Basil: Breaking up BFT with ACID (transactions)

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Abstract

This paper presents Basil, the first transactional, leaderless Byzantine Fault Tolerant key-value store. Basil leverages ACID transactions to *scalably* implement the abstraction of a trusted shared log in the presence of Byzantine actors. Unlike traditional BFT approaches, Basil executes non-conflicting operations in parallel and commits transactions in a single round-trip during fault-free executions. Basil improves throughput over traditional BFT systems by four to five times, and is only four times slower than TAPIR, a non-Byzantine replicated system. Basil's novel recovery mechanism further minimizes the impact of failures: with 30% Byzantine clients, throughput drops by less than 25% in the worst-case.

CCS Concepts: • **Computer systems organization** → **Dependable and fault-tolerant systems and networks**; • **Security and privacy** → **Distributed systems security**; *Database and storage security*.

Keywords: database systems, Byzantine fault tolerance, blockchains, distributed systems

1 Introduction

This paper presents Basil[1] a leaderless transactional key-value store that scales the abstraction of a Byzantine-fault tolerant shared log.

Byzantine fault-tolerance (BFT) systems enable safe online data sharing among mutually distrustful parties, as they guarantee correctness in the presence of malicious (Byzantine) actors. These platforms offer exciting opportunities for a variety of applications, including healthcare [102], financial services [4, 36, 51], and supply chain management [5, 35]. One could for instance design a fully decentralized payment infrastructure between a consortium of banks that omits the need for current centralized automated clearing houses [36]. None of the participating banks may fully trust one another, yet they must be willing to coordinate and share resources to provide the joint service. BFT replicated state machines [25, 29, 47, 56, 110] and permissioned blockchains [6, 9, 13, 23, 45, 55, 101] are at the core of these new services: they ensure that mutually distrustful parties produce the same totally ordered log of operations.

The abstraction of a totally ordered log is appealingly simple. A *scalable* totally ordered log, however, is not only hard to implement (processing all requests sequentially can become a bottleneck), but also often unnecessary. Most distributed applications primarily consist of logically concurrent operations; supply chains for instance, despite their name, are actually complex networks of independent transactions.

Some BFT systems use sharding to try to tap into this parallelism. Transactions that access disjoint shards can execute concurrently, but operations within each shard are still totally ordered. Transactions involving multiple shards are instead executed by running cross-shard atomic commit protocols, which are layered above these totally ordered shards [9, 55, 86, 87, 111]. The drawbacks of systems that adopt this archtitecture are known: (*i*) they pay the performance penalty of redundant coordination—both across shards (to commit distributed transactions) and among the replicas within each shard (to totally order in-shard operations) [83, 112, 113]; (*ii*) within each shard, they give a leader replica undue control over the total order ultimately agreed upon, raising fairness concerns [50, 110, 114]; (*iii*) and often they restrict the expressiveness of the transactions they support [86, 87] by requiring that their read and write set be known in advance.

In this paper, we advocate a more principled, performant, and expressive approach to supporting the abstraction of a totally ordered log at the core of all permissioned blockchain systems. We make our own the lesson of distributed databases, which successfully leverage generic, interactive transactions to implement the abstraction of a sequential, general-purpose log. These systems specifically design highly concurrent protocols that are *equivalent* to a serial schedule [18, 88]. Byzantine data processing systems need be no different: rather than aiming to sequence all operations, they should decouple the *abstraction* of a totally ordered sequence of transactions from its *implementation*. Thus, we flip the conventional approach:

[1] Despite (or because of) his deeply Fawlty character, Basil managed to rise first from paesant to Byzantine emperor (867-886) and then to hotel owner (1975-1979).

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instead of building database-like transactions on top of a sharded, totally ordered BFT log, we directly build out this log abstraction above a partially-ordered distributed database, where total order is demanded only for conflicting operations.

To this effect, we design Basil, a serializable BFT key-value store that implements the abstraction of a trusted shared log, whose novel design addresses each of the drawbacks of traditional BFT systems: (*i*) it borrows databases' ability to leverage concurrency control to support highly concurrent but serializable transactions, thereby adding parallelism to the log; (*ii*) it sidesteps concerns about the fairness of leader-based systems by giving clients the responsibility of driving the execution of their own transactions; (*iii*) it eliminates redundant coordination by integrating distributed commit with replication [83, 113], so that, in the absence of faults and contention, transactions can return to clients in a single round trip; and (*iv*) it improves the programming API, offering support for general interactive transactions that do not require a-priori knowledge of reads and writes.

We lay the foundations for Basil by introducing two complementary notions of correctness. *Byzantine isolation* focuses on safety: it ensures that correct clients observe a state of the database that could have been produced by correct clients alone. *Byzantine independence* instead safeguards liveness: it limits the influence of Byzantine actors in determining whether a transaction commits or aborts. To help enforce these two notions, and disentangle correct clients from the maneuvering of Byzantine actors, Basil's design follows the principle of *independent operability*: it enforces safety and liveness through mechanisms that operate on a per-client and per-transaction basis. Thus, Basil avoids mechanisms that enforce isolation through pessimistic locks (which would allow a Byzantine lock holder to prevent the progress of other transactions), adopting instead an optimistic approach to concurrency control.

Embracing optimism in a Byzantine setting comes with its own risks. Optimistic concurrency control (OCC) protocols [16, 59, 94, 106, 113] are intrinsically vulnerable to aborting transactions if they interleave unfavorably during validation, and Byzantine faults can compound this vulnerability. Byzantine actors may, for instance, intentionally return stale data, or collude to sabotage the commit chances of correct clients' transactions. Consider multiversioned timestamp ordering (MVTSO) [16, 94], which allows writes to become visible to other operations before a transaction commits. While this choice helps reduce abort rates for contended workloads, it can cause transactions to stall on uncommitted operations.

Basil's ethos of independent operability is key to mitigating this issue. The system implements a variant of MVTSO that prevents Byzantine participants from unilaterally aborting correct clients' transactions and ncludes a novel *fallback* mechanism that empowers clients to finish pending transactions issued by others, while preventing Byzantine actors from dictating their outcome. Importantly, this fallback is a per-transaction recovery mechanism: thus, unlike traditional BFT view-changes, which completely suspend the normal processing of all operations, it can take place without blocking non-conflicting transactions.

Our results are promising: on TPC-C [103], Retwis [3] and Smallbank [37]), Basil's throughput is 3.5-5 times higher than layering distributed commit over totally ordered shards running BFT-SMaRt, a state-of-art PBFT implementation [19] and HotStuff [110] (Facebook Diem's core consensus protocol [13]). BFT's cryptographic demands, however, still cause Basil to be 2-4 times slower than TAPIR, a recent non-Byzantine distributed database [113]. In the presence of Byzantine clients, Basil's performance degrades gracefully: with 30% Byzantine clients, the throughput of Basil's correct clients drops by less than 25% in the worst-case. In summary, this paper makes the following three contributions:

- It introduces the complementary correctness notions of Byzantine isolation and Byzantine independence.
- It presents novel concurrency control, agreement, and fallback protocols that balance the desire for high-throughput in the common case with resilience to Byzantine attacks.
- It describes Basil, a BFT database that guarantees Byz-serializability while preserving Byzantine independence. Basil supports interactive transactions, is leaderless, and achieves linear communication complexity.

2 Model and Definitions

We introduce the complementary and system-independent notions of Byzantine isolation and Byzantine independence, which, jointly formalize the degree to which a Byzantine actor can affect transaction progress and safety.

2.1 System Model

Basil inherits the standard assumptions of prior BFT work. A participant is considered correct if it adheres to the protocol specification, and faulty otherwise. Faulty clients and replicas may deviate arbitrarily from their specification; a strong but static adversary can coordinate their actions but cannot break standard cryptographic primitives. A shard contains a partition of the data in the system. We assume that the number of faulty replicas within a shard does not exceed a threshold f and that an arbitrary number of clients may be faulty; we make no further assumption about the pattern of failures across shards. We assume that applications authenticate clients and can subsequently audit their actions. Similar to other BFT systems [23, 25, 29, 41, 56], Basil makes no synchrony assumption for safety but for liveness [40] depends on partial synchrony [39]. Basil also inherits some of the limitations of prior BFT systems: it cannot prevent authenticated

Byzantine clients, who otherwise follow the protocol, from overwriting correct clients' data. It additionally assumes that, collectively, Byzantine and correct clients have similar processing capabilities, and thus Byzantine clients cannot cause a denial of service attack by flooding the system.

