**SplitBFT: Improving Byzantine Fault Tolerance Safety Using Trusted Compartments**

Ines Messadi  
TU Braunschweig, Germany  
Leander Jehl*  
University of Stavanger, Norway

Markus Horst Becker  
TU Braunschweig, Germany  
Sonia Ben Mokhtar  
LIRIS-CNRS, France

Kai Bleeke  
TU Braunschweig, Germany  
Rüdiger Kapitza  
TU Braunschweig, Germany

**ABSTRACT**

Byzantine fault-tolerant agreement (BFT) in a partially synchronous system usually requires $3f + 1$ nodes to tolerate $f$ faulty replicas. Due to their high throughput and finality property BFT algorithms build the core of recent permissioned blockchains. As a complex and resource-demanding infrastructure, multiple cloud providers have started offering Blockchain-as-a-Service. This eases the deployment of permissioned blockchains but places the cloud provider in a central controlling position, thereby questioning blockchains’ fault tolerance and decentralization properties and their underlying BFT algorithm.

This paper presents SplitBFT, a new way to utilize trusted execution technology (TEEs), such as Intel SGX, to harden the safety and confidentiality guarantees of BFT systems thereby strengthening the trust in cloud-based deployments of permissioned blockchains. Deviating from standard assumptions, SplitBFT acknowledges that code protected by trusted execution may fail. We address this by splitting and isolating the core logic of BFT protocols into multiple compartments resulting in a more resilient architecture. We apply SplitBFT to the traditional practical byzantine fault-tolerance algorithm (PBFT) and evaluate it using SGX. Our results show that SplitBFT adds only a reasonable overhead compared to the non-compartmentalized variant.

**CCS CONCEPTS**

- Computing methodologies → Distributed algorithms;  
- Security and privacy → Trusted computing; Distributed systems security.

**KEYWORDS**

Byzantine Fault Tolerance, Intel SGX, Safety

**ACM Reference Format:**

Ines Messadi, Markus Horst Becker, Kai Bleeke, Leander Jehl, Sonia Ben Mokhtar, and Rüdiger Kapitza. 2022. SplitBFT: Improving Byzantine Fault Tolerance Safety Using Trusted Compartments. In 23rd International Middleware Conference (Middleware ’22), November 7–11, 2022, Quebec, QC, Canada. ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3528535.3531516

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*Work done while at TU Braunschweig - Germany

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1 **INTRODUCTION**

Byzantine Fault Tolerance (BFT) agreement algorithms are designed to tolerate arbitrary failures in distributed systems [16, 40]. Over the years, they have been extended to become faster [32, 33], flexible [5, 45], resource-efficient [9, 35], and in many more ways. Recently, they started receiving increasing attention as they order transactions at the heart of many blockchain infrastructures [3, 8].

Blockchains were initially focused on exchanging digital currencies in a trustless, decentralized manner. Yet, their purpose broadened to enable secure transactions of all kinds, e.g., supply chains, NFT marketplaces, secure sharing of medical data [23, 25, 39]. Because setting up a blockchain infrastructure for such purposes is a non-trivial effort, several companies (e.g., cloud providers such as Microsoft Azure [12] and Amazon AWS [2]) launched Blockchain-as-a-Service (BaaS) to spread their blockchain solution while providing the underlying infrastructure. Specifically, they offer public open (also called permissionless) blockchains for use cases in which users can participate unrestrictedly and permissioned blockchains for more sensitive use cases that require a restricted access control list, that allows only authorized participants.

However, having a central blockchain service provider contradicts one of the pillars that made the success of blockchains, i.e., decentralized governance, and it partly jeopardizes the fault model of the utilized BFT algorithm. Indeed, the BaaS provider does not only become a single point of failure, possibly harming the blockchain service availability, but it also requires strong trust in the provider and his personnel regarding the integrity and confidentiality of the hosted blockchain.

For conventional applications, recent Trusted Execution Environments (TEE) remedy the trust issues in terms of integrity and confidentiality of the cloud, as these environments provide an isolated and shielded execution, protecting applications even from local privileged attackers [26]. Today, TEEs (e.g., Intel Software Guard Extension) are readily available in cloud infrastructures, and several applications have been extended for its use [24]. TEEs have already been identified as a technical means to improve the performance and resource-efficiency of BFT in conventional data center settings [9, 35, 58]. However, for these systems, the main idea is to address equivocation based on a hybrid fault model [9, 35, 58], where malicious replicas send conflicting messages during agreement. In these models, a fraction of the codebase is shielded by trusted execution that is assumed to fail only by
crashing and by definition, cannot be subject to Byzantine faults. While introducing trusted execution for BFT, such as in the hybrid fault model, can be beneficial, it does not address the integrity and confidentiality issues of current BaaS-based solutions where the cloud provider has the central control over the infrastructure.

This paper introduces SplitBFT, a TEE-tailored BFT architecture enabling a more trustworthy implementation of BaaS. Specifically, SplitBFT introduces an agreement protocol’s fine-grained, TEE-based compartmentalization. Splitting a BFT protocol into TEE-enabled compartments improves resilience and confidentiality and eases the implementation of diversity.

We illustrate SplitBFT by compartmentalizing Practical Byzantine Fault Tolerance (PBFT). Using our solution, PBFT is decomposed into three independent compartments guarded by trusted execution. The separation follows a careful analysis enforcing that individual steps in the protocol are secured by a quorum decision that makes these steps independent of each other. Based on this approach, the resilience of SplitBFT goes beyond traditional BFT protocols in terms of integrity by tolerating $f$ Byzantine faults of a particular compartment type. In terms of confidentiality, the service tolerates Byzantine faults as long as a specific type of compartment that hosts the service is correct. Also SplitBFT contributes to easing the diversity as it limits the code base that has to be diversified at the level of the BFT protocol implementation to preserve integrity. Orthogonal to these improvements, SplitBFT ensures availability if not more than $f$ nodes are faulty.

We implemented SplitBFT as a Rust-based framework that offers a compartmentalized version of PBFT and utilizes Intel Software Guard Extensions (SGX) as a trusted execution technology. However, SplitBFT is a generic approach to compartmentalizing BFT protocols that is neither limited to PBFT nor SGX. We evaluate SplitBFT in a cloud setting with two use cases: (i) the replication of a trusted key/value store and (ii) an ordering service for a blockchain application. Both use cases show moderate overhead compared to a plain use of PBFT, which instead offers weaker integrity, no confidentiality protection, and is harder to diversify.

In summary, this paper makes the following contributions:

- **Compartmentalized BFT.** We present the first approach towards a multi-compartment paradigm for BFT applications using SGX enclaves and show how a compartmentalized system that uses multiple enclaves can improve safety and preserve integrity with more than $f$ adversaries. We also propose principles that similar BFT protocols can apply.
- **Diversity of Replicas.** We ease the diversity using multiple compartments that share no common code to minimize the number of shared vulnerabilities among enclaves. Furthermore, in our model, enclaves can fail independently.
- **Cloud-tailored BFT.** We propose a confidentiality-enhanced BFT protocol tailored for consortium blockchain in a cloud setting. We present an extensive experimental evaluation of our system in scenarios with up to 150 clients using two applications; a key-value store and a distributed ledger.

