Contributions to Building Efficient and Robust State-Machine Replication Protocols
Vivien Quéma

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Contributions to Building Efficient and Robust State-Machine Replication Protocols

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Abstract

State machine replication (SMR) is a software technique for tolerating failures using commodity hardware. The critical service to be made fault-tolerant is modeled by a state machine. Several, possibly different, copies of the state machine are then deployed on different nodes. Clients of the service access the replicas through a SMR protocol which ensures that, despite concurrency and failures, replicas perform client requests in the same order.

Two objectives underly the design and implementation of a SMR protocol: robustness and performance. Robustness conveys the ability to ensure availability (liveness) and one-copy semantics (safety) despite failures and asynchrony. On the other hand, performance measures the time it takes to respond to a request (latency) and the number of requests that can be processed per time unit (throughput).

In this thesis, we present two contributions to state machine replication. The first contribution is LCR, a uniform total order broadcast (UTO-broadcast) protocol that is throughput optimal in failure-free periods. LCR can be used to totally order the requests received by a replicated state machine. LCR has been designed for small clusters of homogeneous machines interconnected by a local area network. It relies on a perfect failure detector and tolerates the crash failures of all but one replicas. It is based on a ring topology and only relies on point-to-point inter-process communication. We benchmark an implementation of LCR against two of the most widely used group communication packages and show that LCR provides higher throughput than them, over a large number of setups.

The second contribution is Abstract, a new abstraction to simplify the design, proof and implementation of SMR protocols. Abstract focuses on the most robust class of SMR protocols, i.e. those tolerating arbitrary (client and replica) failures. Such protocols are called Byzantine Fault Tolerant (BFT) protocols. We treat a BFT protocol as a composition of instances of our abstraction. Each instance is developed and analyzed independently. To illustrate our approach, we first show how, with our abstraction, the benefits of a BFT protocol like Zyzzyva could have been developed using less than 24% of the actual code of Zyzzyva. We then present Aliph, a new BFT protocol that outperforms previous BFT protocols both in terms of latency (by up to 30%) and throughput (by up to 360%).
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Chapter 1

Introduction

Since I obtained my PhD in December 2005, I have been working on four research topics: component-based software engineering, large-scale distributed systems, system support for multicore architectures, and replication-based fault tolerance. I briefly describe below the main results achieved for each topic.

- **Component-based software engineering.** I have contributed to the design of the Fractal component model. This component model is original in the sense that it was the first model allowing component sharing (a component can simultaneously be a sub-component of two distinct components). Moreover, another distinguishing feature in this model is that components can be endowed with arbitrary reflective capabilities, from plain black-box objects to components that allow a fine-grained manipulation of their internal structure. This work has been published in SP&E in 2006 [24]. We also designed an extensible toolset for easing the development of component-based software systems. The originality of this toolset is that it does not define its own input Architecture Description Language (ADL), but rather uses a grammar description mechanism to accept various input languages, e.g. ADLs, Interface Definition Languages (IDLs), Domain Specific Languages (DSLs). This work has been published at ICSE 2007 [72].

- **Large-scale distributed systems.** I have participated in the design of several gossip-based protocols. Such protocols are used in very large-scale peer-to-peer systems, where nodes cannot have a full knowledge about other nodes in the network. In gossip-based protocols, each node knows a (constantly changing) subset of other nodes in the network, with which it periodically exchanges data. We designed a replication protocol that ensures eventual consistency in large-scale distributed systems subject to network partitions and asynchrony. This work has been published at SSS 2006 [13]. We also designed TERA, a topic-based publish-subscribe protocol. This work has been published at DEBS 2007 [12]. We proposed Nylion, the first gossip-based protocol able to work despite the presence of Network Address Translation (NAT) gateways. This work has been published at ICDCS 2009 [65]. We were also among the first to design and deploy a gossip-based streaming protocol able to take into account the heterogeneity in node capabilities. This protocol, called HEAP, has been published at DSN 2009 [50] and Middleware 2009 [49]. Finally, we have designed FireSpam, the first spam-resilient gossip-based broadcasting protocol. This work has been published at SRDS 2010 [80].

- **System support for multicore architectures.** I have participated in the design of a new runtime supporting event-driven programming for multicore platforms.
driven programming is a popular approach for the development of efficient applications such as networked systems. This programming and execution model is based on continuation-passing between short-lived and cooperatively-scheduled tasks. The originality of our runtime is that it encompasses an efficient workstealing algorithm in charge of balancing the execution of very fine-grain tasks on the available cores. This work has been published at ICDCS 2010 [55].

- Replication-based fault tolerance. I have participated in the design of algorithms and abstractions that are used as core building blocks in reliable distributed systems. In particular, we designed LCR, the first total order broadcast protocol that is throughput-optimal in LAN environments. This work has been published at DSN 2006 [60] and in ACM TOCS in 2010 [61]. We have also designed a throughput-efficient atomic storage algorithm that has been published at ICDCS 2007 [59]. This protocol, as well as LCR, achieve very high throughput by organizing nodes in a ring topology and by only relying on point-to-point communications. Finally, we have designed a new abstraction to ease the design, proof and implementation of Byzantine-resilient replication protocols. The originality of our abstraction lies in the fact that it is possible to build Byzantine-resilient replication protocols as a composition of distinct instances of our abstraction. Each instance can be developed and analyzed independently. This work has been published at EuroSys 2010 [58] and was awarded best paper of the conference.

In this document, I focus on the work I carried out on replication-based fault tolerance. In the reminder of this section, I first describe the context of this work. Then I briefly introduce the main contributions. Finally, I describe the outline of the document.

1.1 Context

As an ever increasing number of critical tasks are being delegated to computers, the unforeseen failure of a computer can have catastrophic consequences. Unfortunately, the observed increase of computing power as predicted by Moore’s law has not been coupled with a similar increase in reliability. On the other hand, because of rapidly decreasing hardware costs, ensuring fault tolerance through state machine replication [86] is gaining in popularity.

State machine replication is a software technique for tolerating failures using commodity hardware. It has been initially proposed by Lamport in his seminal paper “Time, Clocks, and the Ordering of Events in a Distributed System” [69]. The critical service to be made fault-tolerant is modeled by a state machine. Several, possibly different, copies of the state machine are then deployed on different nodes. Clients of the service access the replicas through a state machine replication protocol which ensures that, despite concurrency and failures, replicas perform client requests in the same order. In a replicated database for instance, all replicas must perform the same write queries (INSERT and UPDATE) in the same order. Read queries (SELECT) do not change the state of the replicated database and do not have to be performed by all replicas.

Two objectives underly the design and implementation of a state machine replication protocol: robustness and performance. Robustness conveys the ability to ensure availability (liveness) and one-copy semantics (safety) despite failures and asynchrony. On the other hand, performance measures the time it takes to respond to a request (latency) and the number of requests that can be processed per time unit (throughput).

Replicas are also called “processes” throughout the thesis.
1.2 Contributions

In this thesis, two contributions to state machine replication are presented. I briefly introduce them below before presenting them in details in the next chapters.

The LCR Uniform Total Order Broadcast Protocol. The first contribution presented in this thesis is LCR [60, 61, 73], a uniform total order broadcast (UTO-broadcast) protocol that is throughput optimal in failure-free periods. A UTO-broadcast protocol is a primitive that can be used by replicas of a replicated state machine to order requests received from clients. More formally, a UTO-broadcast protocol ensures the following for all messages that are broadcast [62]: (1) Uniform agreement: if a replica delivers a message \( m \), then all correct replicas eventually deliver \( m \); (2) Strong uniform total order: if some replica delivers some message \( m \) before message \( m' \), then a replica delivers \( m' \) only after it has delivered \( m \).

LCR has been designed for small clusters of homogeneous machines interconnected by a local area network. It relies on a perfect failure detector (P) [28] and tolerates the crash failures of all but one replicas.

The motivation that led us to develop LCR is that most of the total order broadcast protocols that have been designed in the last two decades [64, 8, 26, 54, 21, 97] target low latency. On the other hand, very few protocols have been designed for high throughput. Nevertheless, we believe that in some high load environments, e.g. database replication for e-commerce, throughput is often as important, if not more, than latency. Indeed, under high load, the time spent by a message in a queue before being actually disseminated can grow indefinitely. A high throughput broadcast protocol reduces this waiting time.

The key to achieving high throughput in LCR is to organize processes in a ring topology: each process always sends messages to the same process, thus avoiding any possible collisions. To eliminate bottlenecks, messages in LCR are sequenced using logical vector clocks instead of a dedicated sequencer. Moreover, using a ring topology, acknowledgement messages can easily be piggy-backed, which further reduces the message overhead.

