THE BEDROCK OF BYZANTINE FAULT TOLERANCE: A UNIFIED PLATFORM FOR BFT PROTOCOL DESIGN AND IMPLEMENTATION

Mohammad Javad Amiri1  Chenyuan Wu1  Divyakant Agrawal2
Amr El Abbadi2  Boon Thau Loo1  Mohammad Sadoghi3
1Department of Computer and Information Science, University of Pennsylvania
2Department of Computer Science, University of California Santa Barbara
3Department of Computer Science, University of California Davis

{mjamiri, wucy, boonloo}@seas.upenn.edu, {agrawal, amr}@cs.ucsb.edu, msadoghi@ucdavis.edu

ABSTRACT

Byzantine Fault-Tolerant (BFT) protocols have recently been extensively used by decentralized data management systems with non-trustworthy infrastructures, e.g., permissioned blockchains. BFT protocols cover a broad spectrum of design dimensions from infrastructure settings such as the communication topology, to more technical features such as commitment strategy and even fundamental social choice properties like order-fairness. The proliferation of different BFT protocols has rendered it difficult to navigate the BFT landscape, let alone determine the protocol that best meets application needs. This paper presents BEDROCK, a unified platform for BFT protocols design, analysis, implementation, and experiments. BEDROCK proposes a design space consisting of a set of design choices capturing the trade-offs between different design space dimensions and providing fundamentally new insights into the strengths and weaknesses of BFT protocols. BEDROCK enables users to analyze and experiment with BFT protocols within the space of plausible choices, evolve current protocols to design new ones, and even uncover previously unknown protocols. Our experimental results demonstrate the capability of BEDROCK to uniformly evaluate BFT protocols in new ways that were not possible before due to the diverse assumptions made by these protocols. The results validate BEDROCK’s ability to analyze and derive BFT protocols.

1 Introduction

Large-scale data management systems rely on fault-tolerant protocols to provide robustness and high availability [41,54,60,82,94,132,181]. While cloud systems, e.g., Google’s Spanner [82], Amazon’s Dynamo [94], and Facebook’s Tao [60], rely on crash fault-tolerant protocols, e.g., Paxos [150], to establish consensus, a Byzantine fault-tolerant (BFT) protocol is a key ingredient in decentralized data management systems with non-trustworthy infrastructures. In particular, a BFT protocol is the core component of the most recent large-scale data management system, permissioned blockchains [1–3,24,27,29,30,43,64,78,116–118,125,148,197,204,207]. BFT protocols have also been used in permissionless blockchains [61,140,142,168,231], distributed file systems [13,70,80], locking service [81], firewalls [52,112,113,203,214,229], certificate authority systems [235], SCADA systems [39,139,189,234], key-value datastores [50,98,115,128,203], and key management [171].

BFT protocols use the State Machine Replication (SMR) technique [149,205] to ensure that non-faulty replicas execute client requests in the same order despite the concurrent failure of $f$ Byzantine replicas. BFT SMR protocols are different along several dimensions, including the number of replicas, processing strategy (i.e., optimistic, pessimistic, or robust), supporting load balancing, etc. While dependencies and trade-offs among these dimensions lead to several design choices, there is currently no unifying tool that provides the foundations for studying and analyzing BFT protocols' design dimensions and their trade-offs. We envision that such a unifying foundation will be based on an in-depth understanding of existing BFT protocols and trade-offs among dimensions; and include an API that allows protocol designers to choose among several dimensions, and find a protocol that best fits the characteristics of their applications.

This paper presents BEDROCK, a unified platform that enables us to design, analyze, discover, implement, and experiment with partially asynchronous SMR BFT protocols within the design space of possible variants. It provides an
API that enables BFT protocol designers to analyze and experiment with BFT protocols and their trade-offs and even derive new protocols. Application developers also can query their required BFT protocol characteristics where the platform responds with a list of candidate BFT protocols that match the given query and enables them to choose the BFT protocol that best fits the characteristics of their applications.

**BEDROCK** presents a design space to characterize BFT protocols based on different dimensions that capture the environmental settings, protocol structure, QoS features, and performance optimizations. Each protocol is a plausible point in the design space. Within the design space, **BEDROCK** defines a set of design choices that demonstrate trade-offs between different dimensions. For example, the communication complexity can be reduced by increasing the number of communication phases or the number of phases can be reduced by adding more replicas. Each design choice expresses a one-to-one transformation function to map a plausible input point (i.e., a BFT protocol) to a plausible output point (i.e., another BFT protocol) in the design space.

**BEDROCK** can be used to analyze and navigate the evergrowing BFT landscape to principally compare and differentiate among BFT protocols. On one hand, **BEDROCK** design space and its design choices give fundamentally new insights into the strengths and weaknesses of existing BFT protocols. On the other hand, **BEDROCK** enables new ways to experimentally evaluate BFT protocols by providing a unified deployment and experimentation environment, resulting in the ability to compare different protocols proposed in diverse settings and contexts under one unified framework.

The **BEDROCK** tool has several practical uses:

- **Analyze and experiment with existing BFT protocols.** First, **BEDROCK** supports within one unified platform a wide range of existing BFT protocols, e.g., PBFT [71], SBFT [120], HotStuff [230], Kauri [186], Themis [135], Tendermint [63], Prime [22], PoE [123], CheapBFT [133], Q/U [4], FaB [174], and Zyzzyva [143].

- **Evolve an existing protocol to derive new variants.** Second, a key benefit of **BEDROCK** is in evolving existing protocols to propose new variants. This incremental design paradigm allows one to adapt a BFT implementation over time to suit the deployment environment. For example, we can derive new protocol variants from the well-known PBFT [71] protocol using a subset of design choices.

- **Uncover new protocols.** Finally, **BEDROCK** can also enable us to discover new protocols in the design space simply by combining different design choices not previously explored. As a proof of concept, we present two new protocol instances: a Fast Linear BFT protocol (FLB), that establishes consensus in two linear communication phases, and a Fast Tree-based balanced BFT protocol (FTB) that supports load balancing.

The paper makes the following contributions.

- **Unified design space.** A design space for BFT protocols and a set of design choices is proposed. The proposed design space captures fundamentally new insights into the characteristics, strengths and weaknesses of BFT protocols and their design trade-offs. Moreover, studying the design space of BFT protocols leads to identifying several plausible points that have not yet been explored.

- **Unified platform.** We present the design and implementation of **BEDROCK**, a tool that aims to unify all BFT protocols within a single platform. **BEDROCK** derives valid BFT protocols by combining different design choices.

- **Implementation and evaluation.** Within **BEDROCK**, a wide range of BFT protocols are implemented and evaluated. This unified deployment and experimentation environment provides new opportunities to evaluate and compare different existing BFT protocols in a fair and more efficient manner (e.g., identical programming language, used libraries, cryptographic tools, etc).

The rest of this paper is organized as follows. Section 2 introduces **BEDROCK**. The design space of **BEDROCK** and its design choices are presented in Sections 3 and 4. Section 5 maps some of the known BFT protocols and two new BFT protocols, FLB and FTB, to the design space. The implementation of **BEDROCK** is introduced in Section 6. Section 7 shows the experimental results, Section 8 discusses the related work, and Section 9 concludes the paper.

## 2 The **BEDROCK** Overview

**System model.** A BFT protocol runs on a network consisting of a set of nodes that may exhibit arbitrary, potentially malicious, behavior. BFT protocols use the State Machine Replication (SMR) algorithm [149, 205] where the system provides a replicated service whose state is mirrored across different deterministic replicas. At a high level, the goal of a BFT SMR protocol is to assign each client request an order in the global service history and execute it in that order [210]. In a BFT SMR protocol, all non-faulty replicas execute the same requests in the same order (safety) and all correct client
requests are eventually executed (\textit{liveness}). In an asynchronous system, where replicas can fail, there are no consensus solutions that guarantees both safety and liveness (FLP result) \cite{109}. As a result, asynchronous consensus protocols rely on different techniques such as randomization \cite{46,67,198}, failure detectors \cite{76,169}, hybridization/wormholes \cite{83,188} and partial synchrony \cite{100,103} to circumvent the FLP impossibility result.

\textit{BEDROCK} assumes the partially synchrony model as it is used in most practical BFT protocols. In the partially synchrony model, there exists an unknown global stabilization time (GST), after which all messages between correct replicas are received within some unknown bound $\Delta$. \textit{BEDROCK} further inherits the standard assumptions of existing BFT protocols. First, while there is no upper bound on the number of faulty clients, the maximum number of concurrent malicious replicas is assumed to be $f$. Second, replicas are connected via an unreliable network that might drop, corrupt, or delay messages. Third, the network uses point-to-point bi-directional communication channels to connect replicas. Fourth, the failure of replicas is independent of each other, where a single fault does not lead to the failure of multiple replicas. This can be achieved by either diversifying replica implementation (e.g., \textit{n-version programming}) \cite{38,110} or placing replicas at different geographic locations (e.g., datacenters) \cite{49,104,213,223}. Finally, a strong adversary can coordinate malicious replicas and delay communication. However, the adversary cannot subvert cryptographic assumptions.