2.2 System Properties

To express Basil's correctness guarantees, we introduce the notion of *Byzantine isolation*. Database isolation (serializability, snapshot isolation, etc.) traditionally regulates the interaction between concurrently executing transactions; Byzantine isolation ensures that, even though Byzantine actors may choose to violate ACID semantics, the state observed by correct clients will always be ACID compliant.

We start from the standard notions of transactions and histories introduced by Bernstein et al. [17]. We summarize them here and defer a more formal treatment to our technical report.[2] A transaction T contains a sequence of read and write operations terminating with a commit or an abort. A history H is a partial order of operations representing the interleaving of concurrently executing transactions, such that all conflicting operations are ordered with respect to one another. Additionally, let C be the set of all clients in the system; $Crct \subseteq C$ be the set of all correct clients; and $Byz \subseteq C$ be the set of all Byzantine clients. A projection $H|_{\mathscr{C}}$ is the subset of the partial order of operations in H that were issued by the set of clients $\mathscr{C}$. We further adopt standard definitions of database isolation: a history satisfies an isolation level I if the set of operation interleavings in H is allowed by I. Drawing from the notions of BFT linearizability [72] and view serializability [17], we then define the following properties:

Legitimate History History H is *legitimate* if it was generated by correct participants, *i.e.*, $H = H_{Crct}$.

Correct-View Equivalent History H is *correct-view* equivalent to a history H' if all operation results, commit decisions, and final database values in $H|_{Crct}$ match those in H'.

Byz-I Given an isolation level I, a history H is *Byz-I* if there exists a legitimate history H' such that H is correct-view equivalent to H' and H' satisfies I.

This definition is not Basil-specific, but captures what it means, for any Byzantine-tolerant database, to enforce the guarantees offered by a given isolation level I. Informally, it requires that the states observed by correct clients be explainable by a history that satisfies I and involves only correct participants. It intentionally makes no assumptions on the states that Byzantine clients choose to observe.

Basil specifically guarantees Byz-serializability: correct clients will observe a sequence of states that is consistent with a sequential execution of concurrent transactions. This is a strong safety guarantee, but it does not enforce application progress; a Byz-serializable system could still allow Byzantine actors to systematically abort all transactions. We thus define the notion of *Byzantine independence*, a general system property that bounds the influence of Byzantine participants on the outcomes of correct clients' operations.

Byzantine Independence For every operation o issued by a correct client c, no group of participants containing solely Byzantine actors can unilaterally dictate the result of o.

In a context where clients issue transaction operations, Byzantine independence implies, for instance, that Byzantine actors cannot collude to single-handedly abort a correct client's transaction. This is a challenging property to enforce. It cannot be attained in a leader-based system: if the leader and a client are both Byzantine, they can collude to prevent a transaction from committing by strategically generating conflicting requests. In contrast, Basil can enforce Byzantine independence as long as Byzantine actors do not have full control of the network, a requirement that is in any case a precondition for any BFT protocol that relies on partial synchrony [41, 80]. We prove in our technical report[2] that:

Theorem 1. *Basil maintains Byz-serializability.*

Theorem 2. *Basil maintains Byzantine independence in the absence of network adversary.*

Basil is designed for settings where Byzantine attacks can occur, but are infrequent, consistent with the prevalent assumption for permissioned blockchains today; namely, that to maintain standing in a permissioned system, clients are unlikely to engage in actively detectable Byzantine behavior [48] and, if they cannot break safety undetected, it is preferable for them to be live [74]. We design Basil to be particularly efficient during gracious executions [29] (*i.e.*, synchronous and fault-free) while bounding overheads when misbehavior does occur. In particular, we design aggressive concurrency control mechanisms that maximize common case performance by optimistically exposing uncommitted operations, but ensure that these protocols preserve independent operability, so that Basil can guarantee continued progress under Byzantine attacks [29]. We confirm this experimentally in Section 6.

3 System Overview

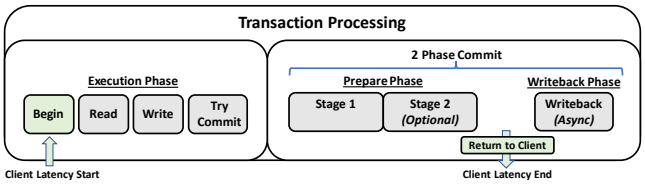


Figure 1. Basil Transaction Processing Overview

Basil is a transactional key-value store designed to be scalable and leaderless. Our architecture reflects this ethos.

[2]Detailed proofs can be found at https://arxiv.org/abs/2109.12443.

Transaction Processing Transaction processing is driven by clients (avoiding costly all-to-all communications amongst replicas) and consists of three phases (Figure 1). First, in an *Execution phase*, clients execute individual transactional operations. As is standard in optimistic databases, reads are submitted to remote replicas while writes are buffered locally. Basil supports interactive and cross-shard transactions: clients can issue new operations based on the results of past operations to any shard in the system. In a second *Prepare phase*, individual shards are asked to vote on whether committing the transaction would violate serializability. For performance, Basil allows individual replicas within a shard to process such requests out of order. Finally, the client aggregates each shard vote to determine the outcome of the transaction, notifies the application of the final decision, and forwards the decision to the participating replicas in an asynchronous *Writeback phase*. Importantly, the decision of whether each transaction commits or aborts must be preserved across both benign and Byzantine failures. We describe the protocol in Section 4.

Transaction Recovery A Byzantine actor could begin executing a transaction, run the prepare phase, but intentionally never reveal its decision. Such behavior could prevent other transactions from making progress. Basil thus implements a *fallback recovery mechanism* (§5) that can terminate stalled transactions while preserving Byz-serializability. This protocol, in the common case, allows clients to terminate stalled transactions in a single additional round-trip.

Replication Basil uses $n = 5f + 1$ replicas for each shard. This choice allows Basil to (*i*) preserve Byzantine independence (*ii*) commit transactions in a single round-trip in the absence of contention, and (*iii*) reduces the message complexity of transaction recovery by a factor of n, all features which would not be possible with a lower replication factor. We expand on this further in Sections 4.5 and 5.

4 Transaction Processing

Basil takes as its starting point MVTSO [16], an aggressive multiversioned concurrency control, and modifies it in three ways: (*i*) in the spirit of independent operability, it has clients drive the protocol execution; (*ii*) it merges concurrency control with replication; and finally (*iii*) it hardens the protocol against Byzantine attacks to guarantee Byz-serializability while preserving Byzantine independence.

Traditional MVTSO works as follows. A transaction T is assigned (usually by a transaction manager or scheduler) a unique timestamp ts_T that determines its serialization order. As MVTSO is multiversioned, writes in T create new versions of the objects they touch, tagged with ts_T. Reads instead return the version of the read object with the largest timestamp smaller than ts_T and update that object's *read timestamp* (RTS) to ts_T. Read timestamps are key to preserving serializability: to guarantee that no read will miss a write from a transaction that precedes it in the serialization order, MVTSO aborts all writes to an object from transactions whose timestamp is lower than the object's RTS.

MVTSO is an optimistic protocol, and, as such, much of its performance depends on whether its optimistic assumptions are met. For example, it uses timestamps to assign transactions a serialization order a-priori, under the assumption that those timestamps will not be manipulated; further, it allows read operations to become *dependent* on values written by ongoing transactions under the expectation that they will commit. This sunny disposition can make MVTSO particularly susceptible to Byzantine attacks. Byzantine clients could use artificially high timestamps to make lower-timestamped transactions less likely to commit; or they could simply start transactions that write to large numbers of keys and never commit them: any transaction dependent on those writes would be blocked too. At the same time, by blocking on dependencies (rather than summarily aborting, as OCC would do) MVTSO leaves open the possibility that blocked transactions may be rescued and brought to commit. In the remainder of this section, we describe how Basil, capitalizing on this possibility, modifies MVTSO to harden it against Byzantine faults.

4.1 Execution Phase

Begin() A client begins a transaction T by optimistically choosing a timestamp $ts := (Time, ClientID)$ that defines a total serialization order across all clients. Allowing clients to choose their own timestamps removes the need for a centralized scheduler, but makes it possible for Byzantine clients to create transactions with arbitrarily high timestamps: objects read by those transactions would cause conflicting transactions with lower timestamps to abort. To defend against this attack, replicas accept transaction operations if and only if their timestamp is no greater than $R_{Time} + \delta$, where R_{Time} is the replica's own local clock. Neither Basil's safety nor its liveness depend on the specific value of δ, though a well-chosen value will improve the system's throughput. In practice we choose δ based on the skew of NTP's clock.