We have proposed a new (simple) distributed system model that we use to define an upper bound on the throughput that can be achieved by UTO-broadcast protocols. Using this model, we have shown that LCR theoretically matches this lower bound. This model is a round-based model [76]: time is decomposed in rounds of equal duration. It assumes that a process can send a message to one (unicast) or more processes (multicast) at the start of each round, and can receive one message sent by other processes at the end of the round. This model is similar to the Postal model [16] with the addition of a multicast primitive which is available on all current local area networks.

We have implemented LCR in order to (i) confirm the theoretical analysis made using our new distributed system model, and (2) compare its performance with that achieved by the two most popular group communication frameworks: Spread [3] and JGroups [14]. Our experiments show that the proposed distributed system model is accurate: the throughput achieved by LCR is very close to the expected one. Our experiments also show that LCR consistently outperforms Spread and JGroups. For instance, with 4 processes, LCR achieves throughput of up to 50% higher than that of Spread and up to 28% higher than that of JGroups.

The Abstract framework. The second contribution presented in this thesis is Abstract [58, 95], a new abstraction that significantly reduces the development cost of state machine replication protocols and makes it significantly easier to develop new efficient ones. Abstract focuses on state machine replication protocols tolerating arbitrary (client and replica) failures. These protocols are commonly called “BFT protocols” (for Byzantine Fault Tolerance).

\(^2\)In contrast with the classical round-based model which assumes that a process can receive several messages at the end of each round.
The motivation that led us to develop Abstract is twofold:

- **BFT protocols are notoriously complex to design and implement.** As an example, the only complete proof of a BFT protocol we know of is that of PBFT [27] and it involves 35 pages. Moreover, any change to an existing protocol, although algorithmically intuitive, is very painful to design and implement (as exemplified by Zyzzyva which can be seen as an extension of PBFT [67]). Regarding implementations, existing research prototypes, although providing often incomplete implementations, involve more than 20,000 lines of (non-trivial) C++ code, e.g., PBFT [27] and Zyzzyva [67].

- **There is no “one size that fits all” BFT protocol.** A recent study [87] of three existing BFT protocols (PBFT [27], Zyzzyva [67], and Q/U [1]) showed that their performance can be heavily impacted by different factors. Our own experiences indeed reveal that the performance of BFT protocols are impacted by the size of messages, the actual number of clients, the total number of replicas, as well as the cost of the cryptographic primitives being used. There are thus good reasons to believe that new BFT protocols will need to be designed in the future in order to efficiently deal with some specific (possibly new) operating conditions.

In order to address the need to develop new BFT protocols, and to decrease the complexity of this task, we have proposed Abstract. Using Abstract, a BFT protocol is viewed as a composition of instances of our abstraction, with each instance targeting and optimized for specific operating conditions. An instance of Abstract looks like a traditional BFT state machine replication protocol, with one exception: it may sometimes abort a client’s request. The (non-triviality) condition under which Abstract cannot abort is a generic parameter. At one extreme, one can for example specify a (useless) Abstract instance that could abort in every execution. At the other extreme, one can prevent Abstract from ever aborting: in such a case, Abstract implements a standard BFT state machine replication protocol. Interesting Abstract instances are “weaker” ones, in which an abort is allowed, e.g., if there are failures or asynchrony (or even contention). When such an instance aborts a client request, it returns an unforgeable request history that can be used by the client to “recover” using another instance of Abstract. Any composition of Abstract instances is possible; we expect many of these to lead to interesting flexible BFT protocols.

We illustrate the benefits of Abstract by developing two BFT protocols. The first protocol, AZyzzyva, illustrates the ability of Abstract to significantly ease the development of BFT protocols. AZyzzyva is a composition of two Abstract instances. It mimics Zyzzyva [67] when there are no asynchrony or failures and requires about 1/4 of the code of Zyzzyva. The second protocol is Aliph, a protocol that demonstrates the ability of Abstract to develop novel efficient BFT protocols. Aliph uses three Abstract instances. It achieves up to 30% lower latency and up to 360% higher throughput than state-of-the-art BFT protocols.

1.3 Outline

The thesis is organized as follows. Chapter 2 presents the LCR protocol. The Abstract framework is presented in Chapter 3. Chapter 4 concludes the thesis.
Chapter 2

LCR: a Throughput Optimal Total Order Broadcast Protocol

This chapter presents LCR [60, 61, 73], the first throughput optimal uniform total order broadcast protocol. LCR is based on a ring topology. It only relies on point-to-point inter-process communication and has a linear latency with respect to the number of processes. LCR is also fair in the sense that each process has an equal opportunity of having its messages delivered by all processes. We benchmark an implementation of LCR against Spread [3] and JGroups [14], two of the most widely used group communication packages. We show that LCR provides higher throughput than them, over a large number of setups.

2.1 Introduction

As explained in the Introduction of this thesis, uniform total order broadcast (UTO-broadcast) protocols can be used to implement state machine replication [86]. The role of the UTO-broadcast protocol is to ensure that all replicas perform the same operations on their copy in the same order, even if they subsequently fail. UTO-broadcast can be formally defined as follows [62]: (1) Uniform agreement: if a replica delivers a message \( m \), then all correct replicas eventually deliver \( m \); (2) Strong uniform total order: if some replica delivers some message \( m \) before message \( m' \), then a replica delivers \( m' \) only after it has delivered \( m \).

Clearly, even though UTO-broadcast is very useful, not all applications need the strong guarantees that it provides. Some applications might only need reliable or even best-effort broadcast. We will show however that there are no weaker broadcast protocols that can obtain higher throughput than the protocol described in this chapter. In a sense, the strong uniform total order guarantees provided by our protocol are free.

Latency vs. Throughput. Historically, most total order protocols have been devised for low broadcast latency [64, 8, 26, 54, 21, 97]. Latency usually measures the time required to complete a single message broadcast without contention. (It is typically captured by a number of rounds in the classical model of [76]: in that model, at the start of each round a process can send a message to one or more processes. It receives the messages sent by other processes at the end of the round.) On the other hand, very few protocols have been designed for high throughput. Throughput measures the number of broadcasts that the processes can complete per time unit. In some high load environments, e.g. database replication for e-commerce, throughput is often as important, if not more, than latency. Indeed, under high load, the time spent by a message in a queue before being actually disseminated can grow indefinitely. A high throughput broadcast protocol reduces this waiting time.
2.1. INTRODUCTION

![Algorithm A and Algorithm B](image.png)

Figure 2.1: Latency vs. Throughput: comparison of two broadcast algorithms A and B. Process \( p_1 \) initiates the broadcast. Broadcast latency is 2 rounds for A and 3 rounds for B. However, B has higher throughput than A: in algorithm B one broadcast is completed every round, while in algorithm A only one broadcast is completed every 2 rounds.

Maybe not surprisingly, protocols that achieve low latency often fail to provide high throughput. To illustrate this, consider the example depicted in Figure 2.1:

1. In algorithm \( A \), process \( p_1 \) first sends a message to \( p_2 \). In the next step \( p_2 \) forwards the message to \( p_4 \) and at the same time \( p_1 \) sends the message to \( p_3 \).

2. In algorithm \( B \), process \( p_1 \) first sends a message to \( p_2 \). In the next step \( p_2 \) forwards the message to \( p_3 \) and finally \( p_3 \) forwards the message to \( p_4 \).

Algorithm \( A \) has a latency of 2 whereas algorithm \( B \) a latency of 3. Latency wise, \( A \) is better than \( B \). If we look at the throughput however, we see that \( A \) can only start a new broadcast every 2 time units, while \( B \) can broadcast a new message every time unit. Therefore even though the latency of \( B \) is higher than that of \( A \), the maximal throughput of \( B \) is twice that of \( A \).

**Contributions.** In this chapter we present LCR [60, 61, 73], a uniform total order broadcast protocol that is throughput optimal in failure-free periods. LCR relies on point-to-point communication channels between processes. It uses logical clocks and a ring topology (hence the name). The ring topology ensures that each process always sends messages to the same process, thus avoiding any possible collisions. To eliminate bottlenecks, messages in LCR are sequenced using logical vector clocks instead of a dedicated sequencer. Furthermore, the ring topology allows all acknowledgement messages to be piggy-backed, reducing the message overhead. These two characteristics ensure throughput optimality and fairness, regardless of the type of traffic. In our context, fairness conveys the equal opportunity of processes to have their broadcast messages delivered.

We give a full analysis of LCR’s performance and fairness. We also report on performance results based on a C implementation of LCR that relies on TCP channels. The implementations are benchmarked against Spread and JGroups on a cluster of 9 machines and we show that LCR consistently delivers the highest throughput. For instance, with 4 machines, LCR achieves throughput of up to 50% higher than that of Spread and up to 28% higher than that of JGroups.