\textbf{Usage model.} \textit{BEDROCK} aims to help application developers experimentally analyze BFT protocols within one unified platform and find the BFT protocol that fits the characteristics of their applications. To achieve this goal, the \textit{BEDROCK} tool makes available the design dimensions of BFT protocols and different design choices, i.e., trade-offs between dimensions, to application developers to tune. Figure 1 illustrates an example highlighting the relation between design space, dimensions, design choices, and protocols in \textit{BEDROCK}. For the sake of simplicity, we present only two dimensions of the design space, i.e., number of replicas and number of commitment phases (the design space of \textit{BEDROCK} consists of more than 10 dimensions as described in Section 3). Each dimension, e.g., number of replicas, can take different values, e.g., $3f+1, 5f+1, 7f+1$, etc. A BFT protocol is then a point in this design space, e.g., $(3, 3f+1)$. Note that each dimension not presented in this figure also takes a value, e.g., communication strategy is assumed to be pessimistic.

Moreover, a subset of points is valid and represents BFT protocols. In Figure 1, green dots (●) specify valid points (i.e., BFT protocols) while red dots (●) show invalid points (i.e., impossible protocols). For example, there is no (pessimistic) BFT protocol with $3f+1$ nodes that commits requests in a single commitment phase. A design choice (Section 4) is then a one-to-one function that maps a BFT protocol in its domain to another protocol in its range. For example, phase reduction (through redundancy) maps a BFT protocol with $3f+1$ nodes and 3 phases of communication, e.g., PBFT \cite{71}, to a BFT protocol with $5f+1$ nodes and 2 phases of communication, e.g., FaB \cite{174} (assuming both protocols are pessimistic and follow clique topology). The domain and range of each design choice is a subset of BFT protocols in the design space.

In a BFT protocol, as presented in Figure 2, clients communicate with a set of replicas that maintain a copy of the application state. A replica’s lifecycle consists of ordering, execution, view-change, checkpointing, and recovery stages. The goal of the ordering stage is to establish agreement on a unique order, among requests executing on the application state. In leader-based consensus protocols, which are the focus of this paper, a designated \textit{leader} node proposes the order, and to ensure fault tolerance, needs to get agreement from a subset of the nodes, referred to as a \textit{quorum}. In the execution stage, requests are applied to the replicated state machine. The view-change stage replaces the current leader. Checkpointing is used to garbage-collect data and enable trailing replicas to catch up, and finally, the recovery stage recovers replicas from faults by applying software rejuvenation techniques.
3 Design Space

In BEDROCK, each BFT protocol can be analyzed along several dimensions. These dimensions (and values associated with each dimension) collectively help to define the overall design space of BFT protocols supported by BEDROCK. The dimensions are categorized into four families: environmental settings and protocol structure that present the core dimensions of BFT protocols and are shared among all BFT protocols, a set of optional QoS features including order-fairness and load balancing that a BFT protocol might support, and a set of performance optimizations for tuning BFT protocols. In the rest of this section, we describe these families of dimensions in greater detail. As we describe each dimension, we prefix label them with "E" for environmental settings, "P" for protocol structure, etc. Hence, "E1" refers to the first dimension in the environmental settings dimensions family.

This section is not meant to provide a fully exhaustive set of dimensions, but rather to demonstrate the overall methodology used to define dimensions usable in BEDROCK.

3.1 Environmental Settings

Environmental settings broadly speaking encompass the deployment environment for a BFT protocol, e.g., network size. These input parameters help scope the class of BFT protocols that can be supported to best fit each deployment environment.

E1: Number of replicas. Our first dimension concerns selecting BFT protocols based on the number of replicas (i.e., network and quorum size) used in a deployment. In the presence of $f$ malicious failures, BFT protocols require at least $3f+1$ replicas to guarantee safety [56, 57, 86, 103, 156]. Using trusted hardware, however, the malicious behavior of replicas can be restricted. Hence, $2f+1$ replicas are sufficient to guarantee safety [79, 85, 87, 200, 223, 222, 224]. Prior proposals on reducing the required number of replicas to $2f+1$ [14–16] involve either leveraging new hardware capabilities or using message-and-memory models. Increasing the number of replicas to $5f+1$ [174] (its proven lower bound, $5f−1$ [11, 147] or $7f+1$ [212], on the other hand, reduces the number of communication phases. A BFT protocol might also optimistically assume the existence of a quorum of $2f+1$ active non-faulty replicas to establish consensus [96, 133]. Using both trusted hardware and active/passive replication, the quorum size is further reduced to $f+1$ during failure-free situations [96, 97, 133].

E2: Communication topology. BEDROCK allows users to analyze BFT protocols based on communication topologies including: (1) the star topology where communication is strictly from a designated replica, e.g., the leader, to all other replicas and vice-versa, resulting in linear message complexity [143, 230], (2) the clique topology where all (or a subset of) replicas communicate directly with each other resulting in quadratic message complexity [71], (3) the tree topology where the replicas are organized in a tree with the leader placed at the root, and at each phase, a replica communicates with either its child replicas or its parent replica causing logarithmic message complexity [140, 141, 186], or (4) the chain topology where replicas construct a pipeline and each replica communicates with its successor replica (constant message complexity) [35].

E3: Authentication. Participants authenticate their messages to enable other replicas to verify a message’s origin. BEDROCK support both signatures, e.g., RSA [202] and authenticators [71], i.e., vectors of message authentication codes (MACs) [219]. Constant-sized threshold signatures [67, 208] have also been used to reduce the size of a set (quorum) of signatures. Signatures are typically more costly than MACs. However, in contrast to MACs, signatures provide non-repudiation and are not vulnerable to MAC-based attacks from malicious clients. A BFT protocol might even use different techniques (i.e., signatures and MACs) in different stages to authenticate messages sent by clients, by replicas in the ordering stage, and by replicas during view-change.

E4: Responsiveness, Synchronization and Timers. A BFT protocol is responsive if its normal case commit latency depends only on the actual network delay needed for replicas to process and exchange messages rather than any (usually much larger) predefined upper bound on message transmission delay [34, 192, 193, 209]. Responsiveness might be
sacrificed in different ways. First, when the rotating leader mechanism is used, the new leader might need to wait for a predefined time before initiating the next request to ensure that it receives the decided value from all non-faulty but slow replicas, e.g., Tendermint [148] and Casper [65]. Second, optimistically assuming all replicas are non-faulty, replicas (or clients) need to wait for a predefined upper bound to receive messages from all replicas, e.g., SBFT [120] and Zyzzyva [143].

BFT protocols need to guarantee that all non-faulty replicas will eventually be synchronized to the same view with a non-faulty leader enabling the leader to collect the decided values in previous views and making progress in the new view [59, 182, 183]. This is needed because a quorum of $2f + 1$ replicas might include $f$ Byzantine replicas and the remaining $f$ "slow" non-faulty replicas might stay behind (i.e., in-dark) and may not even advance views at all. View synchronization can be achieved in different ways such as integrating the functionality with the core consensus protocol, e.g., PBFT [71], or assigning a distinct synchronizer component, e.g., Pacemaker in HotStuff [230], and hardware clocks [5].

Depending on the environment, network characteristics, and processing strategy, BFT protocols use different timers to ensure responsiveness and synchronization. Protocols can be configured with the following timers by BEDROCK to achieve these goals.

\[\begin{align*}
\tau_1. \text{ Waiting for reply messages, e.g., Zyzzyva [143],} \\
\tau_2. \text{ Triggering (consecutive) view-change, e.g., PBFT [71],} \\
\tau_3. \text{ Detecting backup failures, e.g., SBFT [120],} \\
\tau_4. \text{ Quorum construction in an ordering phase, e.g., prevote and precommit timeouts in Tendermint [62],} \\
\tau_5. \text{ Synchronization for view change, e.g., Tendermint [62],} \\
\tau_6. \text{ Finishing a (preordering) round, e.g., Themis [135],} \\
\tau_7. \text{ Performance check (heartbeat timer), e.g., Aardvark [81],} \\
\tau_8. \text{ Atomic recovery (watchdog timer) to periodically hand control to a recovery monitor [69], e.g., PBFT [70].}
\end{align*}\]

3.2 Protocol Structure

Our next family of dimensions concerns customization of the protocol structure by BEDROCK, which will further define the class of protocols permitted.

P 1: Commitment strategy. BEDROCK supports BFT protocols that process transactions in either an optimistic, pessimistic, or robust manner. Optimistic BFT protocols make optimistic assumptions on failures, synchrony, or data contention and might execute requests without necessarily establishing consensus. An optimistic BFT protocol might make a subset of the following assumptions:

\[\begin{align*}
a_1. \text{ The leader is non-faulty, assigns a correct order to requests and sends it to all backups, e.g., Zyzzyva [143],} \\
a_2. \text{ The backups are non-faulty and actively and honestly participate in the protocol, e.g., CheapBFT [133],} \\
a_3. \text{ All non-leaf replicas in a tree topology are non-faulty, e.g., Kauri [186],} \\
a_4. \text{ The workload is conflict-free and concurrent requests update disjoint sets of data objects, e.g., Q/U [4],} \\
a_5. \text{ The clients are honest, e.g., Quorum [35], and} \\
a_6. \text{ The network is synchronous (in a time window), and messages are not lost or highly delayed, e.g., Tendermint [62].}
\end{align*}\]

Optimistic protocols are classified into speculative and non-speculative protocols. In non-speculative protocols, e.g., SBFT [120] and CheapBFT [133], replicas execute a transaction only if the optimistic assumption holds. Speculative protocols, e.g., Zyzzyva [143] and PoE [123], on the other hand, optimistically execute transactions. If the assumption is not fulfilled, replicas might have to rollback the executed transactions. Optimistic BFT protocols improve performance in fault-free situations. If the assumption does not hold, the replicas, e.g., SBFT [120], or clients, e.g., Zyzzyva [143], detect the failure and use the fallback protocol.