Write(key,value) Writes from uncommitted transactions raise a dilemma. Making them readable empowers Byzantine clients to stall all transactions that come to depend on them. Waiting to disclose them only when the transaction commits, however, increases the likelihood that concurrent transactions will abort. We adopt a middle ground: we buffer writes locally until the transaction has finished execution, and make them visible during the protocol's Prepare phase (we call such writes *prepared*). This approach allows us to preserve much of the performance benefits of early write disclosure while enforcing independent operability (§4.2).

Read(key) In traditional MVTSO, a read for transaction T returns the version of the read object with the highest timestamp smaller than ts_T. When replicas process requests independently, this guarantee no longer holds, as the write with

the largest timestamp smaller than ts_T may have been made visible at replica R, but not yet at R': reading from the latter may result in a stale value. Hence, to ensure serializability, transactions in Basil go through a concurrency control check at each replica as part of their Prepare phase (§ 4.2). Further care is required, as Byzantine replicas could intentionally return stale (or imaginary!) values that would cause transactions to abort, violating Byzantine independence. These considerations lead us to the following read logic:

1: C → R: Client C sends read request to replicas.

C sends an authenticated read request $m := \langle \text{READ}, key, ts_T \rangle$ to at least $2f + 1$ replicas for shard S.

2: R → C: Replica processes client read and replies.

Each replica R verifies that the request's timestamp is smaller than $R_{Time} + \delta$. If not, it ignores the request; otherwise, it updates *key*'s RTS to ts_T. Basil may evict clients with a history of reading keys, but never committing the transaction. Then R returns a signed message $\langle Committed, Prepared \rangle_{\sigma_R}$ that contains, respectively, the latest committed and prepared versions of *key* at R with timestamps smaller than ts_T. *Committed* ≡ (*version,* C-CERT) includes a *commit certificate* C-CERT (§ 4.3) proving that *version* has committed, while *Prepared* ≡ ($version, id_{T'}, Dep_{T'}$) includes a digest identifier for T' (§ 4.2) and the write-read dependencies $Dep_{T'}$ of the transaction T' that created *version*. T' cannot commit unless all the transactions in $Dep_{T'}$ commit first.

3: C ← R: Client receives read replies.

A client waits for at least $f + 1$ replies (to ensure that at least one comes from a correct replica) and chooses the *highest-timestamped* version that is *valid*. For committed versions, the criterion for validity is straightforward: a committed version must contain a valid C-CERT. For prepared versions instead, we require that the same version be returned by at least $f + 1$ replicas. Both the validity and timestamp requirement are important for Byzantine independence. Message validity protects the client's transaction from becoming dependent on a version fabricated by Byzantine replicas; and, by choosing the valid reply with the highest-timestamp, the client is certain to never read a version staler than what it could have read by accessing a single correct replica.

The client then adds the selected (*key, version*) to $ReadSet_T$. If *version* was prepared but not committed, it adds a new write-read dependency to the dependency set Dep_T. Specifically, the client adds to Dep_T a tuple ($version$, $id_{T'}$), which will be used during T's Prepare phase to validate that T is claiming a legitimate dependency.

After T has completed execution, the application tells the client whether it should abort T or instead try to commit it:

Abort() The client asks replicas to remove its read timestamps from all keys in $ReadSet_T$. No actions need to be taken for writes, as Basil buffers writes during execution.

Commit() The client initiates the Prepare phase, discussed next, which performs the first phase of the multi-shard two-phase commit (2PC) protocol that Basil uses to commit T.

4.2 Prepare Phase

To preserve independent operability, Basil delegates the responsibility for coordinating the 2PC protocol to clients. For a given transaction T, the protocols begins with a Prepare phase, which consists of two stages (Figure 1).

In stage ST1, the client collects *commit or abort votes* from each shard that T accesses. Determining the vote of a shard in turn requires collecting votes from all the shard's replicas. To avoid the overhead of coordinating replicas within a shard, Basil lets each replica determine its vote independently, by running a local *concurrency control check*. The flip side of this design is that, since transactions may reach replicas in different orders, even correct replicas within the same shard may not necessarily reach the same conclusion about T. Client C tallies replica votes to learn the vote of each shard and, based on how shards voted, decides whether T will commit or abort.

Stage ST2 ensures that C's decision is made durable (or *logged*) across failures. C *logs* the evidence on only one shard. In the absence of contention or failures, Basil's *fast path* guarantees that T's decision is already durable and this explicit logging step can be omitted, allowing clients to return a commit or abort decision in just a single round trip.

Stage 1: Aggregating votes

1: C → R: Client sends an authenticated ST1 request to all replicas in S.

The message format is ST1 := ⟨PREPARE, T⟩, where T consists of the transaction's *metadata* := ts_T, $ReadSet_T$, $WriteSet_T$, Dep_T, and of its identifier id_T. To ensure Byzantine clients neither spoof the list of involved shards nor equivocate T's contents, id_T is a cryptographic hash of T's *metadata*.

2: R ← C: Replica R receives a ST1 request and executes the concurrency control check.

Traditional, non-replicated, MVTSO does not require any additional validation at commit time, as transactions are guaranteed to observe *all* the writes that precede them in the serialization order (any "late" write is detected by read timestamps and the corresponding transaction is aborted). This is no longer true in a replicated system: reads could have failed to observe a write performed on a different replica. Basil thus runs an additional concurrency control check to determine whether a transaction T should commit and preserve serializability (Algorithm 1). It consists of seven steps:

Algorithm 1 MVTSO-Check(T)

```
1:  if ts_T > localClock + δ then
2:      return Vote-Abort
3:  if ∃ invalid d ∈ Dep_T then
4:      return Vote-Abort
5:  for ∀key, version ∈ ReadSet_T do
6:      if version > ts_T then return MisbehaviorProof
7:      if ∃T' ∈ Committed ∪ Prepared : key ∈ WriteSet_T'
          ∧ version < ts_T' < ts_T then
8:          return Vote-Abort, optional: (T', T'.C-CERT)
9:  for ∀key ∈ WriteSet_T do
10:     if ∃T' ∈ Committed ∪ Prepared :
          ReadSet_T'[key].version < ts_T < ts_T' then
11:         return Vote-Abort, optional: (T', T'.C-CERT)
12:     if ∃RTS ∈ key.RTS : RTS > ts_T then
13:         return Vote-Abort
14: Prepared.add(T)
15: wait for all pending dependencies
16: if ∃ d ∈ Dep_T : d.decision = Abort then
17:     Prepared.remove(T)
18:     return Vote-Abort
19: return Vote-Commit
```

① T's timestamp is within the R's time bound (Lines 1-2).
② T's dependencies are valid: R has either prepared or committed every transaction identified by T's dependencies, and the versions that caused the dependencies were produced by said transactions (Lines 3-4).
③ Reads in T did not miss any writes. Specifically, the algorithm (Lines 7-8) checks that there does not exist a write from a committed or prepared transaction T' that (i) is more recent than the version that T's read and (ii) has a timestamp smaller than ts_T (implying that T should have observed it).
④ Writes in T do not cause reads in other *prepared or committed* transactions to miss a write (Lines 9-11).
⑤ Writes in T do not cause reads in *ongoing* transactions to miss a write: T is aborted if there exists an RTS greater than ts_T (Lines 12-13).
⑥ T is prepared and made visible to future reads (Line 14).
⑦ All transactions responsible for T's dependencies have reached a decision. R votes to commit T only if all of its dependencies commit; otherwise it votes to abort (Lines 15-19).

3: R → C: Replica returns its vote in a ST1R message.

After executing the concurrency control check, each replica returns to C a Stage1 Reply ST1R:= $\langle T, vote\rangle_{\sigma_R}$. A correct replica executes this check **at most once** per transaction and stores its vote to answer future duplicate requests (§5).

4: C ← R: The client receives replicas' votes.

C waits for ST1R messages from the replicas of each shard S touched by T. Based on these replies, C determines (i) whether S voted to commit or abort; and (ii) whether the received ST1R messages constitute a *vote certificate* (V-CERT := $\langle id_T, S, Vote, \{\text{ST1R}\}\rangle$) that proves S's vote to be *durable*. A shard's vote is durable if its original outcome can be independently retrieved and verified at any time by any correct client, independent of Byzantine failures or attempts at equivocation. If so, we dub shard S *fast*; otherwise, we call it *slow*. Votes from a slow shard do not amount to a vote certificate, but simply to a *vote tally*. Though vote tallies have the same structure as a V-CERT, the information they contain is insufficient to make S's vote durable. An additional stage (ST2) is necessary to explicitly make S's vote persistent.