## 2 TOWARDS A FINE-GRAINED PARTITIONING OF BFT PROTOCOLS

The crux of BFT Protocols. BFT spanned years of academic research but noticeably gained renewed interest due to its relevance in permissioned blockchains where nodes must be authorized \([3, 65]\), including more recent cases of Blockchain-as-a-Service \([2, 12]\) where a cloud provider hosts the entire blockchain infrastructure for its customers. In a nutshell, a BFT consensus typically runs between nodes assuming a broad spectrum of faults, covering arbitrary and malicious behavior. Thus, they are employed to allow cooperation between participants that do not trust each other or in scenarios where individual replicas may be subject to unpredicted faults or outside attacks. The fault model of BFT systems is extensive and comes at a high cost: typically, at most $f < n/3$ out of $n$ replicas can be faulty. This differs from systems focused on crash failures, where $f < n/2$ can be tolerated. Accordingly, when deploying a BFT system, it is essential to consider failure assumptions. Especially, common failures that may happen on all replicas must be prevented. We argue that for cloud applications, like BaaS, BFT’s basic fault model is hard to maintain, considering the higher likelihood of an attacker or a rogue administrator that controls more than a third of the nodes. Furthermore, traditional BFT designs assume no confidentiality, an essential ingredient for cloud users and sensitive blockchain applications.

**TEE in BFT.** Security threats in cloud infrastructure motivated the use of CPU extensions that support trusted execution (TEEs) in various applications, including BFT \([4, 36]\). BFT protocols leverage Intel SGX as it allows trusted applications with small TCB and for its maturity and availability in commodity hardware compared to its predecessor TEEs \([9, 38]\). Intel SGX’s isolated execution environments are known as enclaves, a hardware-protected and encrypted memory. It offers strong integrity and confidentiality protection from the underlying OS. A fundamental property of SGX is creating multiple separate enclaves on one CPU. Thus, it gives three opportunities for BFT protocols:

- **Integrity-protection.** It allows to guard the integrity of state and code loaded into the enclave from faults and adversaries in the environment of the replica;
- **Inter-enclave protection.** It safeguards code in one enclave from failures in a different enclave and;
- **Confidentiality.** It protects the confidentiality of the data in the enclave from failures and attackers outside that enclave.

Clement et al. \([19]\) have shown that, relying on (2), $f$ replica failures can be tolerated using only $2f + 1$ replicas. They require the use of digital signatures and a TEE that may only fail by crashing. So-called hybrid systems \([9, 35]\) use a minimal trusted subsystem, e.g., a trusted counter, to implement this design. However, like traditional BFT protocols, hybrid systems lose safety and liveness if an attacker gains access to more than $f$ replicas or if an enclave within any replica acts maliciously or deviates from the protocol. Specifically, while secure, SGX enclaves are susceptible to attacks, significantly when increasing the TCB. The application code itself may include bugs and memory corruption that leads to vulnerabilities and security vulnerabilities (e.g., synchronization bugs \([60]\)). Most applications that rely on SGX use the memory-unsafe C/C++
because of the C-based interfaces of the SGX SDK. In this matter, the SGX hardware gives no memory-safety guarantees for the software running in the enclave. Using Rust as a memory-safe alternative improves application code safety, but it is not entirely safe from memory corruption errors \[22\]. In hybrid approaches, a single byzantine fault, e.g., a bug or successful attack breaching the trusted subsystem, puts safety at risk.

**SplitBFT.** Unlike hybrid protocols, we do not aim to use TEEs to reduce BFT protocols’ overhead but rather to increase BFT resilience by enforcing safety despite more complex failure scenarios. We exploit Opportunity \(O_2\) to guarantee safety despite an attacker being present on all machines. To achieve this, we place both the core BFT logic and the execution of client requests into the trusted environment.

Further, we do assume that enclaves can fail and become byzantine, i.e., enclaves can equivocate. SplitBFT design tolerates any \(f\) enclaves failing. To further increase reliability, we aim for a small TCB. Especially, using Opportunity \(O_2\), we separate the complex protocol logic located at each replica into multiple independent compartments, each run in a different enclave. This allows us to even tolerate faults in more than \(f\) individual enclaves, given that these happen in enclaves of different compartment types. Figure 1 shows our compartmentalization of the PBFT algorithm. With four replicas, safety is ensured, even if one enclave of each type is faulty.

Finally, we encrypt client requests and responses and only decrypt them inside the enclave. Thus, we utilize Opportunity \(O_3\) to ensure confidentiality despite an attacker present on one of the replicas, as long as enclaves are fault-free. In our PBFT variant from Figure 1, confidentiality is maintained as long as all enclaves of type *Execution* are correct.

In Table 1, we compare SplitBFT to previous plain BFT protocols such as PBFT and prevailing TEE-based BFT protocols, i.e., hybrid protocols. SplitBFT follows traditional BFT protocols liveness-wise; however, it enhances resilience. Our design guarantees safety despite \(n\) powerful attackers. In other words, an attacker on each replica host, which is not the case for hybrid protocols and PBFT that can only tolerate up to \(f\) byzantine attacks. SplitBFT also tolerates faulty enclaves. Enclaves belong to different compartment types, and \(f\) enclaves belonging to each compartment type may fail. In summary, SplitBFT guarantees safety in cases where PBFT and hybrid protocols do not. SplitBFT separates liveness from safety and tries to ensure safety even when liveness may be lost. Violating safety provides the attacker gains, such as double-spending attacks or clients receiving inconsistent replies but violating liveness does not. Losing liveness means progress happens only at the disposal of Byzantine replicas but may still happen or be regained later.

### Table 1: Comparison of fault models in BFT systems.

| Work          | # Replicas | TEE Faulty | TEE | Liveness | Integrity Enclave | Integrity Host | Confidentiality Enclave | Confidentiality Host |
|---------------|------------|------------|-----|----------|------------------|----------------|------------------------|----------------------|
| PBFT [16]     | \(3f + 1\) | \(\times\) | -   | \(f\)    | \(-\)            | \(f\)          | \(-\)                  | 0                    |
| Hybrid Protocols [9, 35] | \(2f + 1\) | \(\checkmark\) | \(\checkmark\) | \(f\) | \(0\) | \(f\) | 0 | 0 |
| SplitBFT      | \(3f + 1\) | \(\checkmark\) | \(\checkmark\) | \(f\) | \(f_{exec} \land f_{conf} \land f_{prep}\) | 0 | 0 | n |

Finally, we target confidentiality of client requests, a property that is important in a cloud setting. In SplitBFT, the client’s requests and the application state remain confidential despite an attacker corrupting the environment on one or multiple machines.