Pessimistic BFT protocols, on the other hand, tolerate the maximum number of possible concurrent failures $f$ without making any assumptions on failures, synchrony, or data contention. In pessimistic BFT protocols, replicas communicate to agree on the order of requests. Finally, robust protocols, e.g., Prime [22], Aardvark [81], R-Aliph [35], Spinning [222] and RBFT [36], go one step further and consider scenarios where the system is under attack.
In summary, BFT protocols demonstrate different performance in failure-free, low failure, and under attack situations. Optimistic protocols deliver superior performance in failure-free situations. However, in the presence of failure, their performance is significantly reduced especially when the system is under attack. On the other hand, pessimistic protocols provide high performance in failure-free situations and are able to handle low failures with acceptable overhead. However, they show poor performance when the system is under attack. Finally, robust protocols are designed for under-attack situations and demonstrate moderate performance in all three situations.

**P 2: Number of commitment phases.** The number of commitment (ordering) phases or good-case latency [11] of a BFT SMR protocol is the number of phases needed for all non-faulty replicas to commit when the leader is non-faulty, and the network is synchronous. We consider the number of commitment phases from the first time a replica (typically the leader) receives a request to the first time any participant (i.e., leader, backups, client) learns the commitment of the request, e.g., PBFT executes in 3 phases.

**P 3: View-change.** BFT protocols follow either the stable leader or the rotating leader mechanism to replace the current leader. The stable leader mechanism [71, 120, 143, 174] replaces the leader when the leader is suspected to be faulty by other replicas. In the rotating leader mechanism [19, 64, 72–74, 81, 114, 127, 141, 148, 222, 223, 230], the leader is replaced periodically, e.g., after a single attempt, insufficient performance, or an epoch (multiple requests). Using the stable leader mechanism, the view-change stage becomes more complex. However, the routine is only executed when the leader is suspected to be faulty. On the other hand, the rotating leader mechanism requires ensuring view synchronization frequently (whenever the leader is rotated). Rotating the leader has several benefits such as balancing load across replicas [44, 45, 222], improving resilience against slow replicas [81], and minimizing communication delays between clients and the leader [104, 173, 223].

**P 4: Checkpointing.** The checkpointing mechanism is used to first, garbage-collect data of completed consensus instances to save space and second, restore in-dark replicas (due to network unreliability or leader maliciousness) to ensure all non-faulty replicas are up-to-date [71, 95, 123]. The checkpointing stage typically is initiated after a fixed checkpoint window in a decentralized manner without relying on a leader [71].

**P 5: Recovery.** When there are more than \( f \) failures, BFT protocols, apart from some exceptions [79, 164], completely fail and do not give any guarantees on their behavior [95]. BFT protocols perform recovery using reactive or proactive mechanisms (or a combination [214]). Reactive recovery mechanisms detect faulty replica behavior [126] and recover the replica by applying software rejuvenation techniques [90, 130] where the replica reboots, reestablishes its connection with other replicas and clients, and updates its state. On the other hand, proactive recovery mechanisms recover replicas in periodic time intervals. Proactive mechanisms do not require any fault detection techniques, however, they might unnecessarily recover non-faulty replicas [95]. During recovery, a replica is unavailable. A BFT protocol can rely on \( 3f + 2k + 1 \) replicas to improve resilience and availability during recovery where \( k \) is the maximum number of servers that rejuvenate concurrently [214]. To prevent attackers from disrupting the recovery process, each replica requires a trusted component, e.g., secure coprocessor [70], a synchronous wormhole [221] or a virtualization layer [97, 200], that remains operational even if the attacker controls the replica and a read-only memory that an attacker cannot manipulate. The memory content remains persistent (e.g., on disk) across machine reboots and includes all information needed for bootstrapping a correct replica after restart [95].

**P 6: Types of Clients.** BEDROCK supports three types of clients: requester, proposer, and repairer. Requester clients perform a basic functionality and communicate with replicas by sending requests and receiving replies. A requester client might need to verify the results by waiting for a number of matching replies, e.g., \( f + 1 \) in PBFT [71], \( 2f + 1 \) in PoE [123] and PBFT [71] (for read-only requests), or \( 3f + 1 \) is Zyzzyva [143]. Using trusted components, e.g., Troxy [161], or threshold signatures, e.g., SBFT [120], the client does not even need to wait for and verify multiple results from replicas. Clients might also play the proposer role by proposing a sequence number (acting as the leader) for its request [4, 119, 170, 172]. Repairer clients, on the other hand, detect the failure of replicas, e.g., Zyzzyva [143], or even change the protocol configuration, e.g., Scrooge [206], Abstract [35], and Q/U [4].

### 3.3 Quality of Service

There are some optional QoS features that BEDROCK can analyze. We list two example dimensions.

**Q 1: Order fairness.** Order-fairness deals with preventing adversarial manipulation of request ordering [40, 135, 136, 145, 146, 233]. Order-fairness is defined as: "if a large number of replicas receives a request \( t_i \) before another request \( t_j \), then \( t_i \) should be ordered before \( t_j \)" [136]. Order fairness has been partially addressed using different techniques: (1) monitoring the leader to ensure it does not initiate two new requests from the same client before initiating an old request of another client, e.g., Aardvark [81], (2) adding a preordering phase, e.g., Prime [22], where replicas order the received requests locally and share their own ordering with each other, (3) encrypting requests and revealing the
contents only once their ordering is fixed [33, 66, 177, 216], (4) reputation-based systems [33, 93, 142, 159] to detect unfair censorship of specific client requests, and (5) providing opportunities for every replica to propose and commit its requests using fair election [8, 33, 114, 137, 159, 192, 228].

**Q 2: Load balancing.** The performance of fault-tolerant protocols is usually limited by the computing and bandwidth capacity of the leader [17, 53, 77, 179, 180, 186, 226]. The leader coordinates the consensus protocol and multicasts/collects messages to all other replicas in different protocol phases. Load balancing is defined as distributing the load among the replicas of the system to balance the number of messages any single replica has to process.

Load balancing can be partially achieved using the rotating leader mechanism, multi-layer, or multi-leader BFT protocols. When the rotating leader mechanism is used, one (leader) replica is still highly loaded in each consensus instance. In multi-layer BFT protocols [23, 125, 165, 185, 187] the load of the leader is distributed between the leaders of different clusters. However, the system still suffers from load imbalance between the leader and backup replicas in each cluster. In multi-leader protocols [20, 31, 37, 124, 215, 225], all replicas can initiate consensus to partially order requests in parallel. However, slow replicas still affect the global ordering of requests.

### 3.4 Performance Optimization Dimensions

Finally, we present a set of optimization dimensions that target the performance of a BFT protocol.

**O 1: Out-of-order processing.** The out-of-order processing mechanism enables the leader to continuously propose new requests even when previous requests are still being processed by the backups [123]. Out-of-order processing of requests is possible if the leader does not need to include any certificate or hash of the previous request (block) in its next request.

**O 2: Request pipelining.** Using request pipelining, the messages of a new consensus instance are piggybacked on the second round messages of the previous instance [186, 230]. This technique is especially efficient when a protocol rotates the leader after every consensus instance.

**O 3: Parallel ordering.** Client requests can be ordered in parallel by relying on a set of independent ordering groups [44, 45, 162] where each group orders a subset of client requests and then all results are deterministically merged into the final order. Similarly, in multi-leader protocols [20, 31, 32, 37, 105, 124, 162, 178, 215, 225, 225], different replicas are designated as the leader for different consensus instances in parallel and then a global order is determined.

**O 4: Parallel execution.** Transactions can be executed in parallel to improve the system’s overall performance. One approach is to detect non-conflicting transactions and execute them in parallel [25, 108, 144]. This approach requires a priori knowledge of a transaction’s read-set and write-set. Switching the order of agreement and execution stages and optimistically executing transactions in parallel is another approach [30, 134]. If the execution results are inconsistent (due to faulty replicas, conflicting transactions, or nondeterministic execution), replicas need to rollback their states and sequentially and deterministically re-execute the requests. switching the order of agreement and execution stages also enables replicas to detect any nondeterministic execution [30, 134].

**O 5: Read-only requests processing.** In pessimistic protocols, replicas can directly execute read-only requests without establishing consensus. However, since replicas may execute the read requests on different states, even non-faulty replicas might not return identical results. To resolve this, the number of required matching replies for both normal and read-only requests needs to be increased from \( f + 1 \) to \( 2f + 1 \) in order to ensure consistency (i.e., quorum intersection requirement) [70]. This, however, results in a liveliness challenge because non-faulty replicas might be slow (or in dark) and not receive the request. As a result, the client might not be able to collect \( 2f + 1 \) matching responses (since Byzantine replicas may not send a correct reply to the client).