Specifically, C proceeds as follows, depending on the set of ST1R messages it receives:

(1) Commit Slow Path ($3f+1 \leq$ Commit votes $< 5f+1$): The client has received at least a *CommitQuorum* (CQ) of votes, where $|CQ| = \frac{n+f+1}{2} = 3f+1$, in favor of committing T. Intuitively, the size of CQ guarantees that two conflicting transactions cannot both commit, since the correct replica that is guaranteed to exist in the overlap of their CQs will enforce isolation. However, C receiving a CQ of Commit votes is not enough to guarantee that another client C', verifying S's vote, would see the same number of Commit votes: after all, f of the replicas in the CQ could be Byzantine, and provide a different vote if later queried by C'. C thus adds S to the set of slow shards, and records the votes it received in the following *vote tally*: $\langle id_T, S, Commit, \{\text{ST1R}\}\rangle$where $\{\text{ST1R}\}$ is the set of matching (Commit) ST1R replies,

(2) Abort Slow Path ($f+1 \leq$ Abort votes $< 3f+1$): A collection of $f+1$ Abort votes constitutes the minimum *AbortQuorum (AQ)*, i.e., the minimal evidence sufficient for the client to count S's vote as Abort in the absence of a conflicting C-CERT. Requiring an *AbortQuorum* of at least $f+1$ preserves Byzantine independence: Byzantine replicas alone cannot cause a transaction to abort, as at least one correct replica must have found T to be conflicting with a prepared transaction. However, such *AQ's* are not durable; a client other than C might observe fewer than f abort votes and receive a CQ instead. C therefore records the votes collected from S in the following *vote tally*: $(id_T, S, Abort, \{\text{ST1R}\}$ and adds S to the slow set for T.

(3) Commit Fast Path ($5f+1$ Commit votes): No replica reports a conflict. Furthermore, a unanimous vote ensures that, since correct replicas never change their vote, any client C' that were to step in for C would be guaranteed to observe at least a CQ of $3f+1$ Commit votes. C' may miss at most f votes because of asynchrony, and at most f more may come from equivocating Byzantine replicas. C thus records the votes collected from S in the following V-CERT: $\langle id_T, S, Commit, \{\text{ST1R}\}\rangle$ and dubs S fast.

(4) Abort Fast Path ($3f+1 \leq$ Abort votes): T conflicts with a prepared, but potentially not yet committed transaction. S's Abort vote is already durable: since a shard votes to

commit only when at least $3f + 1$ of its replicas are in favor of it, once C observes $3f + 1$ replica votes for Abort from S, it is certain that S will never be able to produce $3f + 1$ Commit votes, since that would require a correct replica to change its ST1R vote or equivocate. C therefore creates V-CERT $\langle id_T, S, Abort, \{\text{ST1R}\}\rangle$, and adds S to the set of fast shards.

(5) Abort Fast Path (One Abort with a C-CERT for a conflicting transaction T'): C validates the integrity of the C-CERT and creates the following V-CERT for S: $\langle id_T, S, Abort, id_{T'}, \text{C-CERT}\rangle$. It indicates that S voted to abort T because T conflicts with T', which, as C-CERT proves, is a committed transaction. Since C-CERT is durable, C knows that the conflict can never be overlooked and that S's vote cannot change; thus, it adds S to the set of fast shards.

After all shards have cast their vote, C decides whether to commit (if all shards voted to commit) or abort (otherwise). Either way, it must make durable the evidence on which its decision is based. As we discussed above, the votes of fast shards already are; if (*i*) there are no slow shards, or (*ii*) a single fast shard voted abort, then, C can move directly to the Writeback Phase (§4.3): this is Basil's fast path, which allows C to return a decision for T after a single message round trip. If some shards are in the slow set, however, C needs to take an additional step to make its tentative 2PC decision durable in a second phase (ST2). Notably though, Basil does *not* need each slow shard to log its corresponding vote tally in order to make it durable. Instead, Basil first decides whether to commit or abort T based on the shard votes it has received, and then logs its *decision* to only a *single* shard before proceeding to the Writeback phase.

Stage 2: Making the decision durable

5: C → R: The client attempts to make its tentative 2PC decision durable.

C makes its decision durable by storing an (authenticated) message ST2 := $\langle id_T, decision, \{\text{SHARDVOTES}\}, view = 0\rangle$ on *one* of the shards that voted in Stage 1 of the Prepare phase; we henceforth refer to this shard, chosen deterministically depending on T's id, as S_{log}. The set {SHARDVOTES} includes the vote tallies of all shards to prove the decision's validity. Like many consensus protocols (e.g. [25, 56, 84]), Basil relies on the notion of *view* for recovery: the value of *view* indicates whether this ST2 message was issued by the client that initated T (*view*= 0) or it is part of a fallback protocol. We discuss *view*'s role in detail in §5.

6: R → C: Replicas in S_{log} receive the ST2 message and return ST2R responses.

Each replica validates that C's 2PC decision is justified by the corresponding vote tallies; if so, the replica logs the decision and acknowledges its success. Specifically, it replies to C with a message of the form ST2R := $\langle id_T, decision, view_{decision}, view_{current}\rangle_{\sigma_R}$; $view_{decision}$ and $view_{current}$ capture additional replica state used during recovery. We once again defer an in-depth discussion of views to §5.

7: C ← R: The client receives a sufficient number of matching replies to confirm a decision was logged.

C waits for $n - f$ ST2R messages whose *decision* and $view_{decision}$ match, and creates a single shard certificate V-CERT$_{S_{log}}$:= $\langle id_T, S, decision, \{\text{ST2R}\}\rangle$ for the logging shard.

4.3 Writeback Phase

C notifies its local application of whether T will commit or abort, and asynchronously broadcasts to all shards that participated in the Prepare phase a corresponding decision certificate (C-CERT for commit; A-CERT for abort).

1: C → R: The client asynchronously forwards decision certificates to all participating shards.

C sends to all involved shards a decision certificate (C-CERT:$\langle id_T, Commit, \{\text{V-CERT}_S\}\rangle$ for a Commit decision, A-CERT: $\langle id_T, Abort, \{\text{V-CERT}_S\}\rangle$ otherwise). We distinguish between the fast, and slow path: On the fast path, C-CERT consists of the full set of Commit V-CERT votes from all involved shards, while an A-CERT need only contain one V-CERT vote for Abort. On the slow path, both C-CERT and A-CERT simply include V-CERT$_{S_{log}}$.

2: R ← C: Replica validates C-CERT or A-CERT and updates store accordingly.

Replicas update all local data structures, including applying writes to the datastore on commit and notifying pending dependencies.

4.4 An Optimization: Reply Batching

To amortize the cost of signature generation and verification, Basil batches messages (Figure 2). Unlike leader-based systems, Basil has no central sequencer through which to batch requests; instead, it implements batching at the replica *after* processing messages. To amortize signature generation for replies, Basil replicas create batches of b request replies, generate a Merkle tree [77] for each batch, and sign the root hash. They then send to each client C that issued a request: (*i*) the root hash *root*, (*ii*) a signed version σ of the same *root*, (*iii*) the appropriate request reply R_C, and (*iv*) all intermediate nodes (denoted π_C in Figure 2) necessary to reconstruct, given R_C, the root hash *root*. Through this batching, the cost of signature generation is reduced by a factor of b, at the cost of $log(b)$ additional messages. To amortize signature verification, Basil uses caching. When a replica successfully verifies the root hash signature in a client message m, it caches a map

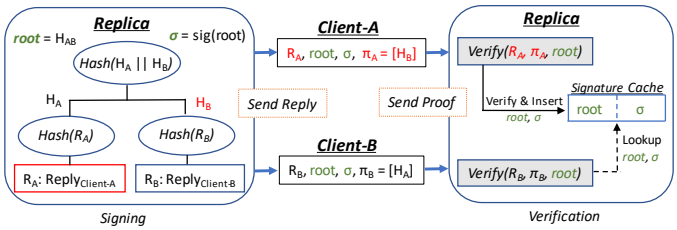


Figure 2. Basil batching for two clients. Signature σ and batch $root$ (green) are the same across batched replies. Reply R_C and proof π_C are unique to each client C and can validate $root$.

between the corresponding root hash value and the signature. If the replica later receives a message m' carrying the same root hash and signature as m (indicating that m and m' refer to the same batch of replies), it can, upon verifying the correctness of the root hash, immediately declare the corresponding signature valid.