**Diversification.** As mentioned, traditional BFT systems need to avoid common failures of multiple replicas. Typically, this is achieved by diversifying the replicas’ environment. Diversity is not trivial due to the complexity of implementations and the wide range of employed techniques and libraries. The most common approach is to use different and diverse OSs \[31\]. However, diversifying the implementation remains a tedious and error-prone task, especially when unsafe languages such as C are susceptible to memory errors, e.g., buffer overflows. SplitBFT’s fault model enables a more accessible approach that diversifies only a fraction of the codebase, namely the code running inside the different enclaves. The use of compartments further simplifies diversification; only common failures in the same compartment need to be avoided.

### 2.1 System Assumptions

We use a similar networking model as presented in the traditional BFT state machine replication model \[16, 64\]. However, the goal is to tolerate many simultaneous replica faults under pre-defined timing and threshold assumptions. The network is unreliable and may discard, reorder, and delay messages but not indefinitely to guarantee liveness. Safety guarantees do not depend on timing or crash failures.
Modeling SplitBFT. The system consists of a set of clients $C$ and a set of replicas $\Pi = \{r_1, r_2, ..., r_n\}$. We deviate from classical BFT assumptions by not treating a replica as a unit of failure. Instead, we assume that a replica $r_i$ contains multiple compartments (enclaves) $C = \{c^i_1, c^i_2, \ldots\}$ and an environment $e_j$ such as $r_i = C \cup e_j$. Both the environment and compartments may fail arbitrarily. Thus, a faulty or byzantine compartment may omit or delay operations, perform arbitrary steps and lie to other compartments. We note that a fault in the environment may render the compartments in that replica unavailable. The environment may fail independently of the compartments, while compartments, whether part of the same or different replicas, fail independently. However, we assume that once a compartment (e.g., $c^i_1$) is faulty, the environment $e_i$ is considered to be faulty (e.g., faulty compartments corrupt the environment).

We consider multiple compartment types, and every replica contains one compartment of each type. Compartments of the same type contain the same logic. Figure 1 shows the 3 types in our adaptation of PBFT, namely Preparation, Confirmation, and Execution compartments. In the remainder of this paper, we use the term enclave to denote a compartment part of a specific replica. On the other hand, we use the term compartment to indicate the code or logic executed by all enclaves of a given compartment type.

An attacker may simultaneously compromise the $n$ machines, manipulating separate compartments but not multiple enclaves of the same type. Still, the risk of compromising similar compartments is somewhat reduced by using diverse enclaves environments (e.g., various programming languages), therefore reducing common vulnerabilities. We assume Intel SGX enclaves implementation and standard cryptographic operations are correct. Still, the developer code may include programming errors/bugs (e.g., buffer overflow) that can lead to arbitrary enclave behavior if exploited. We exclude side-channels on TEEs [14, 17, 37, 50, 54, 60] from our threat model, but mitigations or microcode updates can be applied to SplitBFT [48, 53]. We assume that each enclave has a public and private key pair and that private keys of correct enclaves cannot be derived by either the environment or other enclaves on the same replica. In addition, clients are authorized and identified through public keys.

3 BFT-CENTRIC PARTITIONING

In this section, we address the question: How to identify fitting units for different compartments that fail independently? We first present several principles that guide decisions about what data and logic should be placed into individual compartments. We then apply our reasoning to the traditional PBFT protocol.

3.1 Partitioning Principles

SplitBFT is a customizable approach to designing a multi-enclave BFT architecture. By compartmentalizing safety-sensitive functionalities, we can build a BFT system with improved security and robustness. The core argument is that this allows us to contain failures within one compartment while the other compartments remain intact even when located on the same replica. Intel SGX offers this possibility of partitioning a single program into an untrusted environment and multiple secure enclaves and is noticeably characterized by a small TCB compared to other TEEs. In the following, we propose the principles $P_1 \ldots P_5$ that can guide decisions on how to separate a BFT protocol into an environment and multiple compartments:

- $P_1$ Place only safety-critical state and logic into the enclave. SplitBFT should maintain safety, even if an attacker is present in the environment of every replica. Thus, all safety-related logic and state needs to be placed inside an enclave. If an attacker has compromised the environment, liveness of code running in an enclave cannot be guaranteed. Therefore, logic that is only relevant for liveness should stay in the untrusted environment. The separation of liveness results in a reduced TCB and can thus increase the resilience. Typically, protocol logic must stay in the enclave, while timers, network handling, buffering, static variables, and the output log can remain in the untrusted environment.

- $P_2$ Event handlers as decision units. BFT protocols, as most distributed algorithms are event-driven. They are formulated as a set of event handlers. An event handler is a function invoked on a timeout or the receipt of a message. Event handlers manipulate shared state and may again trigger new messages to be sent. Event handlers should run until completion in a single compartment. Indeed, splitting one event handler into multiple compartments favors complex dependencies that may lead to dependent failures. Also, entering/exiting multiple enclaves during one event handler may be detrimental to performance. Placing an event handler into a compartment imposes that different enclaves communicate via authenticated messages, as is done between various replicas.

- $P_3$ Place event handlers that access the same state into one compartment. We restrict the shared state accessed by different compartments to global and static configurations. To achieve this, event handlers that operate on the same state should be placed in the same compartment.

- $P_4$ Place event handlers including similar logic into one compartment. Sometimes, event handlers do not share state but execute the same or similar logic. Duplicating such logic in multiple compartments may also duplicate vulnerabilities. We therefore suggest placing these event handlers into one compartment.

- $P_5$ Place compartment transitions on quorum decisions. When handling individual messages, a faulty sender may easily influence the receiver. For that reason, BFT protocols typically collect messages from multiple senders and only act upon receiving a super-majority (quorum) of matching messages. These quorum of messages are ideal for compartment transitions since the failure of individual senders cannot corrupt the receiving compartment.
3.2 SplitBFT Principles Applied to PBFT

In the following, we first give some background on the PBFT algorithm and especially the state maintained by the algorithm. We then discuss how we identify safety critical variables and how we partition event handlers into multiple compartments applying Principles (P1) to (P5).

Preliminaries. PBFT is regarded as the baseline for almost all published BFT protocols [21, 32, 38, 64]. The consensus procedures of PBFT can be described as follows: the agreement is a three-phase protocol with one designated sender process, the primary associated with a view, decides on the total order of clients’ requests in a PrePrepare message. All other replicas coordinate through broadcasting Prepare messages to validate the primary proposal. Finally, all replicas agree on the total order of requests after receiving a quorum of Commit messages. These steps are repeated while increasing sequence numbers to order additional requests. Each replica maintains a copy of an application, e.g., a blockchain. PBFT uses the ordered requests as input in the execution stage, executes clients’ operations, and sends replies. In the case of a blockchain, this execution may entail the creation of a new block. PBFT guarantees two properties: Safety and liveness. Safety implies clients receive correct (linearizable) replies. Liveness ensures that they eventually receive replies, given that the network does not delay messages indefinitely. Replicas use timers to detect a faulty primary and trigger the view-change sub-protocol. Upon agreement of a 2f + 1 replicas, the system moves to a new view with a new, dedicated primary. PBFT discards requests already executed using the checkpointing sub-protocol to prevent the log of messages from growing indefinitely. Periodically, replicas obtain proof that their state is correct by collecting a certificate of 2f + 1 Checkpoint messages with the same digest and sequence number. In doing so, they can safely remove old entries from the log.