**Roadmap.** Section 2.2 introduces the relevant system and performance models. Section 2.3 gives an overview of the related work. We describe LCR in Section 2.4, then we give an analytical evaluation of it in Section 2.5, and we report on our experimental evaluation in Section 2.6. Section 2.7 concludes the chapter with some final remarks.
2.2 Model

2.2.1 System Model

Our context is a small cluster of homogeneous machines interconnected by a local area network. In our protocol, each of the \( n \) machines (or processes) creates a TCP connection to only a single process and maintains this connection during the entire execution of the protocol (unless the process fails). Because of the simple communication pattern, the homogeneous environment, and low local area network latency, it is reasonable to assume that, when a TCP connection fails, the server on the other side of the connection failed [46]. We thus directly implement the abstraction of a perfect failure detector (\( P \)) [28] to which each process has access.

2.2.2 Performance Model

Analyzing the performance of a communication abstraction requires a precise distributed system model. Some models only address point-to-point networks, where no native broadcast primitive is available [41, 15]. The model of [91], which was recently proposed to evaluate total order broadcast protocols, assumes that a process cannot simultaneously send and receive a message. This does clearly not capture modern network cards for these provide full duplex connectivity. Round-based models [76] are in that sense more convenient as they assume that a process can send a message to one or more processes at the start of each round, and can receive the messages sent by other processes at the end of the round. Whereas this model is well-suited for proving lower bounds on the latency of protocols, it is however not appropriate for making realistic predictions about the throughput. In particular, it is not realistic to consider that several messages can be simultaneously received by the same process.

In this chapter, we analyze protocols using the model used in [60, 59]. This model assumes that processes can send one message to one (unicast) or more processes (multicast) at the start of each round, but can only receive a single message sent by other processes at the end of the round. If more than one message is sent to the same process in the same round, these messages will be received in different rounds. The rationale behind this model is that machines in a cluster are each connected to a switch via a twisted pair ethernet cable. As modern network cards are full-duplex, each machine can simultaneously send and receive messages. Moreover, as the same physical cable is used to send and receive messages, it makes sense to make the very same assumption on the number of messages that can be received and on the number of messages that can be sent in one round. The model we use can thus be described as follows: in each round \( k \), every process \( p_i \) can execute the following steps:

1. \( p_i \) computes the message for round \( k \), \( m(i,k) \),
2. \( p_i \) sends \( m(i,k) \) to all or a subset of processes,
3. \( p_i \) receives at most one message sent at round \( k \).

In a sense, our model is similar to the Postal model [16] with the addition of a multicast primitive which is available on all current local area networks.

2.2.3 Throughput

Basically, throughput captures the average number of completed broadcasts per round. A complete broadcast of message \( m \) means that all processes delivered \( m \). In this model, a broadcast protocol is optimal if it achieves an average of one complete broadcast per round regardless of the number of broadcasters. Considering a cluster with \( n \) processes, we seek for
2.3 Related Work

The five following classes of UTO-broadcast protocols have been distinguished in the literature [43]: fixed-sequencer, moving sequencer, privilege-based, communication history, and destination agreement. In this section, we only survey time-free protocols, i.e. protocols that do not rely on physical time, since these are the ones comparable to the LCR protocol. The reason is that the assumption of synchronized clocks is not very realistic in practice, especially since clock skew is hard to detect. We also do not discuss protocols with disk writes as in [92] for instance. Our goal (and that of most of the related work surveyed here) is to optimize the broadcasting of messages at the network level.

2.3.1 Fixed Sequencer

In a fixed sequencer protocol [64, 8, 26, 54, 21, 97], a single process is elected as the sequencer and is responsible for the ordering of messages (Figure 2.2). The sequencer is unique, and another process is elected as a new sequencer only in the case of sequencer failure. Three variants of the fixed sequencer protocol exist [11], each using a different communication pattern. Fixed sequencer protocols exhibit linear latency with respect to \( n \) [42], but poor throughput. The sequencer becomes a bottleneck because it must receive the acknowledgments (acks) from all processes\(^1\) and must also receive all messages to be broadcast. Note that this class of protocols is popular for non-uniform total order broadcast protocols since these do not require all processes to send acks back to the sequencer, thus providing much better latency and throughput.

2.3.2 Moving Sequencer

Moving sequencer protocols [31, 96, 66, 40] (Figure 2.3) are based on the same principle as fixed sequencer protocols, but allow the role of the sequencer to be passed from one process to another (even in failure-free situations). This is achieved by a token which carries

\(^{1}\)Acknowledgments in the fixed sequencer can only be piggy-backed when all processes broadcast messages all the time [42].
2.3. RELATED WORK

Figure 2.3: Moving sequencer-based UTO-broadcast.

a sequence number and constantly circulates among the processes. The motivation is to dis-
tribute the load among sequencers, thus avoiding the bottleneck caused by a single sequencer. 
When a process $p$ wants to broadcast a message $m$, it sends it to all other processes. Upon 
receiving $m$, processes store it into a receive queue. When the current token holder $q$ has a 
message in its receive queue, $q$ assigns a sequence number to the first message in the queue 
and broadcasts that message together with the token. For a message $m$ to be delivered, it has 
to be acknowledged by all processes. Acks are gathered by the token. Moving sequencer pro-
tocols have a latency that is worse than that of fixed sequencer protocols [43]. On the other 
hand, these protocols achieve better throughput, although not optimal. Figure 2.3 depicts a 1-
to-$n$ broadcast of one message. It is clear from the figure that it is impossible for the moving 
sequencer protocol to deliver one message per round. The reason is that the token must be re-
ceived at the same time as the broadcast messages. Thus, the protocol cannot achieve optimal 
throughput. Even in the $n$-to-$n$ case, optimal throughput cannot be achieved because at any 
given time there is only one process which can send messages. Thus, the throughput when all 
processes broadcast cannot be higher than when only one process broadcasts. (in Section 2.5.1 
we will show that optimal throughput can only be achieved when all processes broadcast). 
Note that fixed sequencer protocols are often preferred to moving sequencer protocols because 
they are much simpler to implement [43].

2.3.3 Privilege-based Protocols

Figure 2.4: Privilege-based UTO-broadcast.

These protocols [51, 39, 47, 4, 56] rely on the idea that senders can broadcast messages 
only when they are granted the privilege to do so (Figure 2.4). The privilege to broadcast 
(and order) messages is granted to only one process at a time, but this privilege circulates from 
process to process in the form of a token. As with moving sequencer protocols, the throughput 
when all processes broadcast cannot be higher than when only one process broadcasts.

2.3.4 Communication History-based Protocols

As in privilege-based protocols, communication history-based protocols [84, 77, 48, 82, 
81] use sender-based ordering of messages. Nevertheless, they differ by the fact that pro-
cesses can send messages at any time. Messages carry logical clocks that allow processes to observe the messages received by other processes in order to learn when delivering a message does not violate the total order. Communication history-based protocols have poor throughput because they rely on a quadratic number of messages exchanged for each message that is broadcast.

2.3.5 Destination Agreement

In destination agreement protocols, the delivery order results from an agreement between destination processes. Many such protocols have been proposed [29, 20, 75, 53, 7]. They mainly differ by the subject of the agreement: message sequence number, message set, or acceptance of a proposed message order. These protocols have relatively bad performance because of the high number of messages that are generated for each broadcast.

Note that hybrid protocols, combining two different ordering mechanisms have also been proposed [48, 85, 94]. Most of these protocols are optimized for large scale networks instead of clusters, making use of multiple groups or optimistic strategies.

2.4 The LCR Protocol

LCR combines (a) a ring topology for high-throughput dissemination with (b) logical (vector) clocks for message ordering. It is a uniform total order broadcast (UTO-broadcast) protocol exporting two primitives, utoBroadcast and utoDeliver, and ensuring the following four properties:

- **Validity**: if a correct process $p_i$ utoBroadcasts a message $m$, then $p_i$ eventually utoDelivers $m$.
- **Integrity**: for any message $m$, any correct process $p_j$ utoDelivers $m$ at most once, and only if $m$ was previously utoBroadcast by some correct process $p_i$.
- **Uniform Agreement**: if any process $p_i$ utoDelivers any message $m$, then every correct process $p_j$ eventually utoDelivers $m$.
- **Total Order**: for any two messages $m$ and $m'$, if any process $p_i$ utoDelivers $m$ without having delivered $m'$, then no process $p_j$ utoDelivers $m'$ before $m$.

We detail our LCR protocol in the following. We assume a set $\Pi = \{p_0, \ldots, p_{n-1}\}$ of $n$ processes. Processes are organized in a ring: every process has a predecessor and a successor in the ring: $p_0$ is before $p_1$, which is before $p_2$, etc. We call $p_0$ “the first process in the ring”, and $p_{n-1}$ “the last process in the ring”. We first describe how we totally order messages in LCR. We then describe the behavior of the protocol in the absence of failures and then we describe what happens when there is a group membership change, e.g. a node failing or joining/leaving the system.