**O 6: Separating ordering and execution.** The ordering and execution stages can be separated and implemented in different processes. This separation leads to several advantages [95] such as preventing malicious execution replicas from leaking confidential application state to clients [102, 229], enabling large requests to bypass the ordering stage [80], moving application logic to execution virtual machine [97, 200, 227] or simplifying the parallel ordering of requests [44, 47]. Moreover, while \( 3f + 1 \) replicas are needed for ordering, \( 2f + 1 \) replicas are sufficient to execute transactions [229].

**O 7: Trusted hardware.** Using Trusted execution environments (TEEs) such as Intel’s SGX [175], Sanctum [89], and Keystone [158], the number of required replicas can be lowered to \( 2f + 1 \) because the trusted component prevents a faulty replica from sending conflicting messages to different replicas without being detected. A trusted component may include an entire virtualization layer [97, 200, 223], a multicast ordering service executed on a hardened Linux.
kernel [84, 85], a centralized configuration service [201], a trusted log [79], a trusted platform module, e.g., counter [223, 224], a smart card TrInc [160], or an FPGA [96, 133].

**O 8: Request/reply dissemination.** A client can either multicast its request to *all replicas* [51, 91, 222] where each replica relays the request to the leader or optimistically send its request to a *contact replica*, typically the leader. The contact replica is known to the client through a reply to an earlier request [71, 143]. If the client timer for the request \( (r_f) \) expires, the client multicasts its request to all replicas. This optimistic mechanism requires fewer messages to be sent from clients to the replicas. However, this comes at the cost of increased network traffic between replicas, because the leader needs to disseminate the full request to other replicas to enable them to eventually execute it.

On the other hand, all replicas can send the results to clients in their reply messages. This, however, leads to significant network overhead for large results. A protocol can optimistically rely on a designated responder replica (chosen by the client or servers) to send the full results. Other replicas then either send the hash of the results to the client or send a signed message to the responder enabling the responder to generate a proof for the results, e.g., SBFT [120]. While this technique reduces network overhead, the client might not receive the results if the responder replica is faulty, the network is unreliable, or the responder replica was in-dark and skipped the execution and applied a checkpoint to catch up [95].

4 Design Choices Landscape

Given a set of specified dimension values in Section 3, Bedrock generates a set of valid protocols that meet a user query. Each protocol represents a point in the Bedrock design space. In this section, using the classical PBFT [70, 71] as a driving example, we demonstrate how different points in the design space lead to different trade-offs. Each design choice is a *one-to-one function* that maps a valid input point (i.e., a BFT protocol) to another valid output point in the design space. These design choices enable Bedrock to generate valid BFT protocols.

4.1 Background on PBFT

PBFT, as shown in Figure 3, is a leader-based protocol that operates in a succession of configurations called *views* [106, 107]. Each view is coordinated by a *stable leader* (primary) and the protocol *pessimistically* processes requests. In PBFT, the number of replicas, \( n \), is assumed to be \( 3f + 1 \) and the ordering stage consists of *pre-prepare*, *prepare*, and *commit* phases. The *pre-prepare* phase assigns an order to the request, the *prepare* phase guarantees the uniqueness of the assigned order and the commit phase guarantees that the next leader can assign order in a safe manner.

During a normal case execution of PBFT, clients send their signed request messages to the leader. In the *pre-prepare* phase, the leader assigns a sequence number to the request to determine the execution order of the request and multicasts a *pre-prepare* message including the *full request* to all backups. Upon receiving a valid *pre-prepare* message from the leader, each backup replica multicasts a *prepare* message to all replicas and waits for *prepare* messages from \( 2f \) different replicas (including the replica itself) that match the *pre-prepare* message. The goal of the *pre-prepare* phase is to guarantee safety within the view, i.e., a majority of non-faulty replicas received matching *pre-prepare* messages from the leader replica and agree with the order of the request. Each replica then multicasts a *commit* message to all replicas. Once a replica receives \( 2f + 1 \) valid *commit* messages from different replicas (including itself) that match the *pre-prepare* message, it commits the transaction. The goal of the *commit* phase is to ensure safety across views, i.e., the request has been replicated on a majority of non-faulty replicas. The second and third phases of PBFT follow the *clique* topology, i.e., have \( O(n^2) \) message complexity. If the replica has executed all requests with lower sequence numbers, it executes the transaction and sends a reply to the client. The client waits (timer \( r_f \)) for \( f + 1 \) matching results from different replicas.
In the view change stage, upon detecting the failure of the leader of view \( v \) using timeouts (timer \( \tau_2 \)), backups exchange view-change messages including transactions that have been received by the replicas. After receiving \( 2f + 1 \) view-change messages, the designated stable leader of view \( v + 1 \) (the replica with \( ID = v + 1 \mod n \)) proposes a new view message including a list of transactions that should be processed in the new view.

In PBFT replicas periodically generate and send checkpoint messages to all other replicas. If a replica receives \( 2f + 1 \) matching checkpoint messages, the checkpoint is stable. PBFT also includes a proactive recovery mechanism that periodically (timer \( \tau_8 \)) rejuvenates replicas one by one.

PBFT uses either signatures [71] or MACs [70] for authentication. Using MACs, replicas need to send view-change-ack messages to the leader after receiving view-change messages. Since new view messages are not signed, these view-change-ack enable replicas to verify the authenticity of new view messages.

4.2 Expanding the Design Choices of PBFT

Using the PBFT protocol and our design dimensions as a baseline, we illustrate a series of design choices that expose different trade-offs BFT protocols need to make. Each design choice acts as a one-to-one function that changes the value of one or multiple dimensions to map a BFT protocol, e.g., PBFT, to another BFT protocol.

**Design Choice 1: Linearization.** This function explores a trade-off between communication topology and communication phases. The function takes a quadratic communication phase, e.g., prepare or commit in PBFT, and split it into two linear phases: one phase from all replicas to a collector (typically the leader) and one phase from the collector to all replicas, e.g., SBFT [120], HotStuff [230]. The output protocol requires (threshold) signatures for authentication. The collector collects a quorum of (typically \( n - f \)) signatures from other replicas and broadcasts its message including the signatures as the certificate of receiving messages to every replica. Using threshold signatures [66, 67, 199, 208] the collector message size can be further reduced from linear to constant.

**Design Choice 2: Phase reduction through redundancy.** This function explores a trade-off between the number of ordering phases and the number of replicas. The function transforms a protocol with \( 3f + 1 \) replicas and 3 ordering phases (i.e., one linear, two quadratic), e.g., PBFT, to a fast protocol with \( 5f + 1 \) replicas and 2 ordering phases (one linear, one quadratic), e.g., FaB [174]. In the second phase of the protocol, matching messages from a quorum of \( 4f + 1 \) replicas are required. Recently, \( 5f \) – \( 1 \) has been proven as the lower bound for two-step (fast) Byzantine consensus [11, 147]. The intuition behind the \( 5f - 1 \) lower bound is that in an authenticated model, when replicas detect leader equivocation and initiate view-change, they do not include view-change messages coming from the malicious leader reducing the maximum number of faulty messages to \( f – 1 \) [11, 147].

**Design Choice 3: Leader rotation.** This function replaces the stable leader mechanism with the rotating leader mechanism, e.g., HotStuff [230] where the rotation happens after each request or epoch or due to low performance. The function eliminates the view-change stage and adds a new quadratic phase or 2 linear phases (using the linearization function) to the ordering stage to ensure that the new leader is aware of the correct state of the system.

**Design Choice 4: Non-responsive leader rotation.** This function replaces the stable leader mechanism with the rotating leader mechanism without adding a new ordering phase (in contrast to design choice 3) while sacrificing responsiveness. The new leader optimistically assumes that the network is synchronous and waits for a predefined known upper bound \( \Delta \) (Timer \( \tau_4 \)) before initiating the next request. This is needed to ensure that the new leader is aware of the highest assigned order to the requests, e.g., Tendermint [63, 148] and Casper [65].

**Design Choice 5: Optimistic replica reduction.** This function reduces the number of involved replicas in consensus from \( 3f + 1 \) to \( 2f + 1 \) while optimistically assuming all \( 2f + 1 \) replicas are non-faulty (assumption \( a_2 \)). In each phase of a BFT protocol, matching messages from a quorum of \( 2f + 1 \) replicas is needed. If a quorum of \( 2f + 1 \) non-faulty replicas is identified, they can order (and execute) requests without the participation of the remaining \( f \) replicas. Those \( f \) replicas remain passive and are needed if any of the \( 2f + 1 \) active replicas become faulty [96, 133]. Note that \( n \) is still \( 3f + 1 \).