4.5 Discussion

Stripping layers When 2PC is layered above shards that already order transactions internally using state machine replication, then *within every shard* every correct replica has logged the vote of every other correct replica. Basil's design avoids this indiscriminate cost: if all shards are fast, then their votes are already durable without requiring replicas to run any coordination protocol; and if some shards are slow, as we mentioned above, only the replicas of a single shard need to durably log the decision. As a result, the overhead of Basil's logging phase remains constant in the number of involved shards.

Signature Aggregation. Basil, like recent related work [47, 110], can make use of signature aggregation schemes [20–22, 24, 44, 52, 79, 97] to reduce total communication complexity. The client could aggregate the (matching) signed ST1R or ST2R replies into a single signature, thus ensuring that all messages sent by the client remain constant-sized, and hence Basil total communication complexity can be made linear. The current Basil prototype does not implement this optimization.

Why $n = 5f + 1$ replicas per shard? Using fewer replicas has two main drawbacks. First, it eliminates the possibility of a commit fast path. With a smaller replication factor, CQs of size $n - 2f$ (f can differ because of asynchrony, another f can differ because of equivocation) would no longer be guaranteed to overlap in a correct replica, making it possible for conflicting transactions to commit, in violation of Byzantine serializability. Second, it precludes Byzantine independence. For progress, clients must always be able to observe either a CQ or an AQ, but, for Byzantine independence, the size of neither quorum must fall below $f+1$: with $n \leq 5f$, it becomes impossible to simultaneously satisfy both requirements.

5 Transaction Recovery

For performance, Basil optimistically allows transactions to acquire dependencies on uncommitted operations. Without care, Byzantine clients could leverage this optimism to cause transactions issued by correct clients to stall indefinitely. To preserve Byzantine independence, transactions must be able to eventually commit even if they conflict with, or acquire dependencies on, stalled Byzantine transactions. To this effect, Basil enforces the following invariant: if a transaction acquires a dependency on some other transaction T, or is aborted because of a conflict with T, then a correct participant (client or replica) has enough information to successfully complete T.

Specifically, Basil clients whose transactions are blocked or aborted by a stalled transaction T try to finish T by triggering a *fallback* protocol. To this end, Basil modifies MVTSO to make visible the operations of transactions that have *prepared* only. As T's ST1 messages contain all of T's planned writes, any client or replica can use this information to take it upon itself to finish T. A correct client is guaranteed to be able to retrieve the ST1 for any of its dependencies, since $f + 1$ replicas (*i.e.*, at least one correct) must have vouched for that ST1 during T's read phase. Likewise, a correct client's transaction only aborts if at least $f+1$ replicas report a conflict.

Basil's fallback protocol starts with clients: any client blocked by a stalled transaction T can try to finish it. In the **common case**, it will succeed by simply re-executing the previously described Prepare phase; success is guaranteed as long as replicas within the shard S_{log} that logged shard votes in Stage 2 of T's Prepare phase store the same decision for T. The **divergent case**, in which they do not, can occur in one of two ways: (*i*) a Byzantine client issued T and sent deliberately conflicting ST2 messages to S_{log}; or (*ii*) multiple correct clients tried to finish T concurrently, and collected Prepare phase votes (set of ST1R messages) that led them to reach (and try to store at S_{log}) different decisions. Fortunately, in Basil a Byzantine client cannot generate conflicting ST2 messages at will: its ability to do so depends on the odds (which §6 suggests are low) of receiving, from the replicas of at least one shard, votes that constitute *both* a CQ and an AQ (i.e., *3f+1* Commit votes and *f+1* Abort votes). Whatever the cause, if a client trying to finish T observes that replicas in S_{log} store different decisions, it proceeds to elect a *fallback leader*, chosen deterministically among the replicas in S_{log}. Through this process, Basil guarantees that clients are always able to finish dependent transactions after at most $f + 1$ leader elections (since one of them must elect a correct leader).

Though Basil's fallback protocol is reminiscent of the traditional view-change protocols used to evict faulty leaders, it differs in three significant ways. First, it requires no leader in the common case; further, if electing a fallback leader becomes necessary, communication costs can be made linear in

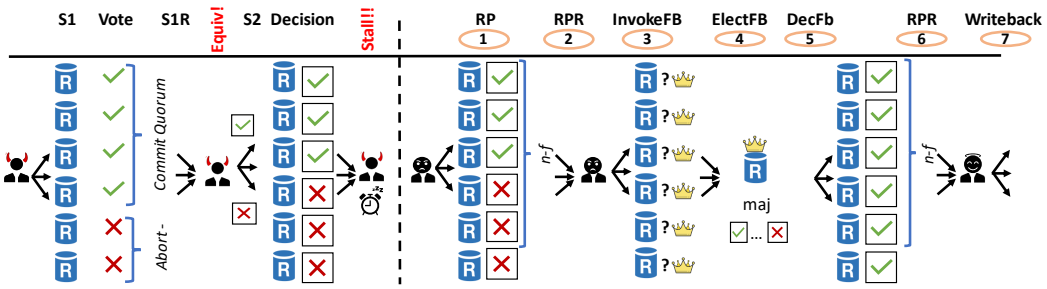


Figure 3. Fallback Scenario. A Byzantine client equivocates ST2R decisions and stalls. An interested client invokes the FB

the number of replicas using signature aggregation schemes (§ 4.4). Second, the fallback election is local, and affects only transactions that access the same operations as the stalled transaction: when a fallback leader is elected for T, the scope of its leadership is limited to finishing T. In contrast, a standard view-change prevents the system from processing *any* operation and the leader, once elected, lords over all consensus operations during its tenure. Finally, Basil' fallback leaders have no say on the ordering of transactions or on what they decide [114].

As in traditional view-change protocols, each leader operates in a *view*. For independent operability, views are defined on a per-transaction basis. Transactions start in $view = 0$; transactions in that view can be brought to a decision by any client. A replica increases its view number for T each time it votes to elect a new fallback leader.

We now describe the steps of the fallback protocol triggered by a client C wishing to finish a transaction T, distinguishing between the aforementioned common and divergent cases.

Common case In the common case, the client simply resends a ST1 message (renamed for clarity *Recovery Prepare* (RP)) in this context) to all the replicas in shards accessed by T. Replicas reply with an RPR message which, depending the progress of previous attempts (if any) at completing T corresponds to either (*i*) a ST1R message; (*ii*) a ST2R message; or (*iii*) a C-CERT or A-CERT certificate. Based on these replies, the client can fast-forward to the corresponding next step in the Prepare or Writeback protocol. In the common case, stalled dependencies thus cause correct clients to experience only a single additional round-trip on the fast path, and at most two if logging the decision is necessary (slow path).

Divergent case If, however, the client only receives non-matching ST2R replies, more complex remedial steps are needed. ST2R can differ (*i*) in their decision value and (*ii*) in their view number $view_{decision}$. The former, as we saw, is the result of either explicit Byzantine equivocation or of multiple clients attempting to concurrently terminate T. The latter indicates the existence of prior fallback invocations: a Byzantine fallback leader, for instance, could have intentionally left the fallback process hanging. In both scenarios, the client elects a fallback leader. The steps outlined below ensure that, once a correct fallback leader is elected, replicas can be reconciled without introducing live-lock.

(1: C → R): Upon receiving non-matching ST2R responses, a client starts the fallback process.

The client sends $InvokeFB := \langle id_T, views \rangle$, where *views* is the set of signed current views associated with the RPR responses received by the client.

(2: R → R_{FL}): Replicas receive fallback invocation *InvokeFB* and start election of a fallback leader R_{FL} for the current view.

R takes two steps. First, it determines the most up-to-date view v'' held by correct replicas in S_{log} and adopts it as its current view $view_{current}$. Second, R sends message ELECTFB $:= \langle id_T, decision, view_{current} \rangle_{\sigma_R}$ to the replica with id $v_{current} + (id_T \mod n)$ to inform it that R now considers it to be T's fallback leader.

R determines its current view as follows: If a view v appears at least $3f+1$ times in the *current views* received in *InvokeFB*, then R updates its $view_{current}$ to $max(v+1, view_{current})$; otherwise, it sets its $view_{current}$ to the largest view v greater than its own that appears at least $f+1$ times in *current views*. When counting how frequently a view is present in the received *current views*, R uses vote subsumption: the presence of view v counts as a vote also for all $v' \leq v$.