2.4.1 Total Order Definition

As we explain later in this section, to broadcast a message, a process sends it to its successor, which itself send its its successor, and so on until every process received the message. We define the total order on messages in LCR as the order according to which messages are received by the last process in the ring, i.e. process $p_{n-1}$. To illustrate this, consider any two messages $m_i$ and $m_j$ broadcast by processes $p_i$ and $p_j$, respectively. Assume $i < j$, i.e. $p_i$ is “before” $p_j$ in the ring. In order to determine whether $m_i$ is ordered before $m_j$, it is enough to know whether $p_j$ had received $m_i$ before sending $m_j$. This is achieved using
vector clocks: process $p_j$ is equipped with a logical vector clock $C_{p_j} = (c_k)_{k=0, n-1}$. At any time, the value $C_{p_j}[i]$ represents the number of broadcasts initiated by process $p_i$ that $p_j$ received so far. Before initiating the broadcast of message $m_i$, process $p_i$ increments the number of broadcasts it initiated (stored in $C_{p_i}[i]$) and timestamps $m_i$ with its clock. Upon reception of message $m_i$, process $p_j$ updates its logical clock to take into account message $m_i$: it increments the value stored in $C_{p_j}[i]$. If later $p_j$ sends message $m_j$, it will timestamp $m_j$ with its logical clock that reflects the fact that it received $m_i$ before sending $m_j$. Every process can thus order $m_i$ and $m_j$ by comparing their clocks. More precisely, let us note $C_{m_i}$ (resp. $C_{m_j}$) the logical clock carried by $m_i$ (resp. $m_j$). Message $m_i$ is ordered before $m_j$, noted $m_i \prec m_j$, if and only if $C_{m_i}[i] \leq C_{m_j}[i]$ when $i < j$, and $C_{m_i}[i] < C_{m_j}[i]$ when if $i = j$.

### 2.4.2 Failure-free Behavior

The pseudo-code of the LCR sub-protocol executed in the absence of failures is depicted in Figure 2.5. To broadcast a message $m_i$, process $p_i$ sends $m_i$ to its successor in the ring. The message is then successively forwarded until it reaches the predecessor of $p_i$. Processes forward messages in the order in which they receive them. To ensure total order delivery, each process ensures, before delivering message $m_i$, that it will not subsequently receive a message that is ordered before $m_i$ (according to the order defined in the previous section). Moreover, for the sake of uniform delivery, each process ensures, before delivering $m_i$, that all other processes already received $m_i$ ($m_i$ is stable). These guarantees rely on a local list, denoted pending, used by every process to store messages before they are delivered. Messages in pending are totally ordered according to the order defined above. We now explain when messages stored in pending are delivered.

When the predecessor of $p_i$ receives message $m_i$, it sends an ACK message along the ring. The ACK message is then successively forwarded until it reaches the predecessor of the process that sent it. Upon receiving this ACK message, each process knows (1) that $m_i$ is stable, and (2) that it already received all messages that are ordered before $m_i$. The first point is obvious. The second point can be intuitively explained as follows. Consider a message $m_j$ that is ordered before $m_i$. We know, by definition of the total order on messages, that process $p_{n-1}$ will receive $m_j$ before $m_i$. Provided that messages are forwarded around the ring in the order in which they are received, we know that the predecessor of $p_i$ will receive $m_j$ before sending the ACK for $m_i$. Consequently, no process can receive the ACK for $m_i$ before $m_j$. Once a message has been set to stable, it can be delivered as soon as it becomes first in the pending list.

To illustrate the behavior of LCR, consider the following simple example (Figure 2.6) assuming a system of 4 processes. For simplicity of presentation, we consider that the computation proceeds in rounds. The arrays in Figure 2.6 depict the state of the pending list stored at each process at the end of each round. At the beginning of round (A), processes $p_1$ and $p_3$ broadcast $m_1$ and $m_3$, respectively. Message $m_1$ is the first message broadcast by $p_1$ and the latter did not receive any message before broadcasting $m_1$. Therefore, $C_{m_1} = [0, 1, 0, 0]$.

Similarly, $C_{m_3} = [0, 0, 0, 1]$. At the end of the round, $p_1$ and $p_2$ (resp. $p_3$ and $p_0$) have $m_1$ (resp. $m_3$) in their pending list. During round (B), $p_0$ (resp. $p_2$) forwards $m_3$ (resp. $m_1$). At the end of the round, the pending lists of $p_1$ and $p_3$ contain two messages: $m_1$ and $m_3$. Note that in both lists, $m_3$ is ordered before $m_1$. Indeed, processes know that $m_3$ is ordered before $m_1$ ($m_3 \prec m_1$) because $p_1 < p_3$ and $C_{m_1}[1] > C_{m_3}[1]$, which indicates that when $p_3$ sent $m_3$, it had not yet received $m_1$.

During round (C), $p_1$ (resp. $p_3$) forwards $m_3$ (resp. $m_1$). At the end of the round, all processes have both $m_1$ and $m_3$ in their pending list. Moreover, $p_0$ (resp. $p_2$) knows that message $m_1$ (resp. $m_3$) completed a full round around the ring. Indeed, $p_0$ (resp. $p_2$) is the predecessor of the process that sent $m_1$ (resp. $m_3$). Consequently, $p_0$ (resp. $p_2$) sets $m_1$ (resp. $m_3$) to stable. At that time, $p_0$ (resp. $p_2$) knows that it will
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Figure 2.5: Pseudo-code of the LCR protocol.
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Figure 2.6: Illustration of a run of the LCR protocol with 4 processes.
no longer receive any message that is ordered before $m_1$ (resp. $m_3$). Indeed, if a message $m$ is ordered before $m_1$ (resp. $m_3$), it means, by definition of the total order on messages, that $p_3$ will receive it before $m_1$ (resp. $m_3$). Consequently, $p_0$ (resp. $p_2$) will also receive $m$ before $m_1$ (resp. $m_3$). Although process $p_0$ knows that $m_1$ is stable, it cannot deliver it. Indeed, it first needs to deliver $m_3$ (which is first in its pending list), which it cannot do. The reason is that it does not know yet whether $m_3$ is stable or not. Delivering $m_3$ could violate uniformity. In contrast, process $p_2$ can deliver $m_3$ because it is stable and first in its pending list. Process $p_2$ thus knows that the delivery of $m_3$ respects total order and uniformity. At the start of round (D), $p_0$ (resp. $p_2$) sends an ACK for $m_1$ (resp. $m_3$). These ACK messages are forwarded in rounds E and F until they reach the predecessor of the process which initiated the ACK message: for instance, the ACK for message $m_1$ was initiated by process $p_0$ in round D. It is forwarded until it reaches process $p_3$ in round F. Upon reception of these ACK messages (rounds D, E, F), processes set $m_1$ and $m_3$ to stable and deliver them as soon as they are first in their pending list.

2.4.3 Group Membership Changes

The LCR protocol is built on top of a group communication system [19]: processes are organized into groups, which they can leave or join, triggering a view change protocol. Faulty processes are excluded from the group after crashing. Upon a membership change, processes agree on a new view. When a process joins or leaves the group, a view change event is generated by the group communication layer and the current view $v_r$ is replaced by a new view $v_{r+1}$. This can happen when a process crashes or when a process explicitly wants to leave or join the group. As soon as a new view is installed, it becomes the basis for the new ring topology.

The view change procedure is detailed in Figure 2.7. Note that when a view change occurs, every process first completes the execution (if any) of all other procedures described in Figure 2.5. It then freezes those procedures and executes the view change procedure. The latter works as follows: every process sends its pending list to all other processes. Upon receiving this list, every process adds to its pending list the messages it did not yet receive. Then the processes send back an ACK_RECOVER message. Processes wait until they receive ACK_RECOVER messages from all processes before sending an END_RECOVERY message to all. When a process receives END_RECOVERY messages from all processes, it can deliver all the messages in its pending list. Thus, at the end of the view change procedure, all pending lists have been emptied, which guarantees that all messages from the old view have been handled.

2.4.4 Correctness

In this section, we prove that LCR is a uniform total order broadcast protocol. We proceed by successively proving that LCR ensures the four properties mentioned at the beginning of Section 2.4: validity, integrity, uniform agreement and total order.