PBFT State. According to Principle (P3), we need to place not only logic but also state into different compartments. We base our partitioning on the PBFT pseudocode [15], where each replica is modeled as an I/O automaton. According to the algorithm, each replica maintains two message logs, in and out, a few variables, and an instance of the application state. The log in contains received messages and some sent messages that are later needed to validate pre-conditions. The out contains messages that should be sent. For variables, we ignore values that can be derived from the input log. For example, the low watermark, a variable marking for which sequence numbers messages have been garbage collected, can be derived from Checkpoint messages in the log in. Similarly, we ignore configuration parameters that stay constant throughout execution and assume they can be safely loaded into enclaves. Examples of such parameters are n, the total number of replicas, and public and private keys.

Local variables are mostly related to the execution of requests, e.g. sequence numbers for the last request executed from each client. Most relevant for the agreement procedure is the view variable, a number used to identify the current primary and ignore all messages sent under previous primaries, i.e. in an earlier view.

Splitting safety and liveness. Following (P1), we start by separating the state into safety-critical variables that should go into the trusted context from liveness variables that may remain in the untrusted environment. Following the replica automaton model in PBFT, we argue that the core safety-critical variables consist of the application state and variables related to request execution, the view, and the input log. We consider the input log in as safety-relevant since even an omission from that log may result in faulty behavior. For example, the omission of sent messages may result in re-sent messages with diverging data, also known as amnesia [7]. Hence, it is easier to protect the integrity of the log in through the enclave memory than to repeatedly verify the authentication of the included messages. Contrarily, the out log remains untrusted as it is only relevant to liveness. The same applies to timers and network connections. Message authentication (i.e., signatures) happens in the enclave before messages are added to the out log. Besides connection handling, we also place the batching of requests into the untrusted environment.

Compartments. Following the principles (P1) to (P5), we partition the PBFT protocol into three compartments:

- **Preparation Compartment**: Receives client requests and initializes its order distribution
- **Confirmation Compartment**: Confirms that a request was prepared by a quorum
- **Execution Compartment**: Collects a quorum of confirmations, executes authenticated requests and sends back the replies to the clients. As this enclave holds the application state, it is also responsible for generating checkpoints.

Figure 2 shows the normal operation, view change, and checkpointing sub-protocols of PBFT. The responsibilities of different compartments are highlighted in different colors.

Separating event handlers. Following Principle (P2), we separate the event handlers from the PBFT algorithm into three compartments, the Preparation, Confirmation, and Execution Compartment. Figure 2 shows the different event handlers in the PBFT algorithm. Event handler (1) is triggered when receiving a batch of requests from the environment and starts the normal operation. Event handlers (5) and (8) are triggered through timeouts and start the view-change or checkpointing procedure, respectively. The remaining event handlers are executed every time a respective message is received.

Following principle (P5), event handlers accessing the same state should be placed in the same compartment. However, a naive application of (P5) would result in a single compartment. Indeed, all the identified message handlers need access to the input log in to receive a message; each handler accesses different messages from in. We eliminate this dependency by separating this log into multiple logs containing one message type.

For event handlers (1)-(4) involved in **normal operation**, we apply Principle (P5) and split them according to quorum decisions. We note that no quorum decision happens between event handlers (1) and (2). Indeed, the Prepare and Prepare messages are used together to form a quorum decision in message handler (3). Thus, if both the enclave sending a PrePrepare, and f enclaves
of the compartment sending PREPARE messages are faulty, safety may be violated. Placing these into one compartment makes this dependency clear.

One problem with this splitting is that PREPARE messages are accessed both by message handlers (2) and (3). Colocating (2) and (3) would violate (P4). We therefore duplicate PREPAREs in the input log of the Preparation and Confirmation Compartments, to avoid shared state (P3). We also duplicate PREPAREs in the input of the Execution Compartment. Thus, the requests are forwarded to this compartment, even if COMMIT messages only contain a hash of that request.

For the checkpointing subprotocol, we note that a checkpoint message includes a snapshot of the application state. As the application state is already needed to execute client requests in the event handler (4), we place the sending of checkpoint messages (8) with (4) in the Execution compartment, following (P3).

Finally, the message handler of CHECKPOINT messages (9) accesses all input logs and deletes old messages. We therefore opt to duplicate this handler in different compartments. Following (P3), each of the duplicates runs independently without dependencies between the different compartments. While this forgoes (P4) and clearly creates additional performance overhead, we argue that this is acceptable since CHECKPOINTs are only performed periodically and lie outside the critical path.

Regarding the view change, we first note that a VIEWCHANGE includes received PREPARE and PREPARE messages. Following (P3) the sending of VIEWCHANGE (5) is co-located with the sending of COMMIT messages (3) in the confirmation enclave. For the handling of NEWVIEW messages, we note that these messages serve two purposes. First, the NEWVIEW contains a checkpoint, applied similar to the checkpointing subprotocol. We extract this functionality as event handler (7’) and duplicate it over all compartments, similar to the handling of checkpoints.

Additional to the checkpoints, a NEWVIEW message contains PREPAREs, which results in the sending of PREPARE messages. Following Principle (P4), we place the sending (6) and receiving (7) of the NEWVIEW in the Preparation compartment, together with the sending and receiving of PREPARE (1,2).

One remaining issue is the view variable, which all event handlers use to avoid processing and sending messages belonging to an outdated view. To avoid merging all event handlers into a single compartment, we instead replicate the view variable. As in PBFT, the view variable is updated when sending a VIEWCHANGE message (5), or when receiving a valid NEWVIEW message (7,7’). Thus, together with the checkpoints in a NEWVIEW message, we update the view in all compartments.

4 SPLITBFT

In this section, we answer the question of how to maintain correctness when splitting an algorithm. We first give a detailed description of our split variant of PBFT. We then argue why it maintains correctness and report on our effort to verify this correctness formally.

SplitBFT Workflow. We now show a request execution workflow with further details and explain how our design prevents enclaves from tricking each other and ensures correctness and safety.

1) Client requests: Clients are identified with a pair of keys a pk_i and sk_i. Additionally, each enclave has an individual key pair. We assume public keys are known to all participants. At the start of the service, the client first attests to the execution and preparation enclave verifying their genuineness and SGX support. When the attestation is successful, the client provides the execution enclave with a session key k_enc to encrypt requests and preserve their confidentiality from the untrusted environment and the rest of the enclaves. The encrypted requests are then signed for authentication. When clients submit corrupted operations, the Execution Compartment will detect this and execute a no-op instead.