**Design Choice 6: Optimistic phase reduction.** Given a linear BFT protocol, this function optimistically eliminates two linear phases (i.e., equal to the quadratic phase prepare) assuming all replicas are non-faulty, e.g., SBFT [120]. The leader (collector) waits for signed messages from all \( 3f + 1 \) replicas in the second phase of ordering, combines signatures and sends a signed message to all replicas. Upon receiving the signed message from the leader, each replica ensures that all non-faulty replicas has received the request and agreed with the order. As a result, the third phase of communication can be omitted and replicas can directly commit the request. If the leader has not received \( 3f + 1 \) messages after a predefined time (timer \( \tau_3 \)), the protocol fall back to its slow path and runs the third phase of ordering.
Table 1: Comparing selected BFT protocols based on different dimensions of BEDROCK design space

| Protocol | E1: Replicas | E2: Topo. | E3: Auth. | E4: Timers | P1: Strategy | P2: Phases | P3: V-change | P5: Recov. | P6: Client Fair | Q1: Load | Design Choices |
|----------|-------------|-----------|-----------|------------|--------------|------------|--------------|-----------|----------------|----------|----------------|
| PBFT [71] | 3f + 1      | clique    | MAC II Sign | \(r_1, r_2, r_3\) | pessimistic | 3          | stable       | pro.      | Req.           |          | 11             |
| Zyzzyva [143] | 3f + 1     | star      | MAC II Sign | \(r_1, r_2\) | optimis: \(a_1, a_2\); Spec | 1 (3)       | stable       | -         | Rep.           |          | 8, 11          |
| Zyzzyva5 [143] | 5f + 1     | star      | MAC II Sign | \(r_1, r_2\) | optimis: \(a_1\); Spec | 1 (3)       | stable       | -         | Rep.           |          | 8, 10, 11      |
| PoE [123] | 3f + 1      | star      | MAC II T-Sign | \(r_1, r_2\) | optimis: \(a_2\); Spec | 3           | stable       | -         | Req.           |          | 1, 7, 11       |
| SBFT [120] | 3f + 1      | star      | T-Sign     | \(r_1, r_2, r_3\) | optimis: \(a_2\) | 3 (5)       | stable       | -         | Req.           |          | 1, 6, 11       |
| Tendermint [63] | 3f + 1    | clique    | Sign       | \(r_1, r_2, r_3, r_4\) | optimis: \(a_3\) | 3           | rotating     | -         | Req.           |          | 4, 11          |
| Themis [135] | 4f + 1      | star      | T-Sign     | \(r_1, r_2, r_3\) | pessimistic | 1 + 7       | rotating     | -         | Req.           |          | 1, 3, 13, 11  |
| Kauri [186] | 3f + 1      | tree      | T-Sign     | \(r_1, r_2\) | optimis: \(a_4\) | 7h          | stable*      | -         | Req.           |          | 3, 14, 11      |
| CheapBFT [133] | 2f + 1      | clique    | MAC IV     | \(r_1, r_2\) | optimis: \(a_5\) | 3           | stable       | -         | Req.           |          | 5             |
| FaB [174] | 5f + 1      | clique    | (Sign)     | \(r_1, r_2\) | pessimistic | 2           | stable       | -         | Req.           |          | 2             |
| Prime [22] | 3f + 1      | clique    | Sign       | \(r_1, r_2, r_3, r_4\) | robust | 6           | stable       | -         | Req.           |          | 11, 12         |
| Q/Us [4] | 5f + 1      | star      | MAC II     | \(r_1, r_2\) | optimis: \(a_6, a_7\) | 1 (3)       | stable       | -         | Req.           |          | 9, 10          |
| PLB [5] | 5f - 1      | clique    | Sign       | \(r_1, r_2\) | pessimistic | 2           | stable       | -         | Req.           |          | 1, 2, 11       |
| FTB [5] | 5f - 1      | tree      | T-Sign     | \(r_1, r_2\) | optimis: \(a_8\) | 3h          | stable       | -         | Req.           |          | 1, 2, 14, 11  |

Hint: 1-Sign is used for threshold signatures. Speculative optimistic protocols are specified by Spec. The number of phases in slow-path of optimistic protocols is shown within parenthesis. While Kauri is implemented on top of HotStuff, it does not use the rotating leader mechanism. Prime provides partial fairness.

**Design Choice 7: Speculative phase reduction.** This function, similar to the previous one, optimistically eliminates two linear phases of the ordering stage assuming that non-faulty replicas construct the quorum of responses, e.g., PoE [123]. The main difference is that the leader waits for signed messages from only \(2f + 1\) replicas in the second phase of ordering and sends a signed message to all replicas. Upon receiving a message signed by \(2f + 1\) replicas from the leader, each replica speculatively executes the transaction, optimistically assuming that either (1) all \(2f + 1\) signatures are from non-faulty replicas or (2) at least \(f + 1\) non-faulty replicas received the signed message from the leader. If (1) does not hold, other replicas receive and execute the transaction during the view-change. However, if (2) does not hold, the replica might have to rollback the executed transaction.

**Design Choice 8: Speculative execution.** This function eliminates the prepare and commit phases while optimistically assuming that all replicas are non-faulty (optimistic assumptions \(a_1\) and \(a_2\)), e.g., Zyzzyva [143]. Replicas speculatively execute transactions upon receiving them from the leader. If the client does not receive \(3f + 1\) matching replies after a predefined time (timer \(t_r\)) or it receives conflicting messages, the client detects failures (repairer) and communicates with replicas to receive \(2f + 1\) commit messages (two linear phases).

**Design Choice 9: Optimistic conflict-free.** Assuming that requests of different clients are conflict-free (assumption \(a_3\)), there is no need for a total order among all transactions. The function eliminates all three ordering phases while optimistically assuming that requests are conflict-free and all replicas are non-faulty. The client becomes the proposer and sends its request to all (or a quorum of) replicas where replicas execute the client requests without any further communication [4, 91].

**Design Choice 10: Resilience.** This function increases the number of replicas by \(2f\) to enable the protocol to tolerate \(f\) more failures with the same safety guarantees. In particular, optimistic BFT protocols that assume all \(3f + 1\) replicas are non-faulty (quorum size is also \(3f + 1\)) tolerate zero failures. By increasing the number of replicas to \(5f + 1\) replicas, such BFT protocols can provide the same safety guarantees with quorums of size \(4f + 1\) while tolerating \(f\) failures, e.g., Zyzzyva5 [143], Q/Us [4]. Similarly, a protocol with \(5f + 1\) can tolerate \(f\) more faulty replicas by increasing the network size to \(7f + 1\) [212].

The function can also be used to provide high availability during the (proactive) recovery stage by increasing the number of replicas by \(2k\) (the quorum size by \(k\)) where \(k\) is the maximum number of servers that recover in parallel [214].

**Design Choice 11: Authentication.** This function replaces MACs with signatures for a given stage of a protocol. If a protocol follows the star communication topology where a replica needs to include a quorum of signatures as a proof of its messages, e.g., HotStuff [230], \(k\) signatures can be replaced with a single threshold signature. Note that in such a situation MACs cannot be used (MACs do not provide non-repudiation).
Design Choice 12: Robust. This function makes a pessimistic protocol robust by adding a preordering stage to the protocol, e.g., Prime [22]. In the preordering stage and, upon receiving a request, each replica locally orders and broadcasts the request to all other replica. All replicas then acknowledge the reception of the request in an all-to-all communication phase and add the request to their local request vector. Replicas periodically share their vectors with each other. The robust function provides (partial) fairness as well. Note that robustness has also been addressed in other ways, e.g., using the leader rotation and a blacklisting mechanism in Spinning [222] or isolating the incoming traffic of different replicas, and check the performance of the leader in Aardvark [81].

Design Choice 13: Fair. This function transforms an unfair protocol, e.g., PBFT, to a fair protocol by adding a pre-ordering phase to the protocol. In the preordering phase, clients send transactions to all replicas and once a round ends (timer $τ_3$), all replicas send a batch of requests in the order received$^1$ to the leader. The leader then initiates consensus on the requests following the order of transactions in received blocks. Depending on the order-fairness parameter $γ (0.5 < γ ≤ 1)$ that defines the fraction of replicas receiving the transactions in that specific order, at least $4f + 1$ replicas ($n > \frac{4f}{2γ−1}$) replicas are needed to provide order fairness [135, 136]$^2$.

Design Choice 14: LoadBalancer. This function explores a trade-off between communication topology and load balancing where load balancing is supported by organizing replicas in a tree topology, with the leader placed at the root, e.g., Kauri [186]. The function takes a linear communication phase, and splits it into $h$ communication phases where $h$ is the height of the tree. Each replica then uniformly communicates with its child/parent replicas in the tree. Using the tree topology, the protocol optimistically assumes all non-leaf replicas are non faulty (assumption $a_3$). Otherwise the tree needs to be reconfigured (i.e., view change).

5 Deriving, Evolving and Inventing Protocols

This section demonstrate how BEDROCK is used to derive a wide range of BFT protocols using design choices. Figure 5 demonstrates the derivation of a wide spectrum of classical and recent BFT protocols from PBFT using design choices. Table 1 provides insights into how each BFT protocol maps into the BEDROCK design space. The table also presents the design choices used by each BFT protocol.

