-reference-impl/tree/20b0dfd5b1e594e0a23bbb7cc508f7f650accdc7. Accessed: 2023-02-15.

[59] Interchain Core Teams. 2023. Cosmos SDK Documentation. https://docs.cosmos.network/v0.47. Accessed: 2023-02-23.

[60] Tendermint. 2023. Tendermint Core. https://tendermint.com/core/. Accessed: 2023-02-23.

[61] Afonso Tinoco, Sixiang Gao, and Elaine Shi. 2022. EnigMap: Signal Should Use Oblivious Algorithms for Private Contact Discovery. Cryptology ePrint Archive, Paper 2022/1083. https://eprint.iacr.org/2022/1083 https://eprint.iacr.org/2022/1083.

[62] Christof Ferreira Torres, Ramiro Camino, and Radu State. 2021. Frontrunner Jones and the Raiders of the Dark Forest: An Empirical Study of Frontrunning on the Ethereum Blockchain. In *30th USENIX Security Symposium (USENIX Security 21)*. USENIX Association, online, 1343–1359. https://www.usenix.org/conference/usenixsecurity21/presentation/torres

[63] Petar Tsankov, Andrei Dan, Dana Drachsler-Cohen, Arthur Gervais, Florian Buenzli, and Martin Vechev. 2018. Securify: Practical security analysis of smart contracts. In *Proceedings of the 2018 ACM SIGSAC Conference on Computer and Communications Security*. 67–82.

[64] Jo Van Bulck, Daniel Moghimi, Michael Schwarz, Moritz Lippi, Marina Minkin, Daniel Genkin, Yuval Yarom, Berk Sunar, Daniel Gruss, and Frank Piessens. 2020. LVI: Hijacking Transient Execution through Microarchitectural Load Value Injection. In *2020 IEEE Symposium on Security and Privacy (SP)*. IEEE, San Francisco, CA, USA, 54–72. https://doi.org/10.1109/SP40000.2020.00089

[65] Jo Van Bulck, Frank Piessens, and Raoul Strackx. 2017. SGX-Step: A Practical Attack Framework for Precise Enclave Execution Control. In *Proceedings of the 2nd Workshop on System Software for Trusted Execution* (Shanghai, China) *(SysTEX'17)*. Association for Computing Machinery, New York, NY, USA, Article 4, 6 pages. https://doi.org/10.1145/3152701.3152706

[66] Stephan van Schaik, Andrew Kwong, Daniel Genkin, and Yuval Yarom. 2020. SGAxe: How SGX Fails in Practice. https://sgaxeattack.com/.

[67] Stephan van Schaik, Marina Minkin, Andrew Kwong, Daniel Genkin, and Yuval Yarom. 2021. CacheOut: Leaking Data on Intel CPUs via Cache Evictions. In *2021 IEEE Symposium on Security and Privacy (SP)*. IEEE, San Francisco, CA, USA, 339–354. https://doi.org/10.1109/SP40001.2021.00064

[68] Stephan van Schaik, Alex Seto, Thomas Yurek, Adam Batori, Bader AlBassam, Christina Garman, Daniel Genkin, Andrew Miller, Eyal Ronen, and Yuval Yarom. 2022. SoK: SGX.Fail: How Stuff Get eXposed. https://sgx.fail.

[69] Ying Yan, Changzheng Wei, Xuepeng Guo, Xuming Lu, Xiaofu Zheng, Qi Liu, Chenhui Zhou, Xuyang Song, Boran Zhao, Hui Zhang, and Guofei Jiang. 2020. Confidentiality Support over Financial Grade Consortium Blockchain. In *Proceedings of the 2020 ACM SIGMOD International Conference on Management of Data* (Portland, OR, USA) *(SIGMOD '20)*. Association for Computing Machinery,

New York, NY, USA, 2227–2240. https://doi.org/10.1145/3318464.3386127
[70] Hang Yin, Shunfan Zhou, and Jun Jiang. 2022. Phala Network: A Secure Decentralized Cloud Computing Network Based on Polkadot. https://files.phala.network/phala-paper.pdf
[71] Yi Zhou, Deepak Kumar, Surya Bakshi, Joshua Mason, Andrew Miller, and Michael Bailey. 2018. Erays: Reverse Engineering Ethereum's Opaque Smart Contracts. In *27th USENIX Security Symposium (USENIX Security 18)*. USENIX Association, Baltimore, MD, 1371–1385. https://www.usenix.org/conference/usenixsecurity18/presentation/zhou
[72] Guy Zyskind, Oz Nathan, and Alex Pentland. 2015. Enigma: Decentralized Computation Platform with Guaranteed Privacy. https://doi.org/10.48550/ARXIV.1506.03471

A SNIP-20 TOKEN STATISTICS

Token Name	Market Cap (USD) [12]	Successful Transactions	Unique Senders
Secret Secret (sSCRT)	$5.94m	477.6k	36.2k
Shade (SHD)	$4.88m	35.7k	10.3k
Sienna	$2.87m	94.2k	6.7k
Secret Eth (SETH)	$1.93m	39.5k	4.3K
Eth (SETH BSC)		5.2k	0.7k
Tether (SUSDT)	$1.55m	53.8k	2.8k
Secret Wrapped BTC (SWBTC)	$950k	22.7k	1.2k
Monero (SXMR)	$890k	26.5k	1.5k
Secret USDC (SUSDC)	$475k	8.3k	0.5K
USDC (SUSDC BSC)		9.6k	1.7k
Secret Finance (SEFI)	$339k	111.5k	8.8k
Binance (SBNB BSC)	$124k	27.0k	3.8k
Buttcoin (BUTT)	$108k	13.4k	1.7k
ALTER	$123k	21.8k	2.7k
Dai (SDAI)	N/A	105.0k	0.5k
StkdSecret (stkd-SCRT)	N/A	32.0k	5.7k
(Combined)	$20.2m	1.08m	44.9k

Table 2: Snip-20 Token Statistics