The thresholds Basil adopts to update a replica's current view are chosen to ensure that all $4f+1$ correct replicas in S_{log} quickly catch up (in case they differ) to the same view, and thus agree on the identity of the fallback leader. Specifically, by requiring $3f+1$ matching views to advance to a new view v, Basil ensures that at least $2f+1$ correct replicas are at most one view behind v at any given time. In turn, this threshold guarantees that (*i*) a correct client will receive at least $f+1$ matching views for $v' \geq v-1$ in response to its RP message and (*ii*) will include them in its *InvokeFB*. These $f+1$ matching views are sufficient for all $4f+1$ correct replicas to catch-up to view v', then (if necessary) jointly move to view v, and send election messages to the fallback leader of v. Refer to our technical report[2] for additional details and proofs.

(3: R_{FL} → R): Fallback leader R_{FL} aggregates election messages and sends decisions to replicas.

R_{FL} considers itself elected upon receiving $4f + 1$ ELECTFB messages with matching views $view_{elect}$. It proposes a new decision $dec_{new} = majority(\{decision\})$ and broadcasts message DECFB := $\langle (id_T, dec_{new}, view_{elect})_{\sigma_{R_{FL}}}, \{\text{ELECTFB}\}\rangle$, which includes the ELECTFB messages as proof of its leadership.

Importantly, an elected leader can only propose *safe* decisions: if a decision has previously been returned to the application or completed the Writeback phase, it must have been *logged* successfully, i.e. signed by $n - f = 4f + 1$ replicas. Thus, in any set of $4f + 1$ ELECTFB messages the decision must appear at least $2f + 1$ times, i.e., a majority. Note that this condition no longer holds when using fewer that $5f + 1$ replicas per shard: using a smaller replication factor would require (*i*) an additional (third) round of communication, and (*ii*) including proof of this communication in all replica votes (an $O(n)$ increase in complexity), to guarantee that conflicting decision values may not be logged for the same transaction.

(4: R → C): Replicas sends a ST2R message to interested clients.

Replicas receive a DECFB message and adopt the message's decision (and $view_{decision}$) as their own if their current view is smaller or equal to $view_{elect}$ and the proof is valid. If so, replicas update their current view to $view_{elect}$ and forward the decision to all interested clients in a ST2R message: $\langle id_T, decision, view_{decision}, view_{current}\rangle_{\sigma_R}$.

(5: C: A client creates a V-CERT or restarts fallback.

If the client receives $n - f$ ST2R with matching decision and decision views, she creates a V-CERT$_{S_{log}}$ and proceeds to the Commit phase. Otherwise, it restarts the fallback using the newly received $view_{current}$ messages to propose a new view.

We illustrate the entire divergent case algorithm in Figure 3, which for simplicity considers a transaction T involving a single shard. With multiple shards, only the common case RP messages (and replies) would involve all shards; the divergent case would always touch only a single shard, S_{log}.

To begin the process of committing T, a Byzantine client sends message ST1 and waits for all ST1R messages. Since the replies it receives allow it to generate both a Commit and Abort quorum, the client chooses to equivocate, sending ST2 messages for both Commit and Abort. It then stalls. A second correct client who acquired a dependency on T attempts to finish it. It sends RP messages (1) and receives non-matching RPR messages (three Commit and two Abort decisions, all from view 0) (2). To redress this inconsistency, the correct client invokes a Fallback with view 0 (3b). Upon receiving this message, replicas transition to view 1 and send their own decision to view 1's leader in an ELECTFB message (4). In our example, having received a majority of Commit decisions, the leader chooses to commit and broadcasts its decision to all other replicas in an DECFB message (5). Finally, replicas send the transaction's outcome to the interested client (6), who then proceeds to the Writeback phase (7).

6 Evaluation

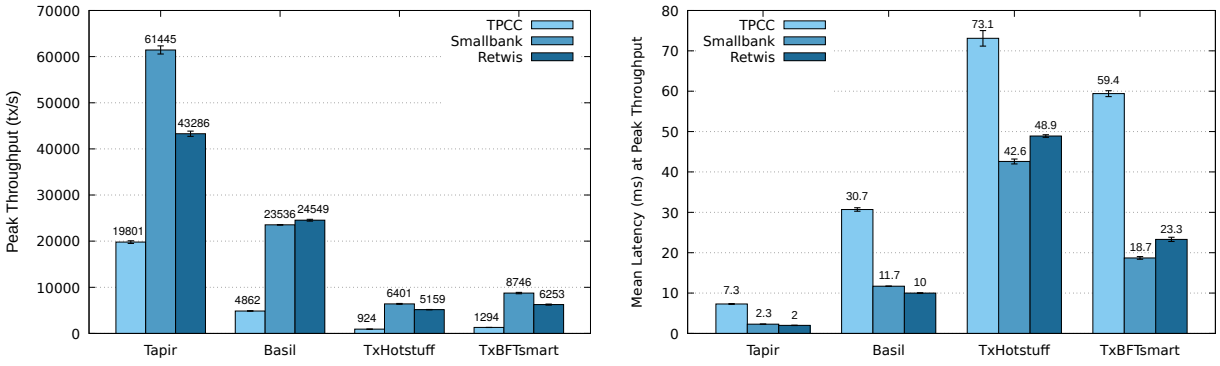
Our evaluation seeks to answer the following questions:

- How does Basil perform on realistic applications? (§6.1)
- Where do Basil's overheads come from? (§6.2)
- What are the impacts of our optimizations in Basil? (§6.3)
- How does Basil perform under failures? (§6.4)

Baselines We compare against three baselines: (*i*) TAPIR [113], a recent distributed database that combines replication and cross-shard coordination for greater performance but does not support Byzantine faults; (*ii*) TxHotstuff, a distributed transaction layer built on top of the standard C++ implementation [109] of HotStuff, a recent consensus protocol that forms the basis of several commercial systems [11, 13, 26, 34, 78], most notably Facebook Diem's Libra Blockchain; and (*iii*) TxBFT-SMaRt, a distributed transaction layer built on top of BFT-SMaRt [1, 19], a state-of-the-art PBFT-based implementation of Byzantine state machine replication (SMR). HotStuff and BFT-SMaRt support general-purpose SMR, and are not fully-fledged transactional systems; we thus supplement their core consensus logic with a coordination layer for sharding (running 2PC) and an execution layer that implements a standard optimistic concurrency control serializability check [59] and maintains the underlying key-value store. This architecture follows the standard approach to designing distributed databases (e.g. Google Spanner [31], Hyperledger Fabric [101] or Callinicos [86, 87]) where concurrency control and 2PC are layered on top of the consensus mechanism. Spanner and Hyperledger (built on Paxos and Raft, respectively) are not Byzantine-tolerant, while Callinicos does not support interactive transactions. To the best of our knowledge, ours is the first academic evaluation of HotStuff as a component of a large system.[3] We use ed25519 elliptic-curve digital signatures [15, 42] for both Basil and the transaction layer of TxHotstuff and TxBFT-SMaRt. Additionally, we augmented both BFT baselines to also profit from Basil' reply batching scheme.

Experimental Setup We use CloudLab [2] `m510` machines (8-core 2.0 GHz CPU, 64 GB RAM, 10 GB NIC, 0.15*ms* ping latency) and run experiments for 90 seconds (30s warm-up/cool-down). Clients execute in a closed-loop, reissuing aborted transactions using a standard exponential backoff

[3] We discussed extensively our setup and implementation with the authors of TAPIR and HotStuff. We corresponded with the authors of Callinicos who were unfortunately unable to locate a fully functional version of their system.



(a) Throughput in tx/s

(b) Latency in ms

Figure 4. Application High-level Performance

scheme. We measure the latency of a transaction as the difference between the time the client first invokes a transaction to the time the client is notified that the transaction committed. Each system tolerates $f = 1$ faults ($n = 2f + 1$ for TAPIR, $3f + 1$ for HotStuff and BFT-SMaRt).

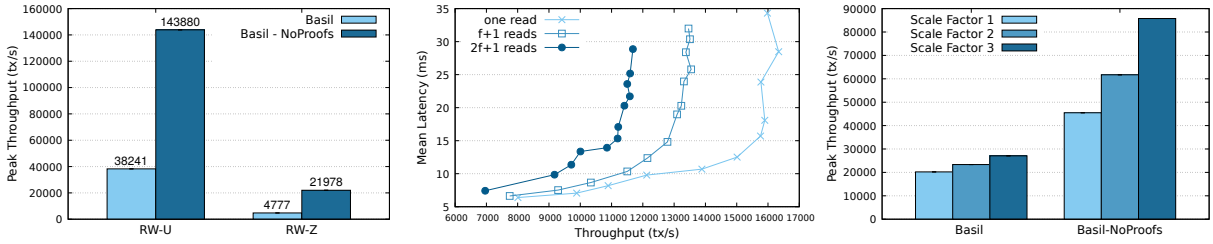
6.1 High-level Performance

We first evaluate Basil against three popular benchmark OLTP applications: TPC-C [103], Smallbank [37], and the Retwis-based transactional workload used to evaluate TAPIR [113]. TPC-C simulates the business logic of an e-commerce framework. We configure it to run with 20 warehouses. As we do not support secondary indices, we create a separate table to (*i*) locate a customer's latest order in the `order status` transaction and (*ii*) lookup customers by last name in the `order status` and `payment` transactions [33, 99]. We configure Smallbank, a simple banking application benchmark, with one million accounts. Access is skewed, with 1,000 accounts being accessed 90% of the time. Users in Retwis, which emulates a simple social network, similarly follow a moderately skewed Zipfian distribution (0.75). Figures 4a and 4b reports results for the three applications.