5.1 Case Studies on Protocol Evolution

In the following case studies, we provide insights into how each BFT protocol maps into the BEDROCK design space, and relate to one another through using design choices. For illustrative purposes, we describe each protocol relative to PBFT along one or more design choices. Figure 4 focuses on different stages of replicas and demonstrates the communication complexity of each stage. The figure presents: (1) the preordering phases used in Themis and Prime, (2) the three ordering phases, e.g., pre-prepare, prepare or commit in PBFT (labeled by $o_1$, $o_2$, and $o_3$), (3) the execution

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1The request propagation time can be estimated by measuring network latency or relying on client timestamps for non-Byzantine clients

2Order fairness can be provided using $3f + 1$ replicas, however, as shown in [135], it either requires a synchronized clock [233] or does not provide censorship resistance [145].
stage, (4) the view-change stages consisting of view-change and new-view phases (labeled by $v_1$ and $v_2$), and (5) the checkpointing stage. As can be seen, some protocols do not have all three ordering phases, i.e., using different design choices, the number of ordering phases is reduced. The dashed boxes present the slow-path of protocols, e.g., the third ordering phase of SBFT is used only in its slow-path. Finally, the order of stages might be changed. For example, HotStuff runs view-change (leader rotation) for every single message and this leader rotation phase takes place at the beginning of a consensus instance to synchronize nodes within a view.

Next, we describe each BFT protocol.

**Zyzzyva** [143]. Zyzzyva\(^3\) (Figure 6) can be derived from PBFT using the speculative execution function (design choice 8) of BEDROCK where assuming the primary and all backups are non-faulty, replicas speculatively execute requests without running any agreement and send reply messages to the client. The client waits for $3f + 1$ matching replies to accept the results. If the timer $r_1$ is expired and the client received matching replies from between $2f + 1$ and $3f$ replicas, as presented in Figure 7, two more linear rounds of communication is needed to ensure that at least $2f + 1$ replicas have committed the request. Finally, Zyzzyva5 is derived from Zyzzyva by using the resilience function (design choice 10) where the number of replicas is increased to $5f + 1$ and the protocol is able to tolerate $f$ and $2f$ failures during its fast and slow path respectively (presented in (Figures 8 and 9) AZyzzyva [35, 119] also uses the fast path of Zyzzyva (called ZLight) in its fault-free situations.

**PoE** [123]. PoE Figure 12 uses the linearization and speculative phase reduction functions (design choices 1 and 7). PoE does not assumes that all replicas are non-faulty and constructs quorum of $2f + 1$ replicas possibly including Byzantine replicas. However, since a client waits for $2f + 1$ matching reply messages, all $2f + 1$ replicas constructing the quorum need to be well-behaving to guarantee client liveness in the fast path.

**SBFT** [120]. BEDROCK derives SBFT\(^4\) from PBFT using the linearization and optimistic phase reduction functions (design choices 1 and 6). SBFT presents an optimistic fast path (Figure 13) assuming all replicas are non-faulty. If the primary does not receive messages from all backups (in the prepare phase) and its timer is expired (i.e., non-responsiveness timer $r_1$), SBFT switches to its slow path (Figure 14) and requires two more linear rounds of communication (commit phase). The Twin-path nature of SBFT requires replicas to sign each message with two schemes (i.e.,

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\(^3\)the view-change stage of the Zyzzyva protocol has a safety violation as described in [6]

\(^4\)SBFT tolerates both crash and Byzantine failure ($n = 3f + 2c + 1$ where $c$ is the number of crashed replicas). Since the focus of this paper is on Byzantine failures, we consider a variation of SBFT where $c = 0$. 

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To send replies to the client, a single (collector) replica receives replies from all replicas and sends a single (threshold) signed reply message.

**HotStuff** [230]. HotStuff (Figure 10) can be derived from PBFT using the linearization and leader rotation functions (design choices 1 and 3) of BEDROCK. The Chained HotStuff (performance optimization 2) benefits from pipelining to reduce the latency of request processing.

**Tendermint** [62, 63, 148]. Tendermint leverages the non-responsive leader rotation function (design choice 4) to rotate leader without adding any new phase. The new leader, however, needs to wait for a predefined time (timer $t_4$), i.e., the worst-case time it takes to propagate messages over a wide-area peer-to-peer gossip network, before proposing a new block. Tendermint also uses timers in all phases where a replica discard the request if it does not receive $2f+1$ messages before the timeout (timer $t_6$). Note that the original Tendermint uses a gossip all-to-all mechanism and has $\Theta(n \log n)$ message complexity.

**Themis** [135]. Themis is derived from HotStuff using the fair function (design choice 13). Themis add a new all-to-all preordering phase where replicas send a batch of requests in the order they received to the leader replica and the leader propose requests in the order received (depending on the order-fairness parameter $\gamma$) [136]. Themis requires at least $4f+1$ replicas (if $\gamma = 1$) to provide order fairness.

**Kauri** [186]. Kauri (Figure 11) can be derived from HotStuff using the loadbalancer function (design choice 14) that maps the star topology to the tree topology. The height of the tree is $h = \log_d n$ where $d$ is the fanout of each replica.

**CheapBFT** [133]. CheapBFT (Figure 15) and its revised version, ReBFT [96] is derived from PBFT using the optimistic replica reduction function (design choice 5). Using trusted hardware (performance optimization 07), a variation of ReBFT, called RWMinBFT, processes requests with $f+1$ active and $f$ passive replicas in its normal case (optimistic) execution.

**FaB** [174]. FaB (Figure 16) uses the phase reduction function (design choice 2) to reduce one phase of communication while requiring $5f+1$ replicas. Fab does not use authentication in its ordering stage, however, requires signatures for the view-change stage (design choice 11). Note that using authentication, $5f-1$ replicas is sufficient to reduce one phase of communication [11, 147].

**Prime** [22]. Prime is derived from PBFT using the robust functions (design choice 12). In prime a preordering stage is added where replicas exchange the requests they receive from clients and periodically share a vector of all received requests, which they expect the leader to order request following those vectors. In this way, replicas can also monitor the leader to order requests in a fair manner.

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5Tendermint uses a Proof-of-Stake variation of PBFT where each replica has a voting power equal to its stake (i.e., locked coins).

6FaB similar to a family of Paxos-like protocol separates proposers from acceptors. In our implementation of FaB, however, replicas act as both proposers and acceptors.
Q/U [4]. Q/U (Figure 17) utilizes optimistic conflict-free and resilience functions (design choices 9 and 10). Clients play the proposer role and replicas immediately execute an update request if the object has not been modified since the client’s last query. Since Q/U is able to tolerate $f$ faulty replicas, a client can optionally communicate with a subset $(4f + 1)$ of replicas (preferred quorum). The client communicate with additional replicas only if it does not received reply from all replicas of the preferred quorum (Figure 18). Both signatures (for large $n$) and MACs (for small $n$) can be used for authentication in Q/U. Quorum [35] uses a similar technique with $3f + 1$ replicas, i.e., only the conflict-free function (design choices 9) has been used.

5.2 Deriving Novel BFT Protocols

The previous case studies demonstrate the value of BEDROCK in providing a unified platform for analyzing the strengths and weaknesses of a range of existing BFT protocols. BEDROCK’s utility goes beyond an experimental platform towards a discovery tool as well. The system provides a systematic way to explore new valid points in the design space and help BFT researchers uncover novel BFT protocols. We uncover several such new protocols, although not all are necessarily practical or interesting. For example, simply making a protocol fair by adding the preordering phase of fairness results in a new protocol. While this is an interesting insight, the resulting protocol may have limited practical impact. We select as highlights two new BFT protocols (FLB and FTB) that are new and have practical value that we have uncovered using BEDROCK.

Fast Linear BFT (FLB). FLB is a fast linear BFT protocol that commits transactions in two phases of communication with linear message complexity. To achieve this, FLB uses the linearization and phase reduction through redundancy functions (design choices 1 and 2). FLB requires $5f - 1$ replicas (following the lower bound results on fast Byzantine agreement [11, 147]). The ordering stage of FLB is similar to the fast path of SBFT in terms of the linearity of communication and the number of phases. However, FLB expands the network size to tolerate $f$ failures (in contrast to SBFT, which optimistically assumes all replicas are non-faulty).

Fast Tree-based balanced BFT (FTB). A performance bottleneck of consensus protocols is the computing and bandwidth capacity of the leader. While Kauri [186] leverages a tree communication topology (design choice 14) to distribute the load among all replicas, Kauri requires $7h$ phases of communication to commit each request, where $h$ is the height of the communication tree. FTB reduces the latency of Kauri based on two observations. First, we noticed that while Kauri is implemented on top of HotStuff, it does not use the leader rotation mechanism. As a result, it does not need the two linear phases of HotStuff (2h phases in Kauri) that are added for the purpose of leader rotation (design choice 3). Second, similar to FLB, we can use the phase reduction through redundancy function (design choice 2) to further reduce $2h$ more phases of communication. FTB establishes agreement with $5f - 1$ replicas in $3h$ phases. FTB also uses the pipelining stretch mechanism of Kauri, where the leader continuously initiates consensus instances before receiving a response from its child nodes for the first instance. This is similar to the out-of-order processing mechanism (performance optimization O 1) used by many BFT protocols.
EDROCK enables users, e.g., application developers, to analyze and navigate the BFT landscape by querying their required BFT protocol characteristics. Using a constraint checker, EDROCK finds all plausible points (i.e., BFT protocols) in the design space that satisfy the input query. Moreover, EDROCK provides an execution engine that enables users to implement different BFT protocols.