**Lemma 2.4.1 (Validity)** If any correct process $p_i$ sends a message $m$, then it eventually emitsDelivers $m$.

Let $p_i$ be a correct process and let $m_i$ be a message broadcast by $p_i$. This message is added to $p_i$’s pending list (Line 7 of Figure 2.5). If there is a membership change, $p_i$ being a correct process, it will be in the new view. Consequently, the view change procedure guarantees that $p_i$ will deliver all messages stored in its pending list (Line 6 of Figure 2.7). It will thus deliver $m_i$. Let us now consider the case when there is no membership change. All processes (including $p_i$) will eventually set $m_i$ to stable (Line 21 of Figure 2.5). This is due to the fact that $m_i$ will be forwarded along the ring (because $C_{m_i}[2]$ is higher than the $i$th value
stored in the clock of each process) until it reaches the predecessor of $p_i$. The latter marks $m_i$ as stable (line 15 of Figure 2.5) and sends an ACK to its successor in the ring containing $C_{m_i}$. Similarly to $m_i$, the ACK message is forwarded along the ring (line 22 of Figure 2.5) until it reaches the predecessor of the predecessor of $p_i$. Upon receiving the ACK message, each process marks $m_i$ as stable. When $p_i$ sets $m_i$ to stable, its pending list starts with a (possibly empty) set of messages $m$ such that $m \prec m_i$ and $m$ has not been yet delivered by $p_i$. Let us call undelivered this set of messages. Let us first remark that this set cannot grow. Consider, for instance, the case of a message $m_i$ sent by a process $p_i$ that precedes $m_i$ (i.e. $m_j \prec m_i$). We know that $p_j$ sent $m_j$ before receiving $m_i$. Consequently, the predecessor of $p_i$ will receive $m_j$ before receiving $m_i$, and thus before sending the ACK for $m_i$. As each process forwards messages in the order in which it receives them, we know that $p_j$ will necessarily receive $m_j$ before receiving the ACK for message $m_i$. Let us now consider every message in undelivered. As there is no membership change, the same reasoning as the one we did for $m_i$ applies to messages in undelivered: every process will eventually set these messages to stable. Consequently, all messages in undelivered will be delivered. Message $m_i$ will thus be first in pending and marked as stable. It will thus also be delivered by $p_i$.

Lemma 2.4.2 (Integrity) For any message $m$, any process $p_j$ uDelivers $m$ at most once, and only if $m$ was previously uBroadcast by some process $p_i$. No spurious message is ever uDelivered by a process as we assume only crash failures. Thus, only messages that have been uBroadcast are uDelivered. Moreover, each process keeps a vector clock $C$, which is updated in such a way that we are sure that every message is only delivered once. Indeed, if there is no membership change, Lines 10 and 18 of Figure 2.5 guarantee that no message can be processed twice by $p_j$. Similarly, when there is a membership change, Line 10 of Figure 2.7 guarantees that process $p_j$ will not deliver messages twice. Moreover, Line 17 of Figure 2.7 guarantees that $p_j$’s vector clock is updated after the membership change, thus preventing the future delivery of messages that have been delivered during the view_change procedure.
Lemma 2.4.3 (Uniform Agreement) If any process $p_i$ \texttt{utoDelivers} any message $m$ in the current view, then every correct process $p_j$ in the current view eventually \texttt{utoDelivers} $m$.

Let $m_k$ be a message sent by process $p_k$ and let $p_i$ be a process that delivered $m_k$ in the current view. There are two cases to consider. In the first case, $p_i$ delivered $m_k$ during a membership change. This means that $p_i$ had $m_k$ in its pending list before executing line 15 of Figure 2.7. Since all correct processes exchange their pending list during the view change procedure, we are sure that all correct processes that did not deliver $m_k$ before the membership change will have it in their pending list before executing line 6 of Figure 2.7. Consequently, all correct processes in the current view will deliver $m_k$. The second case to consider is when $p_i$ delivered $m_k$ outside of a membership change. The protocol ensures that $m_k$ did a full round around the ring before being delivered by $p_i$; indeed $p_i$ can only deliver $m_k$ after having set it to \texttt{stable}, which either happens when it is the predecessor of $p_k$ in the ring or when it receives an ACK for message $m_k$. Consequently, all processes stored $m_k$ in their pending list before $p_i$ delivered it. If a membership change occurs after $p_i$ delivered $m_k$ and before all other correct processes delivered it, the protocol ensures that all correct processes that did not yet deliver $m_k$ will do it (Line 6 of Figure 2.7). If there is no membership change after $p_i$ delivered $m_k$ and before all other processes delivered it, the protocol ensures that an ACK for $m_k$ will be forwarded around the ring, which will cause all processes to set $m_k$ to \texttt{stable}. Each correct process will thus be able to deliver $m_k$ as soon as $m_k$ will be first in the pending list (Line 26 of Figure 2.5). The protocol ensures that $m_k$ will become first eventually. The reasons are the following: (1) the number of messages that are before $m_k$ in the pending list of every process $p_j$ is strictly decreasing, and (2) all messages that are before $m_k$ in the pending list of a correct process $p_j$ will become stable eventually. The first reason is a consequence of the fact that once a process $p_j$ sets message $m_k$ to stable, it can no longer receive any message $m$ such that $m \prec m_k$. Indeed, a process $p_j$ can only produce a message $m_l \prec m_k$ before receiving $m_k$. As each process forwards messages in the order in which it received them, we are sure that the process that will produce an ACK for $m_k$ will have first received $m_l$. Consequently, each process setting $m_k$ to stable will have first received $m_l$. The second reason is a consequence of the fact that for every message that is \texttt{utoBroadcast} in the system, the protocol ensures that an ACK will be forwarded around the ring (Lines 16 and 22 of Figure 2.5), implying that all correct processes will mark the message as stable. Consequently, all correct processes will eventually deliver $m_k$.

Lemma 2.4.4 (Total Order) For any two messages $m$ and $m'$, if any process $p_i$ \texttt{utoDelivers} $m$ without having delivered $m'$, then no process $p_j$ \texttt{utoDelivers} $m'$ before $m$.

We prove the lemma by contradiction. Let $m$ and $m'$ be any two messages and let $p_j$ be a process that \texttt{utoDelivers} $m$ without having delivered $m'$. Consider a process $p_j$ that \texttt{utoDelivers} $m'$ before delivering $m$. Let us denote $t_i$ the time at which $p_i$ delivered $m$ and $t_j$ the time at which $p_j$ delivered $m'$. Let us first note that the protocol ensures that at time $t_i$ (resp. $t_j$), all processes have already received $m$ (resp. $m'$). Indeed, when there is no membership change, a message can only be delivered after it is set to \texttt{stable}, which requires the message to have done a full round around the ring. When there is a membership change, the protocol ensures (by broadcasting messages stored in pending lists and waiting for all processes to have received all broadcast before delivering any message) that all processes have a consistent pending list before delivering messages (Lines 2 to 5 of Figure 2.7).

\textbf{Case 1:} $t_j \leq t_i$. It follows that at time $t_i$, process $p_i$ had already received $m'$. Consequently, $m \prec m'$, otherwise, $p_i$ would have delivered $m'$ first. We will show that in that case, we are sure that $p_j$ received $m$ before $m'$, thus contradicting the fact that it delivered $m'$ before $m$. Let us note $p_k$ the process that \texttt{utoBroadcast} $m$. Provided $m \prec m'$, we know that $p_k$ sent $m$ before receiving $m'$. There are two cases to consider: if there is no membership change before $p_j$ delivers $m'$, as each process forwards messages in the order in which it
received them, we are sure that $p_j$ will receive $m$ before it can set $m'$ to stable. The second case is when there is a membership change before $p_j$ delivers $m'$. Process $p_j$ could not receive $m$ before the membership change, otherwise, it would not deliver $m'$ before $m$ (since we know that $m \prec m'$). Provided that $p_i$ delivers message $m$, we know that this can only happen during the membership change. Indeed, the message can not have been delivered before, otherwise $p_j$ would have received it. Consequently, at the beginning of the view change procedure, $p_i$ has $m$ in its pending list and will send it to all processes. Consequently, $p_j$ will receive $m$ during the view change procedure. In both cases, we are sure that $p_j$ received $m$ before delivering $m'$, which is in contradiction with the fact that it delivered $m'$ before $m$ provided that $m \prec m'$.

Case 2: $t_i < t_j$. It follows that at time $t_j$, process $p_j$ had already received $m$. Consequently, $m' \prec m$, otherwise, $p_j$ would have delivered $m$ first. With a similar reasoning as the one we did for case 1, we know that $p_i$ received $m'$ before delivering $m$, which is in contradiction with the fact that it delivered $m$ without delivering $m'$ provided that $m' \prec m$.

**Theorem 2.4.5** LCR is a uniform total order broadcast protocol.

By lemmas 2.4.1, 2.4.2, 2.4.3, and 2.4.4, we can derive the very fact that the LCR protocol ensures validity, integrity, uniform agreement, and total order. Thus, it is a uniform total order broadcast protocol.

## 2.5 Theoretical Analysis

This section analyzes several key aspects of LCR’s performance from a theoretical perspective. The performance of LCR is evaluated in failure free runs which we expect to be the common case. We prove that LCR is throughput optimal in such case. Then we discuss its fairness.

### 2.5.1 Throughput

In this section we show that the throughput of LCR is optimal and that no other broadcast protocol (even with weaker consistency guarantees) can obtain strictly higher throughput. We do this by proving an upper bound on the performance of any broadcast protocol and show that LCR matches this bound.