TPC-C Basil's TPC-C throughput is 5.2x higher than TxHotstuff's and 3.8x higher than TxBFT-SMaRt's – but 4.1x lower than TAPIR's. All these systems are contention-bottlenecked on the read-write conflict between `payment` and `new-order`. Basil has 4.2x higher latency than TAPIR: this increases the conflict window of contending transactions, and thus the probability of aborts. Basil's higher latency stems from (*i*) its replicas need for signing and verifying signatures; (*ii*) its larger quorum sizes for both read and prepare phases; and (*iii*) its need to validate read/prepare replies at clients.

Throughput in Basil is higher than in TxHotStuff and TxBFT-SMaRt. Basil's superior performance is directly linked to its lower latency (2.4x lower than TxHotstuff, 1.2x lower than TxBFT-SMaRt). By merging 2PC with agreement, Basil allows transactions to decide whether to commit or abort in a single round-trip 96% of the time (through its fast path) . TxHotstuff and TxBFT-SMaRt, which layer a 2PC protocol over a black-box consensus instance, must instead process and order two requests for each decision (one to Prepare, and one to Commit/Abort), each requiring multiple roundtrips. In particular, Hotstuff and BFT-SMaRT incur respectively nine and five message delays before returning the Prepare result to clients. In a contention-heavy application like TPC-C, this higher latency translates directly into lower throughput, since it significantly increases the chances that transactions will conflict. Indeed, for these applications layering transaction processing on top of state machine replication actually turns a classic performance booster for state machine replication—running agreement on large batches—into a liability, as large batches increase latency and encourage clients to operate in lock-step, increasing contention artificially. In practice, we find that TxHotstuff and TxBFT-SMaRt perform best with comparatively small batches (four transactions for TxHotStuff, 16 for TxBFT-SMaRT).

Smallbank and Retwis Basil is only 1.8/2.6x slower than TAPIR for these workloads, which are resource bottlenecked for both systems. The lower contention in Smallbank and Retwis (due to the relatively small transactions) allows Basil to use a batch size of 16 for signature generation (up from 4 in TPC-C), thus lowering the cryptographic overhead that Basil pays over TAPIR. With this larger batch, both TAPIR and Basil are bottlenecked on message serialization/deserialization and networking overheads. Because of their higher latency, however, TxHotStuff and TxBFT-SMaRt continue to be contention bottlenecked: Basil's commit rates for Smallbank and Retwis are respectively 93% and 98%, but for TxHotStuff they drop to 75% and 85% and for TxBFT-SMaRt to 85% for both benchmarks. Even on their best configuration (batch size of 16 for TxHotStuff and 64 for TxBFT-SMaRt), Basil outperforms them, respectively, by 3.7x and 2.7x on Smallbank, and by 4.8x and 3.9x on Retwis.



(a) Impact of signatures **(b)** Impact of read quorums **(c)** Impact of shard count

Figure 5. BFT Overheads

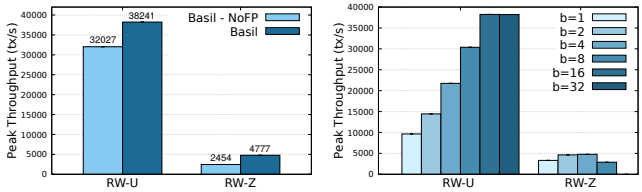
6.2 BFT Overheads

Besides additional replicas (from $2f+1$ to $5f+1$), tolerance to Byzantine faults requires both additional cryptography to preserve Byz-serializability and more expensive reads to preserve Byzantine independence. To evaluate these overheads, we configure the YCSB-T microbenchmark suite [30] to implement a simple workload of identical transactions over ten million keys. We distinguish between a uniform workload (*RW-U*) and a Zipfian workload (*RW-Z*) with coefficient 0.9.

We first quantify the cost of cryptography. To do so, we measure the relative throughput of Basil with and without signatures. Transactions consist of two reads and two writes. Figure 5a describes our results. We find that Basil without cryptography performs 3.7x better than Basil with cryptography on the uniform workload, and up to 4.6x better on the skewed workload. Without cryptography, Basil can use cores that would have been dedicated for signing/ signature verification for regular operation processing. This effect is more pronounced on the skewed workload as reducing latency (through increased operation parallelism, lack of batching, and absence of signing/verification latency) reduces contention, and thus further increases throughput.

In all sharded BFT systems, the number of signatures necessary per transaction grows linearly with the number of shards: each replica must verify that other shards also voted to commit/abort a transaction before finalizing the transaction decision locally. This requires a signature per shard. In Figure 5c, we quantify this cost by increasing the number of shards from one to three on the CPU-bottlenecked *RW-U* workload (three reads/writes). Basil without cryptography increases by a factor of 1.9 (on average, transactions with three read operations will touch two distinct shards). In contrast, Basil's throughput increases by only 1.3x.

To guarantee Byzantine independence, individual clients must receive responses from $f+1$ replicas instead of a single replica. Reading from $2f+1$ replicas (thus sending to 3f+1) increases the chances of a transaction acquiring a valid dependency over reading outdated data. We measure the relative cost of these different read quorum sizes in Figure 5b. We use a simple read-only workload of 24 operations per transaction, and a batch size of 16. Unsurprisingly, increasing the number of read operations increases the load on each replica due to the (*i*) additional signature generations that must be performed, and (*ii*) the additional messages that must be processed. Throughput decreases by 20% when reading from $f+1$ replicas (instead of one), and a further 16% when reading from $2f+1$.



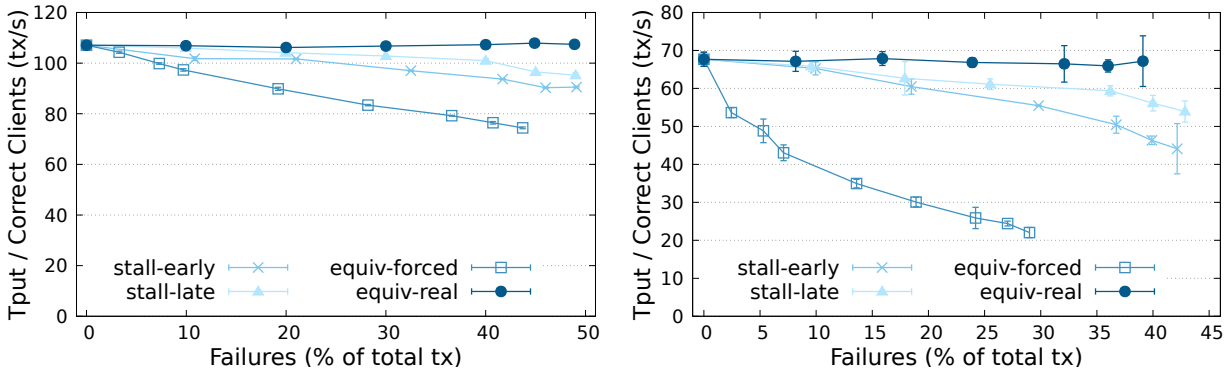
(a) Throughput with/without fast path **(b)** Throughput vs. batch size

Figure 6. Basil Optimizations

6.3 Basil Optimizations

We measure how Basil's performance benefits from batching and from its fast path option. We report results for YCBS-T with and without fast path (NoFP) on a workload of two reads and two writes (Figure 6a). For the uniform workload, enabling fast paths leads to a 19% performance increase; the ST2R messages that fast paths save contain a signature that must be verified, but require little additional processing. For a contended Zipfian workload, however, the additional phase incurred by the slow path increases contention (as it increases latency): adding the fast path increases throughput by 49%. Note that Byzantine replicas, by refusing to vote or voting abort, can effectively disable the fast path option; Basil can prevent this by removing consistently uncooperative replicas.