2) Ordering protocol: The Preparation enclave on the primary replica authenticates the request, assigns it a sequence number and then stores it in its input log inprep. After checking the correctness of the request, the preparation enclave creates a PREPARE message, signs it using its private key, and then pushes it into the output log. Preparation enclaves on the backups receive the PREPARE message, verify its correctness, and create and sign a PREPARE
messages. PrePrepares are also forwarded to the Confirmation Compartment.

The Confirmation Compartment waits for a Prepare certificate containing one PrePrepare and 2f matching Prepare messages from different enclaves of type Preparation Compartment. Then each Confirmation enclave creates and signs a COMMIT. Finally, the Execution Compartment waits for a quorum of COMMITS. Since COMMIT may only include a hash of the request, the Execution also receives PrePrepares containing the full request. It then executes requests and sends replies to the clients.

Following (P2), we note that in the above, an enclave does not react to a single message from a different compartment, but only reacts to a certificate of 2f + 1 messages. This ensures that failures in individual enclaves cannot affect other compartments and protects the quorum certificate from any unanticipated changes.

3) Garbage collection: Each compartment keeps a separate private log and executes checkpoints. The CHECKPOINT message originates from the Execution Compartment, which holds the application state. Each compartment erases old message upon receiving 2f + 1 CHECKPOINTS. Compartments keep the CHECKPOINTS and discard messages for sequence numbers before the checkpoint, even if they are received later.

4) View-change: As in PBFT, our replicas set a timer on receiving a request from a client. If this timer expires before the request is executed, replicas suspect the primary to be faulty. These timers are managed by the environment but upon suspicion, the Confirmation Compartment sends the VIEWCHANGE message. This message contains a certificate of 2f + 1 CHECKPOINTS and all PREPARE certificates from in_conf. Upon sending this VIEWCHANGE, a Confirmation enclave increases its view. Thus, it will no longer process PrePrepares or send COMMITS in the old view. The Preparation Compartment receives the VIEWCHANGE messages, validates them, and sends a NewView.

The NewView in PBFT has three important functions. First, it updates the view and primary on all replicas, second, it distributes a checkpoint, and third, it allows the new primary to resend PrePrepares for requests that have been assigned a sequence numbers in the previous view, but are not included in the checkpoint yet. The new primary needs to create PrePrepare messages for the NewView based on the Prepare certificates included in VIEWCHANGES. This logic is complex and it is repeated when validating the NewView in the Preparation Compartment. The Confirmation and Execution Compartments also receive the NewView but do not validate the PrePrepares included. They only validate and apply the checkpoint and update their view number, if they did not yet do so.

Correctness. We first argue informally why our splitting of PBFT is correct. We then report on our formal verification. We need to argue that our split protocol maintains both liveness and safety if, on 2f + 1 replicas, both the environment and all enclaves are correct. If the environment of a replica is correct, PrePrepare, CHECKPOINT, and NewViews are forwarded to all compartments at the same time. A replica in SplitBFT thus behaves like a replica in PBFT. Safety and liveness follow from the respective properties in PBFT.

There is one corner case, namely that a NewView that contains false PrePrepares but is otherwise correct will be accepted by the Confirmation and Execution Compartment, but not by the Preparation Compartment. In this case, the replica may send COMMITS in the new view but will not send PrePrepares. We note that a prepare certificate containing 2f PREPARE and one PrePrepare message is still needed to send a COMMIT. Thus, safety is guaranteed.

Furthermore, we have to argue that our compartmentalized version of PBFT does maintain safety as long as 2f + 1 enclaves from each compartment-type are correct. In this case, messages may arrive selectively or reordered at the different compartments. Regarding checkpoints, we note that receiving CHECKPOINT messages in a different order gives the same result. A replica only handles messages in a fixed window of sequence numbers above the last checkpoint. Thus, the replica may not respond to messages in higher sequence numbers after omitting a checkpoint. This does not endanger safety.

In case the Preparation Compartment at the primary is faulty, a replica may receive two different PrePrepares and forward them once to the Preparation and once to the Confirmation enclave. However, if 2f + 1 Preparation enclaves are correct, no two replicas can receive different PREPARE certificates. Therefore, safety still holds.

Finally, given a faulty environment, the Preparation enclave may process a PrePrepare and send a Prepare after the Confirmation enclave has sent a VIEWCHANGE. If that additional Prepare is used in a PREPARE certificate triggering a COMMIT on some replica, then this replica will include the certificate in its VIEWCHANGE. Otherwise, it remains without effect. BFT protocols are known for their complexity, and some previous protocols are known to contain faults [1, 11]. We formally verify that SplitBFT does maintain safety under the complex conditions stated above. To do that, we proved safety using the Ivy verification tool [47]. Ivy is a tool that can verify safety proofs for parametrized models. This gives better confidence in correctness than finite model checkers like TLA+ that only verify the model for fixed parameters and suffer from state explosion. Since no synchronization between different enclaves on one replica can be ensured in case of a faulty environment, we modeled the different enclaves as individual nodes in our proof. For deriving the proof, we adjusted an existing proof of PBFT [57]. This derivation was surprisingly straightforward and only required minor adjustments to the proof. This gives us additional confidence that our model is correct.¹

Discussions and Extensions

Further Compartmentalization. PBFT is not the only fault-tolerant protocol that can be compartmentalized. The principles and ideas we show apply to other BFT protocols, including streamlined variants such as the recent Hotstuff protocol [65]. Besides, the application included in our execution enclave may significantly increase the TCB for certain use cases. In such cases, further compartmentalization may be applied by (i) separating the application in its own enclave and (ii) a more fine-grained partitioning of the application, e.g., applying sharding techniques [29].

Enclave recovery. When enclaves are identified to either be corrupted by a memory leak or fail by crashing, we consider rebooting the single affected component. Enclaves that possibly store data

¹Formal models are available online: https://github.com/leandernikolaus/splitbft-proofs.
We implement SplitBFT on top of Themis, a Rust-based implementation of PBFT [51] (using the nightly-2021-02-17 v1.1.3 [34]). To avoid synchronization primitives inside enclaves, we only allow a single thread to execute in each enclave.

The SDK defines calls between the enclave and the outside world that are part of the application logic. An ecall into the enclave or an ocall into the untrusted side. An essential practice when enclavising an application is minimizing the performance overhead that comes from these transitions (≈ 8,640 cycles [61]).