**Constraint checker.** The constraint checker uses a decision tree-like algorithm to find all plausible points in the design space where each node of the tree is labeled with a dimension, and outgoing edges represent possible values for that particular dimension. A user issues a query that indicates, for each dimension, an assigned value (chosen from a preset of values) that characterizes the requirements of their application. The user can customize some dimensions while leaving the rest unspecified. For example, the user might search for a pessimistic linear BFT protocol with $3f+1$ nodes and linear message complexity. Based on the initial query, the constraint checker begins with the dimensions that the end-user has specified, e.g., processing strategy, the number of replicas, and topology in Figure 21, and then checks plausible values for unspecified dimensions, e.g., since the end-user has chosen the star topology, the constraint checker chooses signatures for authentication to be able to provide non-repudiation. The leaf nodes of the decision tree specify the candidate BFT protocols. If some queries do not match any points in the design space (e.g., an impossible protocol such as a pessimistic linear BFT protocol with 2 communication phases and $3f+1$ replicas), the empty set is returned to the user.

**Execution engine.** The user receives a list of BFT protocols, e.g., HotStuff [230] is returned as a pessimistic linear protocol with $3f+1$ nodes. EDROCK maintains a library including the implementation of common BFT protocols. When a protocol is chosen by the user, EDROCK simply returns it if the protocol implementation already exists. Otherwise, the system generates a config file for the protocol, including all dimensions and the chosen value for each dimension. The config file is then used by EDROCK to implement the stateMachine of the protocol. The stateMachine includes different states and their transitions for each role (leader, backups, and clients), exchange messages, quorum conditions, etc. The execution engine takes the stateMachine and a set of related classes that are defined outside the stateMachine and handles environmental conditions such as message exchanges, timers, clocks, message validation, etc. to implement the protocol. Once the protocol implementation is completed, the execution engine initializes replicas and clients (based on the system config), deploys the stateMachine on nodes, coordinates key exchange, etc. At this point, the system is ready to run experiments.

EDROCK is implemented in Java. The modular design of EDROCK enables a fair and efficient evaluation of BFT protocols using identical libraries, cryptographic functions, etc. In particular, we use java.security and javax.crypto libraries for cryptographic operations, the eo-YAML library to facilitate the storage and retrieval of BFT protocol configuration files, protocol buffers (com.google.protobuf) to serialize data, and Java streams for parallel processing.

**7 Experimental Evaluation**

Our evaluation studies the practical impact of the design dimensions and the exposed trade-offs presented as design choices on the performance of BFT protocols to reveal the strengths and weaknesses of existing BFT protocols. The goal is to test the capability of the EDROCK design space to analyze the performance of different protocols that were proposed in diverse settings and different contexts under one unified framework. We evaluate the performance of BFT protocols in typical experimental scenarios used for existing BFT protocols and permissioned blockchains, including (1) varying the number of replicas, (2) under a backup failure, (3) multiple request batch sizes, and (4) a geo-distributed setup.

All protocols listed in Table 1 are implemented in EDROCK. Using the platform, we also experimented with many new protocols resulting from the combination of design choices. Due to space limitations, we present the performance evaluation of a subset of protocols. In particular, we evaluate PBFT, Zyzzyva, SBFT, FaB, PoE, (Chained) HotStuff, Kauri, Themis, and two of the more interesting new variants (FLB and FTB). This set of protocols enables us to see the impact of design choices 1, 2, 3, 6, 7, 8, 10, 11, 13, and 14 (discussed in Section 4). We also use the out-of-order processing technique (optimization O1) for protocols with a stable leader and the request pipelining technique.
In the first set of experiments, we evaluate the throughput and latency of the protocols by increasing the number of replicas \( n \) in a failure-free situation. We vary the number of replicas in an experiment from 4 to 100. For some protocols, the smallest network size might differ, e.g., FaB requires \( 5f + 1 = 6 \) replicas. We use batching with the batch size of 400 (we discuss this choice in later experiments) and a workload with client request/reply payload sizes of 128/128 byte. Figure 22 reports the results.

Zyzzyva shows the highest throughput among all protocols in small networks due to its optimistic ordering stage that does not require any communication among replicas (design choice 8). However, as \( n \) increases, its throughput significantly reduces as clients need to wait for reply from all replicas. Increasing the number of replicas also has a large impact on PBFT and FaB (65% and 63% reduction, respectively) due to their quadratic message complexity.

On the other hand, the throughput of Kauri and FTB is less affected (31% and 32% reduction, respectively) by increasing \( n \) because of their tree topology (design choice 14) that reduced the bandwidth utilization of each replica. Similarly, PoE, SBFT and HotStuff incur less throughput reduction (39%, 55% and 45% respectively) compared to PBFT and FaB due to their linear message complexity (design choice 1). It should be noted that in Bedrock, chained HotStuff has been implemented using the pipelining technique (optimization O 2). Hence, the average latency of requests has been reduced. In comparison to HotStuff, SBFT has slightly lower throughput in large networks (e.g., 8% lower when \( n = 100 \)) because the leader waits for messages from all replicas. SBFT, on the other hand, shows higher throughput compared to HotStuff in smaller networks (e.g., 12% higher when \( n = 4 \)) due to its fast ordering stage (design choice 6). PoE demonstrates higher throughput compared to both SBFT and HotStuff, especially in larger networks (e.g., 39% higher than SBFT and 26% higher than HotStuff when \( n = 100 \)). This is expected because, in PoE, the leader does not need to wait for messages from all replicas and optimistically combines signatures from \( 2f + 1 \) replicas (design choice 7).

Compared to PBFT, while HotStuff demonstrates better throughput (e.g., 48% higher when \( n = 64 \)), the latency of PBFT is lower (e.g., 32% lower when \( n = 64 \)). One reason behind the high latency of HotStuff is its extra communication round (design choice 3).

Supporting order-fairness (design choice 13) leads to deficient performance of Themis compared to HotStuff (83% lower throughput when \( n = 5 \)). In Themis, replicas need to order transactions and send batches of transactions to the leader, and the leader needs to generate a fair order. As the number of replicas increases, Themis incurs higher latency.
(the latency increases from 9 ms to 137 as the \( n \) increases from 5 to 101). One main source of latency is the time the leader takes to generate the dependency graph and reach a fair order. It should also be noted that in the BEDROCK implementation of Themis, ZKP has not been used and the leader sends all transaction orderings received from replicas to all of them in the prepare phase. This might slightly increase the latency. Using design choice 2 and reducing the number of communication phases results in 41% higher throughput and 46% lower latency of FTB compared to Kauri in a setting with 99 replicas (100 for Kauri).

Finally, in FLB, by combining design choices 1 and 2 demonstrates high throughput and low latency for large value of \( n \) (2.25x throughput and 0.55x latency compared to PBFT). This is expected because first, FLB reduces both message complexity and communication phases, and second, in contrast to SBFT and Zyzzyva, replicas in FLB do not need to wait for responses from all other replicas.

Figure 22 demonstrates the performance of protocols with different numbers of replicas. However, with the same number of replicas, different protocols tolerate different numbers of failures. For instance, PBFT requires \( 3f + 1 \) and when \( n = 100 \) tolerates 33 failures while FaB requires \( 5f + 1 \) and tolerates 19 failures with \( n = 100 \). To compare protocols based on the maximum number of tolerated failures, we represent the results of the first experiments in Figure 23. When protocols tolerate 20 failures, Themis incurs the highest latency. This is because Themis requires 81 \((4f + 1)\) replicas and deals with the high cost of achieving order-fairness.

### 7.2 Performance with Faulty Backups

In this set of experiments, we force a backup replica to fail and repeat the first set of experiments. Figure 24 reports the results. Zyzzyva is mostly affected by failures (82% lower throughput) as clients need to collect responses from all replicas. A client waits for \( \Delta = 5ms \) to receive reply from all replicas and then the protocol switches to its normal path).
We also run this experiment with and without faulty backups on Zyzzyva to validate design choice \( f \), i.e., tolerating \( f \) faulty replicas by increasing the number of replicas. With a single faulty backup, Zyzzyva incurs only 8% lower throughput when \( n = 6 \).

Backup failure reduces the throughput of SBFT by 42%. In the fast path of SBFT, all replicas need to participate, and even when a single replica is faulty, the protocol falls back to its slow path that requires two more phases. Interestingly, while the throughput of PoE is reduced by 26% in a small network (4 replicas), its throughput is not significantly affected in large networks. This is because the chance of the faulty replica (which participates in the quorum construction but does not send reply messages to the clients) to be a member of the quorum is much higher in small networks.