**Theorem 2.5.1 (Maximum throughput for any broadcast protocol)** For a broadcast protocol in a system with $n$ processes in the round-based model introduced in Section 2.2.2, the maximum throughput $\mu_{\text{max}}$ in completed broadcasts per round is:

$$\mu_{\text{max}} = \begin{cases} \frac{n}{(n-1)} & \text{if there are } n \text{ senders} \\ 1 & \text{otherwise} \end{cases}$$

We first consider the case with $n$ senders. Each broadcast message must be received at least $n - 1$ times in order to be delivered. The model states that at each round at most $n$ messages can be received. Thus, for $n$ processes to broadcast a message, a minimum of $n - 1$ rounds are necessary. Therefore, on average, at most $n/(n-1)$ broadcasts can be completed each round. In the case with less than $n$ senders it is sufficient to look at a non sending process. Such a process can receive at most 1 message per round and since it doesn’t broadcast any messages itself, it can deliver at most 1 message per round. Since the throughput is defined as the number of completed broadcasts per round, the maximum throughput with less than $n$ senders is equal to 1.
Determining the throughput of LCR is straightforward: processes receive one message per round and the acknowledgements are piggy-backed. Thus LCR allows each process to deliver one message per round if there is at least one sender. When there are \( n \) senders, each process can deliver one message per round broadcast by other processes in addition to its own messages. LCR thus matches the bound of Theorem 2.5.1 and is theoretically throughput optimal. Thus, from a throughput perspective, the strong uniform total order guarantees provided by LCR are free.

### 2.5.2 Fairness

Even though the throughput of LCR as described thus far is optimal, there is still a problem. Consider two processes \( p_1 \) and \( p_2 \) that are neighbors on the ring. If \( p_1 \) is continuously broadcasting messages and \( p_2 \) systematically forwards \( p_1 \)'s messages, then \( p_2 \) cannot broadcast its own messages. Consequently, the protocol is not fair.

Fairness captures the fact that each process has an equal opportunity of having its messages delivered by all processes. Intuitively, the notion of fairness means that in the long run no single process has priority over other processes when broadcasting messages. Said differently, when two processes want to broadcast a large number of messages during a time interval \( \tau \), then each process should have approximately the same number of messages delivered by all processes during \( \tau \).

![Figure 2.8: Illustration of the fairness mechanism as implemented in LCR. Each process has two queues (send and forward) and uses the burst_size, received, and sent variables to determine whether to forward messages or send its own.](image)

The mechanism for ensuring fairness in LCR acts locally at each process. If a process wishes to broadcast a new message, it must decide whether to forward a message received from its predecessor or to send its own. Figure 2.8 provides an illustration of the fairness mechanism as implemented in LCR. Processes have two queues: send and forward. Processes put broadcast requests coming from the application level in their send queue. Messages received from predecessors that need to be forwarded are buffered in the forward queue. When a process has a burst of messages to send (i.e. it has more than one message in its send queue), it uses the burst_size variable to determine whether to forward messages or send its own.
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queue), it piggybacks on the first message it sends an integer burst_size representing the number of messages currently stored in its send queue. Each process keeps a data structure which stores 3 integers per process in the ring: burst_size, received and sent. For each process \( p_i \), the burst_size variable is updated every time \( p_i \) piggybacks a new burst_size value on a message it sends. The received variable keeps track of the number of messages that the process received from \( p_i \) since \( p_i \)'s burst_size has been updated. The sent variable keeps track of the number of messages that the process sent since \( p_i \)'s burst_size has been updated. When the received variable is equal to the burst_size, the three integers kept for process \( p_i \) are reset (i.e. the burst initiated by \( p_i \) is finished). When the process wants to send a message, it retrieves the first message in the forward list. Assume that this message has been sent by process \( p_j \). The process only sends its own message if the received integer stored for \( p_j \) is higher or equal than the sent integer stored for \( p_j \), which intuitively means that since \( p_j \) started its last burst, the process initiated less broadcasts than \( p_j \).

2.5.3 Latency

The theoretical latency of broadcasting a single message is defined as the number of rounds that are necessary from the initial broadcast of message \( m \) until the last process delivers \( m \). The latency of LCR is equal to \( 2n - 2 \) rounds.

2.6 Experimental Evaluation

This section compares the performance of LCR to that of two existing group communication systems: JGroups and Spread. Spread ensures uniform total order delivery of messages, whereas JGroups only guarantees non-uniform total order delivery. The experiments only evaluate the failure free case because failures are expected to be sufficiently rare in the targeted environment. Furthermore, the view change procedure that is used in LCR is similar to that of other total order broadcast protocols [43].

We first present the experimental setting we used in the experiments and then study various performance metrics: throughput, response time, fairness, and CPU consumption. In particular, we show that LCR always achieves a significantly better throughput than Spread and JGroups when all processes broadcast message. We also show that when only one process broadcasts messages, LCR outperforms Spread and has similar performance than JGroups. Regarding response time, we show that LCR exhibits a higher response time than Spread and JGroups when there is only one sender in the system. In contrast, it outperforms both protocols when all processes broadcast messages. Finally, we show that LCR and Spread are both fair and have a low CPU consumption. This contrasts with JGroups that is not fair and has a higher CPU consumption than Spread and LCR.

2.6.1 Experimental Setup

The experiments were run on a cluster of machines with a 1.66GHz bi-processor and 2GB RAM. Machines run the Linux 2.6.30 – 1 SMP kernel and are connected using a Fast Ethernet switch. The raw bandwidth over IP is measured with Netperf [63] between two machines and displayed in Table 2.1.

The LCR protocol is implemented in C (\( \approx 1000 \) lines of code). It relies on the Spread toolkit to provide a group membership layer and uses TCP for communication between processes. As explained in [46], it is reasonable to assume, in an low-latency cluster, that when a TCP connection fails, the server on the other side of the connection failed. It is thus easy to implement the abstraction of a perfect failure detector [28]. Moreover, using TCP, it is not

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2.6. EXPERIMENTAL EVALUATION

### Table 2.1: Raw network performance measured using Netperf.

<table>
<thead>
<tr>
<th>Protocol</th>
<th>Bandwidth</th>
</tr>
</thead>
<tbody>
<tr>
<td>TCP</td>
<td>93 Mb/s</td>
</tr>
<tr>
<td>UDP</td>
<td>93 Mb/s</td>
</tr>
</tbody>
</table>

necessary to implement a message retransmission mechanism: a message sent from a correct process to another correct process will be delivered eventually.

The implementation of LCR is benchmarked against two industry standard group communication systems:

- **Spread.** We use Spread version 4.1 [3]. The message type was set to `SAFE_MESS` which guarantees uniform total order. Spread implements a privilege-based ordering scheme (see Section 2.3.3). A Spread daemon was deployed on each machine. All daemons belong to the same Spread segment. Spread was tuned for bursty traffic according to Section 2.4.3 of the Spread user guide [89]. Our benchmark uses the native C API provided by Spread.

- **JGroups.** We use JGroups version 2.7.0 [14] with the Java HotSpot Server 1.6.0_16 virtual machine. We use the “sequencer” stack that contains the following protocols: UDP, PING, MERGE2, FD_SOCK, FD_ALL, VERIFY_SUSPECT, BARRIER, pbcast.NAKACK, UNICAST, pbcast.STABLE, VIEW_SYNC, pbcast.GMS, SEQUENCER, FC, FRAG2, STATE_TRANSFER. This stack provides non uniform total ordering. It implements a fixed-sequencer ordering scheme without acknowledgements (see Section 2.3.1).

All experiments we present in this section start with a warm-up phase, followed by a phase during which performance are measured. Finally, there is a cool-down phase without measurements. The warm-up and cool-down phases last 5 minutes. The measurement phase lasts 10 minutes.

### 2.6.2 Throughput

To assess the throughput of total order broadcast protocols, we use the following benchmark: \( k \) processes out of the \( n \) processes in the system broadcast messages at a predefined throughput (we call this experiment \( k \)-to-\( n \) broadcast). Each message has a fixed size, which is a parameter of the experiment. Each process periodically computes the throughput at which it delivers messages. The throughput is calculated as the ratio of delivered bytes over the time elapsed since the end of the warm-up phase. The plotted throughput is the average of the values computed by each process.

We first want to confirm our claim that LCR achieves optimal throughput. Figure 2.9 shows the results of an experiment with \( n = 5 \) processes. We vary the number \( k \) of broadcasting processes (X axis). The size of messages broadcast by processes is 10kB. Moreover, each broadcasting processes produce messages at the maximum throughput it can sustain. We first execute LCR without enabling the fairness mechanism described in Section 2.5.2. We observe that the throughput obtained by LCR is far from optimal: in practice, a theoretical throughput of 1 should be equal to the raw link speed between the processes, i.e. 93Mbit/s as shown in Table 2.1. The reason why the throughput is not optimal is that when the fairness mechanism is disabled, senders can broadcast more messages than can be delivered, resulting in overflowing network buffers and the data structures maintained by each process.
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Figure 2.9: LCR throughput with the fairness mechanism disabled in a system with 5 processes. Buffers are quickly saturated, which explains the low throughput.