To digitally sign enclave messages, we use the implementation of 256-bit ED25519 from the ring library v0.16.20 [55]. For authenticating client requests and replies, we use the HMAC-SHA2 function.

| Shared types | Logic | Total LOC | Binary Size (MB) |
|--------------|-------|-----------|-----------------|
| Preparation Enc. | 2430 | 487 | 2917 | 1.1 |
| Confirmation Enc. | 2430 | 458 | 2888 | 1.1 |
| Execution Enc. | 2430 | 579 | 3009 | 1.2 |
| Untrusted Env. | 12565 | - | - | - |
| Trusted Counter | 439 | - | - | 0.524 |

Table 2: TCB sizes for all enclaves

**Analysis.** As there is a correlation between the amount of code and the likelihood of vulnerabilities or defects, we analyze our software in terms of lines of code (using the tokei utility) and enclave size. We show the code that executes within each enclave and the untrusted infrastructure. Table 2 shows the resulting LOC. The table shows separate line numbers for the type definitions and data structures used in all enclaves and the logic unique to the enclave. While the Teaclave SGX SDK, serde, and ring dependencies are included in the TCB, they are not included in the numbers presented. The untrusted line consists of the broker layer, the communication handling between replicas, and networking (i.e., sockets). For comparison, we also report the LOC of a Rust implementation of the trusted counter, as used in hybrid systems. The execution enclave code mostly depends on the application and how the developer decides to engineer it. In our case, the LOC of the execution enclave includes the key-value store. While these numbers do not reveal the complexity of the implementation, it gives us an impression of the TCB. Indeed, we show that individual enclaves are significantly smaller than a complete application. An attacker who targets a non-split application has a larger attacker surface to explore than a split BFT application.

**5 IMPLEMENTATION**

We deploy SplitBFT on a cluster of four SGX-enabled Azure VMs Standard DC4s_v2 (4 vcpus, 16 GiB memory), each equipped with an Intel Xeon E-2288G CPU comprising four cores running at 3.7 GHz without HyperThreading connected
Figure 3: Throughput (ops/s) and latency (ms) for SplitBFT and PBFT without batching and with 200 batches using two applications: a blockchain and a key-value store (KVS).

Figure 4: Average latency for ecalls done during the processing of one request/batch in different compartments for 40 clients. Measurements are taken on the leader using the KVS application.

SplitBFT uses a dedicated thread for each enclave, which performs ecalls, and an additional thread running the event loop. We configure PBFT to use a pool of 4 worker threads using the work stealing thread pool from the tokio library. Instead, SplitBFT uses regular OS threads that are more suited for the enclaves development.

As SplitBFT, our PBFT implementation uses HMACs to authenticate client requests and responses but signatures for messages between replicas. In our PBFT implementation, networking and message authentication are parallelized, but the core protocol is not. We target two custom applications as use-cases: a key-value store and a blockchain. Clients constantly issue synchronous requests and collect the replies. We report the latency and throughput based on these measurements and save the average of five runs. The blockchain application creates blocks of five messages in the execution enclave and writes them using an ocall into the untrusted memory to be stored and encrypted persistently. For that, we use the sgx_tprotected_fs crate that allows secure I/O operations.

Our throughput and latency measurements evaluate a PUT operation that updates the entries. To better understand the overhead introduced by SplitBFT we also measured the latency for different ecalls done on our enclaves. Our evaluation shows that multithreading significantly reduces the overhead of SplitBFT and that the

Configuration and baseline. We chose PBFT as a general baseline to evaluate the performance of SplitBFT with batching and without batching using a payload of 10 bytes and reply size of 10 bytes.

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overhead due to enclave transitions can be amortized over request batches.

Throughput and Latency Without Batching. Figure 3 (a) shows the throughput and latency without batching. We see that SplitBFT reaches about 43%-74% of the throughput of PBFT for the key-value store and 38%-59% for the blockchain application. The key-value store application performs up to 33% better than the blockchain application due to the additional I/O operation and encryption when writing a block persistently.

Compared to the baseline, SplitBFT adds performance overhead due to many reasons, including: (i) enclave transitions, (ii) data copying in and out of enclaves, and (iii) added serialization and de-serialization of protocol messages and client requests. From the results, we observe that measuring SplitBFT with a single thread performing all ecalls reduces the performance significantly. To better understand the overhead, we evaluate SplitBFT running enclaves in simulation mode. As the simulation mode omits costly enclave transitions, results suggest that (i) enclave transitions cause 20% of the overhead. To further analyze the overhead, we measure execution times of the ecalls performed in different enclaves during normal request processing. Figure 4 shows the average time spent in different enclaves during the processing of one request. All ecalls sum up to 841μs. Thus, if a single thread is performing all ecalls, a maximum throughput of ≈1190 rps could be reached. Without batching, ecalls to the Execution compartment have the longest latency, with a total of 343μs. In multithreaded SplitBFT, a single thread performs all ecalls to the Execution compartment. This thread thus cannot process more than 2900 rps. We see that the throughput in Figure (a) comes close to these theoretical upper limits. Thus, the overhead for unbatched SplitBFT is due to ecalls to the Execution compartment. The added overhead in the blockchain application is also located in the Execution compartment and therefore effects the overall throughput.

Throughput and Latency With Batching. Figure 3 (b) show results for SplitBFT and PBFT, when client requests are processed as batches. This experiment allows each client to have 40 outstanding requests in parallel. In both systems, we create batches on either receiving 200 requests or expiration of a 10ms timeout. The results show that splitBFT reaches ≈ 64% the throughput of PBFT for the key-value store and 55% for the blockchain application. SplitBFT key-value store performs better than the blockchain application with up to a 4.6× more throughput. Indeed, the execution enclave performs one ocall for each block (5 requests), while in the case of the key-value store, we only perform one ocall on executing each batch.

From Figure 4, we see that the ecalls to the Preparation and Execution compartment are significantly longer now. Ecalls to the Confirmation compartment are similar to the unbatched mode since this compartment only handles a hash of the request batch. Here, ecalls to the Preparation compartment are the longest. These ecalls give a theoretical upper limit of ≈ 227k operation per second. The long ecalls compared to the non batched mode are due to the authentication verification of a batch of client requests instead of a single request and the copy in/out of the enclave. For the Execution, requests need to be un-marshaled and executed. Responses need to be authenticated and copied out of the enclave. The last is also a good example of how enclaves add additional overhead. All responses are collected, marshaled, and passed out of the enclave to avoid multiple enclave transitions (ecalls). The collection then needs to be split and sent to individual clients. On the other hand, in PBFT, marshaling and authentication of different responses are performed concurrently by all threads.

7 RELATED WORK

Using TEEs on BFT protocols and Blockchains. A number of BFT systems explored the use of TEEs to isolate a small fraction of the system functionality thereby establishing a hybrid fault model, where the protected part is excluded from the Byzantine fault assumption and can only fail by crashing [9, 35, 43, 58]. In particular, they aim at reducing the degree of replication by achieving non-equivocation. Clement et al. [19] show that non-equivocation is not enough to decrease the number of required replicas unless it is coupled with transferable authentication.

MinBFT [58], CheapBFT [35] and Hybster [9] assume a trusted subsystem where replicas sign messages using a monotonic counter to address equivocation and thus reduce the fault requirement to 2f + 1. Damysus [27] addresses the case of streamlined BFT protocols such as HotStuff, proposing two trusted services that improve the resilience and reduce the communication rounds as in Hybrid protocols. These services record additional information relevant to blocks to guarantee nodes cannot lie about the last prepared blocks. Recent Avocado places a crash tolerant replica into a TEE, to tolerate ensure confidentiality and integrity despite an attacker present on all nodes, but assumes that TEEs remain correct.