Next, we quantify the effects of batching. We report the throughput for both workloads (transactions consist of two reads and two writes) while changing the batch size from 1 to 32 ((Figure 6b). As expected, on the resource-bottlenecked uniform workload, throughput increases linearly with increased batch size until peaking at 16 (a 4x throughput increase) – at which point additional hashing costs of the batching Merkle tree nullify any further reduction in signature costs. On the Zipfian workload instead, throughput only increases by up 1.4x, peaking at a small batch size of 4, and degrading



(a) Tput vs. Failures (RW-U) **(b)** Tput vs. Failures (RW-Z)

Figure 7. Basil performance under Client Failures

afterwards as higher wait times and batch-induced client lock step increase contention (thus reducing throughput).

6.4 Basil Under Failures

Basil can experience Byzantine failures from both replicas and clients. We have already quantified the effect of Byzantine replicas preventing fast paths (Figure 6a) and, by being unresponsive, forcing $(2f+1)$-sized read quorums (Figure 5b). We then focus here on quantifying the effects of clients failing.

Basil clients are in charge of their own transactions. Byzantine clients can thus only disrupt honest participants when their own transactions conflict with those of correct clients. Otherwise, they hurt only themselves. A Byzantine client's best strategy for successfully disrupting execution is (*i*) to follow the (estimated/observed) workload access distribution (only contending transactions cause conflicts), (*ii*) choose conservative timestamps (only committing transactions cause conflicts) and (*iii*) delay committing a prepared transaction (forcing dependencies to block, and conflicts to abort).

Byzantine clients can stall after sending ST1 messages (*stall-early*), or before sending vote certificates V-CERT$_S$ (*stall-late*). To equivocate, they must instead receive votes that allow them to generate, and send to replicas, conflicting V-CERT certificates. We remark that equivocating, and hence triggering the divergent case recovery path, is *not* a strategy that can be pursued deterministically or even just reliably, since its effectiveness depends on the luck of the draw in the composition of ST1R's quorum. We evaluate two scenarios: a worst-case, in which we artificially allow clients to always equivocate (*equiv-forced*), and a realistic setup where clients only equivocate when the set of messages received allows them to (*equiv-real*). For both scenarios, we report the throughput of correct clients (measured in $tx/s/client_{correct}$). We keep a constant number of clients, a fraction of which exhibits Byzantine behavior in some percentage of their newly admitted transactions; we refer to those transactions as faulty). Faulty transactions that abort because of contention are not retried, while correct transactions that abort for the same reason may need to re-execute (and hence prepare) multiple times until they commit. When measuring throughput, we report the percentage of faulty transactions as a fraction of all processed (not admitted) transactions. Figures 7a and 7b illustrate our results.

For the RW-U workload, the additional CPU cost of fallback invocations on the CPU-bottlenecked servers causes correct clients' throughput to decrease slowly and linearly. Clients invoke fallbacks only rarely, as there is no contention. Moreover, stalled transactions can be finished in a single round-trip (a pair of RP, RPR) messages thanks to the fallback's common case and fast path. The small throughput drop over *stall-late* is an artefact of Byzantine clients directly starting a new transaction before finishing the old one, increasing the throughput of malicious clients over correct ones. The cost of forced equivocation is higher as it requires three rounds of message processing (fallback invocation, election, and decision adoption). In reality, *equiv-real* sees no throughput drop, as the lack of contention makes equivocation impossible: Byzantine clients cannot build the necessary conflicting V-CERT's.

The RW-Z workload is instead contention-bottlenecked: higher latency implies more conflicts, and thus lower throughput. The impact of *stall-late* stalls remains small, as all affected clients still recover the transaction on the common case fast path (incurring only one extra roundtrip). The performance degradation is slightly higher in *stall-early*, as stalled-early transactions do not finish the transactions on which they depend before stalling. Instead, affected correct clients must themselves invoke the fallback for stalled dependent transactions, which increases latency. In practice, dependency chains remain small: because of the Zipfian nature of the workload, correct clients quickly notice stalled transactions and aggressively finish them. We note that stalled transactions do not themselves increase contention: Basil allows the stalled writes of prepared but uncommitted transactions to become visible to other clients as dependencies. A stalled transaction

thus causes dependency chains to grow, but does not increase the conflict window. The throughput drop that results from forcing equivocation failures is, in contrast, significant: equivocation requires three round-trip to resolve and may lead to transactions aborting and to cascading aborts in dependency chains. In practice, Byzantine clients in *equiv-real* are once again rarely successful in obtaining the conflicting ST1R messages necessary to equivocate, even in a contended workload (0.048% of the time for 40 % faulty transactions) as 99% of transactions commit or abort on the fast path.

Basil expects some level of cooperation from its participants and can remove, without prejudice, clients that frequently stall or timeout (in addition to explicitly misbehaving clients). To avoid spurious accusations towards correct clients, such exclusion policies can be lenient, since Basil's throughput remains robust even with high failure rates.

7 Related Work

State machine replication (SMR) [96] maintains a total order of requests across replicas, both in the crash failure model [27, 53, 61–64, 66, 69, 71, 84, 85, 104]) and in the Byzantine setting [12, 19, 23, 25, 28, 29, 38, 46, 47, 56, 57, 65, 70, 74, 76, 92, 108, 110], where they have been used as a main building block of Blockchain systems [6, 9, 10, 13, 23, 45, 55, 101]. To maintain a total order abstraction, existing systems process all operations sequentially (for both agreement and execution), thus limiting scalability for commutative workloads. They are, in addition, primarily leader-based which introduces additional scalability bottlenecks [81, 98, 113] as well as fairness concerns. Rotating leaders [23, 29, 110] reduce fairness concerns, and multiple-leader based systems [12, 67, 81, 98] increase throughput. Recent work [50, 54, 60, 114] discusses how to improve fairness in BFT leader-based systems with supplementary ordering layers and censorship resilience. Basil sidesteps these concerns by adopting a leaderless approach and addresses the effects of Byzantine actors beyond ordering through the stronger notion of Byzantine Independence.

Fine-grained ordering Existing replicated systems in the crash-failure model leverage operation semantics to allow commutative operations to execute concurrently [58, 63, 68, 81–83, 89, 100, 107, 113]. This work is much rarer in the BFT context, with Byblos [14] and Zzyzyx [49] being the only BFT protocol that seek to leverage commutativity. However, unlike Basil, Byblos is limited to a static transaction model and introduces blocking between transactions that are *potentially* concurrent with other conflicting transactions; while Zzyzyx resorts to a SMR substrate protocol under contention. Other existing Quorum-based systems naturally allow for non-conflicting operations to execute concurrently, but do not provide transactions [7, 32, 72, 75].

Sharding Some Blockchains rely on sharding to parallelize independent transactions, but continue to rely on a total-order primitive within shards [9, 55, 111]. As others in the crash-failure model have highlighted [83, 112, 113], this approach incurs redundant coordination and fails to fully leverage the available parallelism within a workload.

DAGs Other permissionless Blockchains use directed acyclic graphs rather than chains [91, 93, 95], but require dependencies and conflicts to be known prior to execution.

Byzantine Databases Basil argues that BFT systems and Blockchains are in fact simply databases and draws on prior work in BFT databases. HRDB [105] offers interactive transactions for a replicated database, but relies on a trusted coordination layer. Byzantium [43] designs a middleware system that utilizes PBFT as atomic broadcast (AB) and provides Snapshot Isolation using a primary backup validation scheme. Augustus [87] leverages sharding for scalability in the mini-transaction model [8] and relies on AB to implement an optimistic locking based execution model. Callinicos [86] extends Augustus to support armored-transactions in a multi-round AB protocol that re-orders conflicts for robustness against contention. BFT-DUR [90] builds interactive transactions atop AB, but does not allow for sharding. Basil instead supports general transactions and sharding without a leader or the redundant coordination introduced by atomic broadcast.

Byzantine Clients Basil, being client-driven, must defend against Byzantine clients. It draws from prior work targeted at reducing the severity and frequency of client misbehavior [43, 72, 73, 86, 87, 90] and extends Liskov and Rodrigues' [72] definition of Byz-Linearizability to formalize the first safety and liveness properties for transactional BFT systems.

8 Conclusion

This paper presents Basil, the first leaderless BFT transactional key-value store supporting ACID transactions. Basil offers the *abstraction* of a totally-ordered ledger while supporting highly concurrent transaction processing and ensuring *Byz-serializability*. Basil clients make progress *independently*, while *Byzantine Independence* limits the influence of Byzantine participants. During fault and contention-free executions Basil commits transactions in a single round-trip.

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