Figure 2.10 depicts the throughput obtained by LCR when the fairness mechanism is enabled. The throughput clearly improves and is now close to optimal. The reason why the throughput improves is that the fairness mechanism throttles the senders, and does thus prevent them from injecting too many new messages into the ring. Note that the throughput with 5 senders is higher than with fewer senders, the reason being LCR’s theoretical throughput of \( \frac{n}{(n - 1)} \) when all processes are senders. Finally, note that in all subsequent experiments, the fairness mechanism is enabled.

Figure 2.10: LCR throughput with the fairness mechanism enabled in a system with 5 processes. Senders are throttled, which improves the throughput.

The next experiments we present (Figure 2.11 and 2.12) measure the impact of varying the message size on the throughput of LCR, Spread and JGroups for a system with 5 processes.
In the experiment depicted in Figure 2.11, only one process broadcasts messages, whereas all processes broadcast messages in the experiment depicted in Figure 2.12. In both cases, we can observe that if the messages are too small, the throughput of all protocols suffers. This is due to the cost of ordering which remains constant despite a decrease in payload size. We can nevertheless observe that LCR achieves significantly better performance with small messages than Spread and JGroups. To improve performance, it is possible to batch small messages together into bigger messages when the load on the system is high as suggested in [52]. For all further experiments the message size is set to $10\text{kB}$, which is the optimal message size for the three protocols in both the 1-to-\(n\) and \(n\)-to-\(n\) cases.

![Figure 2.11: Throughput with respect to message size for a system of 5 processes with one sender.](image1)

![Figure 2.12: Throughput with respect to message size for a system of 5 processes with 5 senders.](image2)

Having studied the impact of message size, we now study how the throughput evolves as a
function of the number of processes. Figure 2.13 plots the results of an experiment consisting in 1-to-$n$ broadcasts of 10kB messages. The throughput achieved by LCR and JGroups is close to optimal and almost constant despite the increasing number of processes. Note that JGroups does not provide uniformity, and does thus implement a very simple communication pattern: the sender sends its messages to the sequencer, which multicast them to all other processes. Spread’s throughput suffers a bit more from increasing the number of processes. This can be explained by the fact that Spread uses a token to order messages and ensure uniformity. Increasing the number of processes increases the time it takes for the token to circulate among all processes.

Figure 2.13: 1-to-$n$ throughput comparison. The optimal line is constant at 93Mb/s.

Figure 2.14: $n$-to-$n$ throughput comparison. The optimal line is calculated as $n/(n-1) \times 93Mb/s$.

Figure 2.14 plots the throughput as a function of the number of processes in a system
2.6. EXPERIMENTAL EVALUATION

where all processes broadcast 10\(kB\) messages. The optimal line for best effort broadcast \((n/(n - 1))\) times the maximum link speed of 93\(Mb/s\) is plotted as a reference. We can first observe that the throughput of LCR is very close to optimal. Since the optimality line is calculated for best effort broadcast and LCR provides uniform total order broadcast, we can conclude that the ordering, reliability and uniformity properties of LCR are effectively almost free. The throughput of JGroups is almost constant (at 92\(Mb/s\)) and only slightly better than the throughput achieved with only one sender (Figure 2.13). This can be easily explained by the fact that the throughput is limited by the throughput at which the sequencer can broadcast messages to other processes in the system (using IP multicast). The throughput achieved by Spread is better than in the 1-to-n case due to the fact that every process makes use of the token to broadcast the messages it produces. Nevertheless, as in the 1-to-n case, the throughput slightly decreases when the number of processes increases due to the increasing cost of ensuring uniformity (cost that JGroups does not have).

To summarize, we can say that LCR is the only protocol that fully exploits available network links when all processes broadcast messages, which we believe is the common case in many applications. It does thus sustain a significantly higher throughput than other protocols. For instance, the gain in throughput in a system with 4 processes is of about 28% compared to JGroups and of about 49% compared to Spread.

2.6.3 Response Time

In this section, we evaluate the response time of LCR, Spread and JGroups in the 1-to-n and n-to-n cases. We setup a system with 5 processes. We vary the throughput at which the sender processes inject new messages. The size of messages that are broadcast is 10kB. During the measurement phase, for every message \(m\) it broadcasts, the sender evaluates the elapsed time between the broadcast and the delivery of \(m\). For each protocol, we stop the curve when the injected load is higher than the throughput the protocol is able to sustain.

Figure 2.15 depicts the results obtained with one sender. In order to evaluate the general case where every process could be the sender, we do not colocate the sender and the sequencer in JGroups. We observe that Spread exhibits a consistently lower response time than JGroups and LCR (3ms against 4ms for JGroups and 5ms for LCR when the input load is below 10Mb/s). The fact that LCR exhibits higher response time in the 1-to-n case is not surprising provided that processes are organized in a ring topology. Interestingly, LCR’s response time does not degrade when the input load increases. This is in contrast with the response time of JGroups which increases when the input load is greater than 10Mb/s (a similar behavior is observed in the n-to-n case). Finally, a last remark we can make is that, although providing uniform delivery of messages, Spread achieves better response time than JGroups. This is due to the fact that Spread uses a token. Once the sender process obtains the token, it can send messages in burst, thus decreasing the average response time. In JGroups, the sender always needs to first send the message to the sequencer, which will then multicast the message to other processes. Finally, note that the fact that the sender in Spread can send multiple messages in burst when it owns the token also explains why the response time slightly decreases when the load gets higher (between 20Mb/s and 40Mb/s).

Figure 2.16 depicts the results obtained with \(n\) senders (note that the scale used on the Y axis is different than in Figure 2.15). LCR and JGroups exhibit a lower response time than Spread (5.2ms for JGroups against 5.4ms for LCR and 7ms for Spread when the input load is below 10Mb/s). The reason is that with Spread, senders must wait to have the token before sending their messages. As every process has messages to send, it takes a longer time to obtain the token. Note that the response time of Spread is almost constant, and only slightly increases when the maximum delivery throughput is reached. The same remark applies to LCR for which the response time only slightly increases when the input load is higher than 80Mb/s but remains low until the maximum delivery throughput is reached (up
to $108 \text{Mb/s}$, the response time is below $7.5 \text{ms}$). In contrast, the response time of JGroups starts degrading when the input load is higher than $10 \text{Mb/s}$. It becomes high for input loads higher than $70 \text{Mb/s}$. This is probably due to the fact that the sequencer simultaneously receives messages from all other processes, which fills up its network buffers and increases the time it takes for a message to be sequenced.

To summarize, LCR exhibits a higher response time than other protocols when there is only one sender. When there are multiple senders, LCR’s response time equals or outperforms those of other protocols. More precisely, it exhibits better response time than Spread and JGroups (when the load is higher than $20 \text{Mb/s}$), and similar response time than JGroups (when the load is below $20 \text{Mb/s}$), but contrarily to the latter, it ensures uniform delivery of messages and the response time does not degrade when the input load increases.
2.6.4 Fairness

We evaluate the fairness of LCR, JGroups and Spread as follows: we setup a system with 5 processes, of which 3 are senders. Each sender continuously broadcasts messages. At the end of the measurement phase, every process computes the percentage of messages it delivered that were issued by each of the 3 senders (called \( p_1 \), \( p_2 \) and \( p_3 \)). In the case of JGroups, process \( p_1 \) is also the sequencer. The results are depicted in Figure 2.17. We can first observe that both LCR and Spread are fair: each process delivers 33% of messages from each sender. Concerning LCR, this is due to the fact that it implements the fairness mechanism described in Section 2.5.2. Concerning Spread, this is due to the fact that, on average, each sender owns the token for the same amount of time. We can also observe that JGroups is not fair. This comes from the fact that processes \( p_2 \) and \( p_3 \) first need to send their messages to the sequencer \( p_1 \), whereas the latter can directly broadcast the messages it produces. This induces a significant unbalance: 50% of the messages that are delivered have been broadcast by \( p_1 \).

![Figure 2.17: Fairness assessment of the LCR, Spread and JGroups protocols. Experiments were performed with 5 processes and 3 senders.](image)

2.6.5 CPU Usage

The last performance metric we evaluate is the CPU usage of LCR, Spread and JGroups under high load. During the experiment, the CPU usage of all active protocol threads was periodically logged, added up and averaged. We study both the 1-to-\( n \) and \( n \)-to-\( n \) cases.