Fairy [56] leverages TEEs as a layer on top of an ordering service to add fairness when executing client’s requests. Troxy [41] uses a TEE to intercept client requests and replies as a proxy layer, resulting in removing the client-side library functionality and making the use of BFT transparent while improving performance. However, these hybrid protocols as well as the work of Clement et al. assume achieving equivocation entails the TEE only fails by crashing, an assumption that comes with a high confidence in the protected code, especially with increased TCB. A recent line of research aims to leverage the security guarantees of TEEs in blockchain and BFT. CCF [52] implements a consortium-based blockchain, assumes that TEE can deviate from the utilized protocol. Therefore, the services record enough signed evidence to attribute the TEE. Ekiden [18] uses TEE-backed smart contracts to preserve confidentiality in blockchain applications.

Another line of Blockchain and cryptocurrency solutions [10, 59] rely on Zero-knowledge proof as an encryption scheme to protect their users’ privacy which is application-specific and requires a large amount of computation power.

Separating Execution Replica. Previous research focused on the separation of the responsibility of execution replicas [18, 64]. Yin et al. [64] give a system that runs the agreement and execution on separate clusters, preventing execution replicas from leaking confidentiality through a privacy firewall. This also brings the benefit of reducing the number of execution replicas. Other works such as Spare [30], TwinBFT [28] rely on separation using virtualization,
facilitating recovery, or as a trusted separate component. Hyperledger Fabric [3] separates the ordering and execution allowing it to occur in a separate processes which gives performance advantages.

Alternative fault models. Many proposed alternative faults models to reduce the complexity or require fewer replicas, e.g., XFT [44], FaB [46], UpRight [20]. These works do not target improving the resilience to byzantine faults as in SplitBFT and focus mainly on performance and scalability. UpRight [20] and Visigoth [49] enable different thresholds for safety and liveness.

Resilience and Robustness. A common goal in BFT research is to further increase the robustness and the resilience of a protocol, as preserving the initial fault model seems hard to achieve in practical scenarios. Flexible BFT [63] aim is to prevent a fraction of faults besides byzantine, assuming an alive-but-corrupt replica, which may deviate from breaking safety however will not try to break liveness. BFT2F exploits the design space beyond $f$ failures [42]. When no more than $f$ replicas fail, it preserves the same guarantees as PBFT. With more than $f$, it prohibits certain kinds of safety violations. While these works improves the resilience to some degree, some rely on certain timing assumptions. Furthermore, none leverage the security of TEEs to increase the resilience to byzantine faults.

Partitioning. Partitioning applications is not a new concept and has been explored in different scenarios. Whittaker et al. [62] presents compartmentalized Paxos to improve the scalability and performance. It separates the application logic based on the identified bottleneck. To our knowledge, SplitBFT is the first protocol to leverage compartmentalization based on TEEs to increase resilience.

8 CONCLUSION

SplitBFT introduces compartmentalization based on TEE to Byzantine fault tolerance. While our approach is neutral to the availability guarantees of BFT, integrity and confidentiality are substantially strengthened. SplitBFT is especially useful in cloud-based deployments where resources and availability are the main concerns of a provider, and the provider can, to some extent, be relieved from concerns regarding the integrity and confidentiality of the hosted code and data. This becomes particularly evident in the context of BaaS, where the central role of the cloud providers contradicts the decentralization and fault tolerance demands of permissionless blockchains. The performed experiments highlight the approach’s feasibility but make the additional overhead of switching between different TEE compartments visible. While SplitBFT exercises the compartmentalization of PBFT using SGX, the approach can be transferred to other BFT protocols that feature quorum decisions as part of the agreement and other trusted execution technology that enables fine-grained trusted execution preferable at the process level.

ACKNOWLEDGMENT

We thank our anonymous reviewers for their helpful comments. This work was supported by the German Research Foundation (DFG) under grant no. KA 3171/9-1.

REFERENCES

[1] Ittai Abraham, Guy Golan-Gueta, Dahlia Malkhi, Lorenzo Alvisi, Ramakrishna Kotla, and Jean-Philippe Martin. 2017. Revisiting Fast Practical Byzantine Fault Tolerance. (2017). https://doi.org/10.48550/arXiv.1712.01367 arXiv:arXiv:hep-ph/1609.057

[2] Amazon. 2022. Amazon Managed Blockchain. Retrieved May 9, 2022 from https://aws.amazon.com/managed-blockchain/

[3] Eli Androulaki, Artem Barger, Vita Beznosova, Christian Chin, Konstantinos Christidis, Angelo De Caro, David Enyeart, Christopher Ferris, Gennady Laventman, Yacov Manevich, Srinivasan Muralidharan, Chet Murthy, Binh Nguyen, Manish Sethi, Gari Singh, Keith Smith, Alessandro Sorniotti, Christos Stathakopoulos, Marko Vukolić, Sharon Weed Cocro, and Jason Yellick. 2018. Hyperledger Fabric: A Distributed Operating System for Permissioned Blockchains. In Proceedings of the Thirteenth EuroSys Conference (Porto, Portugal) ’18. ACM, New York, NY, USA, Article 30, 15 pages. https://doi.org/10.1145/3190508.3190538

[4] Sergej Arnautov, Bohdan Trach, Franz Gregor, Thomas Knauf, Andrei Khrushchev, Christian Priebre, Joshua Lind, Deyra Muthukumaran, Dan O’Keefe, Mark L. Stillwell, David Goltzsche, David Eyers, Rüdiger Kapitza, Peter Pietrzuch, and Christoph Fetzer. 2016. SCOME: Secure Linux Containers with Intel SGX. In Proceedings of the 12th USENIX Conference on Operating Systems Design and Implementation (Savannah, GA, USA) (OSDI’16). USENIX Association, USA, 689–703.

[5] Jean-Paul Bausous, Rachid Guerraoui, and Ali Shokor. 2015. Making BFT Protocols Really Adaptive. In 2015 IEEE International Parallel and Distributed Processing Symposium. IEEE, Hyderabad, India. 904–913. https://doi.org/10.1109/IPDPS.2015.21

[6] Maurice Baillieu, Jörg Thalheim, Pramod Bhattacharyya, Christof Fetzer, Michio Honda, and Kapil Vaswani. 2019. SPEECHER: Securing LSM-Based Key-Value Stores Using Shielded Execution. In Proceedings of the 2019 USENIX Conference on Usenix Annual Technical Conference (Boston, MA, USA) (FAST’19). USENIX Association, USA, 173–190.

[7] Shehar Bano, Alberto Sontino, Andrey Chursin, Dmitri Perelman, and Dahlia Malkhi. 2020. Twins: White-Glove Approach for BFT Testing. (2020). https://doi.org/10.48550/arXiv.2004.10617 arXiv:arXiv:2004.10617

[8] Mathieu Baudet, Avery Ching, Andrey Chursin, George Danezis, François Garillot, Zekun Li, Dahlia Malkhi, Oded Naor, Dmitri Perelman, and Alberto Sontino. 2019. State machine replication in the libra blockchain. The Libra Assn., Tech. Rep. (2019).