Faulty backups also affect the performance of HotStuff, especially in small networks. This is expected because HotStuff uses the rotating leader mechanism. When \( n \) is small, the faulty replica is the leader of more views during the experiments, resulting in reduced performance. HotStuff demonstrates its best performance when \( n = 31 \) (still, 36% lower throughput and 2.7x latency compared to the failure-free scenario). While Themis uses HotStuff as its ordering stage, a single faulty backup has less impact on its performance compared to HotStuff (25% reduction vs. 66% reduction in throughput). This is because Themis has a larger network size (\( 4f + 1 \) vs. \( 3f + 1 \)) that reduces the impact of the faulty replica. In Kauri and FTB, we force a leaf replica to fail in order to avoid triggering a reconfiguration. As a result, the failure of a backup does not significantly affect their performance (e.g., 3% lower throughput with 31 replicas in Kauri). Finally, in small networks, FLB demonstrates the best performance as it incurs only 8% throughput reduction.

### 7.3 Impact of Request Batching

In the next set of experiments, we measure the impact of request batching on the performance of different protocols implemented in \( \text{BEDROCK} \). We consider three scenarios with batch size of 200, 400 and 800. The network includes 16 replicas (17 replicas for Themis, 14 replicas for FLB and FTB) and all replicas are non-faulty. Figure 25 depicts the results for three batch sizes of 200, 400 and 800.

Increasing the batch size from 200 to 400 requests improves the performance of all protocols. This is expected because, with larger batch sizes, more transactions can be committed while the number of communication phases and exchanged messages is the same and the bandwidth and computing resources are not fully utilized yet. Different protocols behave differently when the batch size increases from 400 to 800. First, Kauri and FTB still process a higher number of transactions (42% and 34% higher throughput). This is because Kauri and FTB balance the load and utilize the bandwidth of all replicas. Second, SBFT and FaB demonstrate similar performance as before; a trade-off between smaller consensus quorums and higher cost of signature verification and bandwidth utilization. Third, the performance of Themis decreases (24% lower throughput and 3.16x latency) compared to a batch size of 400 due to two main reasons. First, the higher cost of signature verification and bandwidth utilization, and second, the higher complexity of generating fair order for a block of 800 transactions (CPU utilization).

### 7.4 Impact of a Geo-distributed Setup

We measure the performance of different protocols in a wide-area network. Replicas are deployed in 4 different AWS regions, i.e., Tokyo (TY), Seoul (SU), Virginia (VA), and California (CA) with an average Round-Trip Time (RTT) of...
Figure 26: Performance with a geo-distributed setup

TY ⇌ SU: 33 ms, TY ⇌ VA: 148 ms, TY ⇌ CA: 107 ms, SU ⇌ VA: 175 ms, SU ⇌ CA: 135 ms, and VA ⇌ CA: 62 ms. The clients are also placed in Oregon (OR) with an average RTT of 97, 126, 68 and 22 ms from TY, SU, VA and CA respectively. We use a batch size of 400 and perform experiments in a failure-free situation. In this experiment, the pipelining stretch of Kauri and FTB is increased to 6. Figure 26 depicts the results.

Zyzzyva demonstrates the best performance when n is small. However, when n increases, its performance is significantly reduced (87% throughput reduction and 115x latency when n increases from 4 to 100). This is because, in Zyzzyva, clients need to receive reply messages from all replicas. Similarly, SBFT incurs a significant reduction in its performance due to its optimistic assumption that all replicas participate in a timely manner. In both protocols, replicas (client or leader) wait for Δ = 500 ms to receive responses from all replicas before switching to the normal path. This reduction can be seen in PBFT as well (84% throughput reduction when n increases to 100) due to its quadratic communication complexity. PoE incurs a smaller throughput reduction (51%) in comparison to Zyzzyva, SBFT, and PBFT because it does not need to wait for all replicas and it has a linear communication complexity. Increasing the number of replicas does not significantly affect the throughput of FTB compared to other protocols (36% throughput reduction when n increases to 99) due to its logarithmic message complexity and pipelining technique.

In HotStuff, the leader of the following view must wait for the previous view’s decision before initiating its value. Even though Chained HotStuff is implemented in BEDROCK, the leader still needs to wait for one communication round (an RTT). As a result, in contrast to the single datacenter setting where each round takes ~1 ms, request batches are proposed on average every ~190 ms. In this setting, a larger batch size possibly improves the performance of HotStuff. Similarly, in Themis and FLB, the leader must wait for certificates from n − f replicas before initiating consensus on the next request batch. In Themis, network latency also affects achieving order-fairness as replicas might propose different orders for client requests. This result demonstrates the significant impact of the out-of-order processing of requests (optimization O1) on the performance of the protocol, especially in a wide area network.

### 7.5 Evaluation Summary

We summarize some of the evaluation results as follows. First, optimistic protocols that require all nodes to participate, e.g., Zyzzyva and SBFT, do not perform well in large networks, especially when nodes are far apart. In small networks also, a single faulty node significantly reduces the performance of optimistic protocols. Second, the performance of pessimistic protocols highly depends on the communication topology. While the performance of protocols with quadratic communication complexity, e.g., PBFT and FaB, is significantly reduced by increasing the network size, the performance of protocols with linear complexity, e.g., HotStuff, and especially logarithmic complexity, e.g., Kauri and FTB, is less affected. Interestingly in small networks, protocols that use the leader rotation mechanism show poor performance. This is because the chance of the faulty node becoming the leader is relatively high. Third, increasing the request batch size enhances the performance of all protocols to the point where the bandwidth and computing resources are fully utilized. However, the load-balancing techniques, e.g., tree topology, enable a protocol to process larger batches. Finally, in a wide area network, out-of-order processing of transactions significantly improves performance. In such a setting, protocols that require a certificate of the previous round to start a new round, e.g., HotStuff, show poor performance even with pipelining techniques.
8 Related Work

SMR regulates the deterministic execution of client requests on multiple replicas, such that every non-faulty replica executes every request in the same order [149, 205]. Several approaches [150, 191, 205] generalize SMR to support crash failures. CFT protocols [18, 58, 75, 77, 99, 129, 131, 151, 152, 154, 155, 157, 163, 166, 184, 190, 191, 194, 220] utilize the design trade-offs between different design dimensions. For instance, Fast Paxos [152] adds $f$ more replicas to reduce one phase of communication.

Byzantine fault tolerance refers to nodes that behave arbitrarily after the seminal work by Lamport, et al. [156]. BFT protocols have been analyzed in several surveys and empirical studies [6, 7, 21, 26, 42, 48, 51, 68, 88, 95, 111, 122, 195, 210, 232]. We discuss some of the more relevant studies.

Berger and Reiser [48] present a survey on BFT protocols used in blockchains where the focus is on the scalability techniques. Similarly, a survey on BFT protocols consisting of classical protocols, e.g., PBFT, blockchain protocols, e.g., PoW, and hybrid protocols, e.g., OmniLedger [142], and their applications in permissionless blockchains, is conducted by Bano et al. [42]. Platania et al. [195] classify BFT protocols into client-side and server-side protocols depending on the client’s role. The paper compares these two classes of protocols and analyzes their performance and correctness attacks. Three families of leader-based, leaderless, and robust BFT protocols with a focus on message and time complexities have been analyzed by Zhang et al. [232]. Finally, Distler [95] analyzes BFT protocols along several main dimensions: architecture, clients, agreement, execution, checkpoint, and recovery. The paper shares several dimensions with BEDROCK.

A recent line of work [9–12] also study good-case latency of BFT protocols. BEDROCK, in contrast to all these survey and analysis papers, provides a design space, systematically discusses design choices (trade-offs), and, more importantly, provides a tool to experimentally analyze BFT protocols.

BFTSim [210] is a simulation environment for BFT protocols that leverages declarative networking system. The paper also compares a set of representative protocols using the simulator. Abstract [35] presents a framework to design and reconfigure BFT protocols where each protocol is developed as a sequence of BFT instances. Abstract presents Azyzyya, Aliph, and R-Aliph as three BFT protocols. Each protocol itself is a composition of Abstract instances presented to handle different situations (e.g., fault-free, under attack). For instance, R-Aliph is a composition of Quorum, Chain, and Aardvark. In contrast to such studies, BEDROCK attempts to develop a unified design space for BFT protocols, enabling end-users to choose a protocol that best fits their application requirements.

In addition to CFT and BFT protocols, consensus with multiple failure modes has also been studied for both synchronous [138, 176, 211, 218], and partial synchronous [28, 80, 120, 167, 196, 206] models. Finally, leaderless protocols [55, 92, 101, 121, 153, 177, 217] have been proposed to avoid the implications of relying on a leader.

9 Conclusion

We present BEDROCK, a toolkit that unifies all BFT protocols within a platform for analysis, design, implementation, and experimentation. In using BEDROCK, we demonstrate how different BFT protocols relate to one another within a design space and evaluate BFT protocols under a unified deployment and experimentation environment in a fair and efficient manner. By providing a unified platform for all the different BFT protocols, BEDROCK is able to highlight the strengths and weaknesses of diverse properties, e.g., optimistic vs. pessimistic. The tool also provides a basis for discovering protocols not previously proposed.

While this paper focuses on the platform, the ultimate decision process lies with the end-user for selecting and generating the BFT protocol. As future work, we plan to explore incorporating automatic selection strategies in BEDROCK based on deployment environment and application requirements. Machine learning techniques may be useful here in aiding the user in selecting the appropriate BFT protocol, or evolving one protocol to another at runtime as system parameters are updated. Furthermore, we will extend BEDROCK by enabling protocol designers to define new dimensions and values systematically.

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