[9] Johannes Behl, Tobias Distler, and Rüdiger Kapitza. 2017. Hybrids on Steroids: SGX-Based High Performance BFT. In Proceedings of the Twelfth European Conference on Computer Systems (Belgrade, Serbia) (EuroSys ’17). ACM, New York, NY, USA, 222–237. https://doi.org/10.1145/3064176.3064217

[10] Eli Ben Saxon, Alessandro Chiesa, Christina Garman, Matthew Green, Ian Miers, Eran Tromer, and Madars Virza. 2014. Zerocash: Decentralized Anonymous Payments from Bitcoin. In 2014 IEEE Symposium on Security and Privacy. IEEE, San Jose, California, 439–474. https://doi.org/10.1109/SP.2014.36

[11] Christian Berger, Hans-P. Reiner, and Alysson Bessani. 2021. Making Reads in BFT State Machine Replication Fast, Linearizable, and Live. In 2021 40th International Symposium on Reliable Distributed Systems (SRDS). IEEE, Chicago, IL, USA, 1–12. https://doi.org/10.1109/SRDS53918.2021.00010

[12] Gael Blanchenain. 2018. Azure BaaS. Retrieved July 7, 2021 from https://docs.netherum.com/en/latest/azure/set-up-blockchain-on-azure/

[13] Marcus Brandenburg, Christian Chin, Matthias Lorenz, and Rüdiger Kapitza. 2017. Rollback and Forking Detection for Trusted Execution Environments Using Lightweight Collective Memory. In 47th Annual IEEE/IFIP International Conference on Dependable Systems and Networks, DSN 2017, Denver, CO, USA, June 26-29, 2017. IEEE, Denver, CO, USA, 157–168. https://doi.org/10.1109/DSN.2017.45

[14] Jo Van Bulck, Marina Minkin, Olaf Weiser, Daniel Genkin, Baris Kanikci, Frank Piessens, Mark Silverstein, Thomas W. Enwusch, Yuval Yarom, and Raoul Strackx. 2017. Rollback and Forking Detection for Trusted Execution Environments Using Shielded Execution. In Proceedings of the 30th Annual Technical Conference (Boston, MA, USA) (FAST’17). USENIX Association, USA, 689–703.

[15] Miguel Castro. 2001. Practical Byzantine Fault Tolerance. Ph.D. MIT. Also as Technical Report MIT-LCS-TR-817.

[16] Miguel Castro and Barbara Liskov. 1999. Practical Byzantine Fault Tolerance. In Proceedings of the Third Symposium on Operating Systems Design and Implementation (New Orleans, Louisiana, USA) (OSDI ’99). USENIX Association, USA, 173–186. https://dl.acm.org/doi/abs/10.5555/296606.296624

[17] Michal Chen, Georgios Vasalos, Kit Murdock, Edward Dean, David Oswald, and Flavio D. Garcia. 2021. VohPillager: Hardware-based fault injection attacks against Intel SGX Enclaves using the SVID voltage scaling interface. In 30th USENIX Security Symposium (USENIX Security 21). USENIX Association, 689–716. https://www.usenix.org/conference/usenixsecurity18/presentation/chen-mihal

[18] Raymond Cheng, Fang Zhang, Jereon Kos, Warren He, Nicholas Hynes, Noah Johnson, Ari Juel, Andrew Miller, and Dawn Song. 2019. Eliden: A Platform for
[57] Marcelo Taube, Giuliano Losa, Kenneth L. McMillan, Oded Padon, Moosy Saggiv, Sharon Shoham, James R. Wilcox, and Doug Woos. 2018. Modularity for Decidability of Deductive Verification with Applications to Distributed Systems. https://doi.org/10.5281/zenodo.2577183

[58] Giuliana Santos Veronez, Miguel Correia, Alysson Neves Bessani, Lau Cheuk Lung, and Paulo Verissimo. 2011. Efficient byzantine fault-tolerance. IEEE Trans. Comput. 62, 1 (2011), 16–50.

[59] Zhipeng Wang, Stefanos Chalasinos, Kaixua Qin, Liyi Zhou, Lifeng Gao, Pascale Bertrand, Ben Livshits, and Arthur Gervais. 2022. On How Zero-Knowledge Proof Blockchain Mixers Improve, and Worsen User Privacy. https://doi.org/10.48550/ARXIV.2201.09035

[60] Giuliana Santos Veronez, Miguel Correia, Alysson Neves Bessani, Lau Cheuk Lung, and Paulo Verissimo. 2011. Efficient byzantine fault-tolerance. IEEE Trans. Comput. 62, 1 (2011), 16–30.

[61] Zhipeng Wang, Stefanos Chalasinos, Kaixua Qin, Liyi Zhou, Lifeng Gao, Pascale Bertrand, Ben Livshits, and Arthur Gervais. 2022. On How Zero-Knowledge Proof Blockchain Mixers Improve, and Worsen User Privacy. https://doi.org/10.48550/ARXIV.2201.09035

[62] Ofir Weisse, Valeria Bertacco, and Todd Austin. 2017. Regaining Lost Cycles with HotCalls: A Fast Interface for SGX Secure Enclaves. In Proceedings of the 44th Annual International Symposium on Computer Architecture (Toronto, ON, Canada) (ISCA ’17). ACM, New York, NY, USA, 81–93. https://doi.org/10.1145/3079856.3080208

[63] Michael Whittaker, Aididani Ailijiang, Aleksey Charapko, Murat Demirbas, Neil Giridharan, Joseph M. Hellerstein, Heidi Howard, Ion Stoica, and Adriana Seekeres. 2021. Scaling Replicated State Machines with Compartmentalization. Proc. VLDB Endow. 14, 11 (Jul 2021), 2203–2215. https://doi.org/10.14778/3476249.3476273

[64] Zhuoshu Xiang, Dahlia Malkhi, Kartik Nayak, and Ling Ren. 2021. Strengthened Fault Tolerance in Byzantine Fault Tolerant Replication. In 2021 IEEE 41st International Conference on Distributed Computing Systems (ICDCS). IEEE, DC, USA, 205–215. https://doi.org/10.1109/ICDCS51616.2021.00028

[65] Jian Yin, Jean-Philippe Martin, Arun Venkataramani, Lorenzo Alvisi, and Mike Dahlin. 2003. Separating Agreement from Execution for Byzantine Fault Tolerant Services. SIGOPS Oper. Syst. Rev. 37, 5 (Oct 2003), 253–267. https://doi.org/10.1145/1165389.945470

[66] Maofan Yin, Dahlia Malkhi, Michael K. Reiter, Goy Golan Gueta, and Ittai Abraham. 2019. HotStuff: BFT Consensus with Linearity and Responsiveness. In Proceedings of the 2019 ACM Symposium on Principles of Distributed Computing (Toronto ON, Canada) (PODC ’19). ACM, New York, NY, USA, 347–356. https://doi.org/10.1145/3293611.3331591