The experiment in Figures 2.18, 2.19, and 2.20 plot the CPU usage measured in a system with 5 processes, of which one broadcasts 10kB messages. The X axis represents the message size (in kB). The Y axis represents the CPU consumption (in %). To ease the comparison between the various protocols, the three graphs use the same scale. In the case of JGroups, the sender was not sequencer in order to be able to isolate the CPU consumption of the sequencer, the sender and receiver processes, respectively. The first remark we can make is that among the three protocols, JGroups has the highest CPU consumption. In particular, the sequencer process consumed more than 55% of the CPU in all experiments we performed. The sender performs also significantly more work than receiver processes due to the fact that it needs both to send and receive the messages it broadcasts. Spread and LCR have a CPU
usage that is very reasonable: it is systematically below 30% with messages bigger than 1kB.
In LCR, it is interesting to notice that the sender has less work to do than other processes.
The reason is that the sender does not receive messages to forward; it only receives acks. In contrast, the sender and the receivers in Spread use the same percentage of CPU time. Finally, it is interesting to note that Spread uses more CPU than LCR for large messages.

![Figure 2.18: CPU usage during high load 1-to-n broadcasts of the LCR protocol.](image)

![Figure 2.19: CPU usage during high load 1-to-n broadcasts of the Spread protocol.](image)

The experiment in Figure 2.21, 2.22, and 2.23 plot the CPU usage measured in a system with 5 processes, each broadcasting 10kB messages. As was the case with only one sender, we observe that JGroups consumes more CPU than other protocols. Interestingly, the consumption of the sequencer is a bit lower than what it was in the previous experiment. We
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Figure 2.20: CPU usage during high load 1-to-n broadcasts of the JGroups protocol.

explain this by the fact that in this experiment, the sequencer itself broadcasts messages, thus reducing the number of messages it gets from other processes, and thus its CPU consumption. We can also remark that Spread and LCR have a slightly higher CPU usage than in the previous case. This is explained by the fact that both protocols handle more messages (they achieve higher throughput) in the n-to-n case than in the 1-to-n case, thus requiring higher CPU usage. Finally, we observe that, similarly to the previous case, LCR consumes less CPU than Spread when messages are larger.

Figure 2.21: CPU usage during high load n-to-n broadcasts of the LCR protocol.
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Figure 2.22: CPU usage during high load \( n \)-to-\( n \) broadcasts of the Spread protocol.

Figure 2.23: CPU usage during high load \( n \)-to-\( n \) broadcasts of the JGroups protocol.
2.7 Conclusion

In this chapter, we have presented LCR [60, 61, 73], a uniform total order broadcast protocol that can be used as the main communication block of a state machine replication scheme to achieve software-based fault-tolerance.

LCR is the first uniform total order broadcast protocol that is throughput optimal in failure-free periods. In short, throughput optimality captures the ability to deliver the largest possible number of message broadcasts, regardless of message broadcast patterns. This notion is precisely defined in a round-based model of computation which accurately captures message passing interaction patterns over clusters of homogeneous machines interconnected by a fully switched LAN. LCR is based on a ring topology and only relies on point-to-point inter-process communication. LCR is also fair in the sense that each process has an equal opportunity of having its messages delivered by all processes. Performance benchmarks showed that LCR had a very high throughput in all cases, while exhibiting very reasonable response time. Moreover, benchmarks showed that LCR has a low CPU usage.
Chapter 3

ABsTRACT: a Modular Approach to Building BFT Protocols

This chapter presents Abstract [58, 95], a new abstraction to simplify the design, proof and implementation of BFT protocols. We treat a BFT protocol as a composition of instances of our abstraction. Each instance is developed and analyzed independently. To illustrate our approach, we first show how, with our abstraction, the benefits of a BFT protocol like Zyzzyva could have been developed using less than 24% of the actual code of Zyzzyva. We then present Aliph, a new BFT protocol that outperforms previous BFT protocols both in terms of latency (by up to 30%) and throughput (by up to 360%).

3.1 Introduction

In this chapter, we focus on the most robust class of state machine replication (SMR) protocols. These protocols tolerate (a) arbitrarily large periods of asynchrony, during which communication delays and process relative speeds are unbounded, and (b) arbitrary (Byzantine) failures of any client as well as up to one-third of the replicas (this is the theoretical lower bound [70]). These are called Byzantine-Fault-Tolerance SMR protocols, or simply BFT protocols, e.g., PBFT, QU, HQ and Zyzzyva [1, 27, 38, 67]. The ultimate goal of the designer of a BFT protocol is to exhibit comparable performance to a non-replicated server under “common” circumstances that are considered the most frequent in practice. The notion of “common” circumstance might depend on the application and underlying network, but it usually means network synchrony, rare failures, and sometimes also the absence of contention.

Not surprisingly, even under the same notion of “common” case, there is no “one size that fits all” BFT protocol. According to our own experience, the performance differences among the protocols can be heavily impacted by the actual network, the size of the messages, the very nature of the “common” case (e.g., contention or not); the actual number of clients, the total number of replicas as well as the cost of the cryptographic libraries being used. This echoes [87] which concluded for instance that “PBFT [27] offers more predictable performance and scales better with payload size compared to Zyzzyva [67]; in contrast, Zyzzyva offers greater absolute throughput in wider-area, lossy networks”. In fact, besides all BFT protocols mentioned above, there are good reasons to believe that we could design new protocols outperforming all others under specific circumstances. We do indeed present an example of a such protocol in this chapter.

To deploy a BFT solution, a system designer will hence certainly be tempted to adapt a state-of-the-art BFT protocol to the specific application/network setting, and possibly keep
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Adapting it whenever the setting changes. But this can rapidly turn into a nightmare. All protocol implementations we looked at involve around 20,000 lines of (non-trivial) C++ code, for example, PBFT and Zyzzyva. Any change to an existing protocol, although algorithmically intuitive, is very painful. The changes of the protocol needed to optimize for the “common” case have sometimes strong impacts on the part of the protocol used in other cases (e.g., “view-change” in Zyzzyva). The only complete proof of a BFT protocol we knew of is that of PBFT and it involves 35 pages (even without using any formal language). This difficulty, together with the impossibility of exhaustively testing distributed protocols would rather plead for never changing a protocol that was widely tested, for example PBFT.

We propose in this chapter a way to have the cake and eat a big chunk of it. We present Abstract [58, 95] (Abortable Byzantine fault-tolerant state machine replication): a new abstraction to reduce the development cost of BFT protocols. Following the divide-and-conquer principle, we view BFT protocols as a composition of instances of our abstraction, each instance targeted and optimized for specific system conditions. An instance of Abstract looks like BFT state machine replication, with one exception: it may sometimes abort a client’s request.

The progress condition under which an Abstract instance should not abort is a generic parameter. An extreme instance of Abstract is one that never aborts: this is exactly BFT. Interesting instances are “weaker” ones, in which an abort is allowed, for example, if there is asynchrony or failures (or even contention). When such an instance aborts a client request, it returns a request history that is used by the client (proxy) to “recover” by switching to another instance of Abstract, for example, one with a stronger progress condition. This new instance will commit subsequent requests until it itself aborts. This paves the path to composability and flexibility of BFT protocol design. Indeed, the composition of any two Abstract instances is idempotent, yielding yet another Abstract instance. Hence, and as we will illustrate in the chapter, the development (design, test, proof and implementation) of a BFT protocol boils down to:

- Developing individual Abstract instances. This is usually way much simpler than developing a full-fledged BFT protocol and allows for very effective schemes. A single Abstract instance can be crafted solely with its progress in mind, irrespective of other instances.

- Ensuring that a request is not aborted by all instances. This can be made very simple by reusing, as a black-box, an existing BFT protocol as one of the instances, without indulging into complex modifications.

To demonstrate the benefits of Abstract, we present two BFT protocols:

1. AZyzzyva, a protocol that illustrates the ability of Abstract to significantly ease the development of BFT protocols. AZyzzyva is the composition of two Abstract instances: (i) ZLight, which mimics Zyzzyva [67] when there are no asynchrony or failures, and (ii) Backup, which handles the periods with asynchrony/failures by reusing, as a black-box, a legacy BFT protocol. We leveraged PBFT which was widely tested, but could replace it with any BFT protocol. The code line count and proof size required to obtain AZyzzyva are, conservatively, less than 1/4 than those of Zyzzyva. In some sense, had Abstract been identified several years ago, the designers of Zyzzyva would have had a much easier task devising a correct protocol exhibiting the performance they were seeking. Instead, they had to hack PBFT and, as a result, obtained a protocol that is way less stable than PBFT.

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1. It took Roberto De Prisco a PhD (MIT) to formally (using IOA) prove the correctness of a state machine protocol that does not even deal with malicious faults.

2. Abstract can be viewed as a virtual type; each specification of the this progress condition defines a concrete type. These genericity ideas date back to the seminal chapter of Landin: The Next 700 Programming Languages (CACM, March 1966).
2. *Aliph*, a protocol that demonstrates the ability of *Abstract* to develop novel efficient BFT protocols. *Aliph* achieves up to 30% lower latency and up to 360% higher throughput than state-of-the-art protocols. *Aliph* uses, besides the *Backup* instance used in *AZyzyva* (to handle the cases with asynchrony/failures), two new instances: (i) *Quorum*, targeted for system conditions that do not involve asynchrony/failures/contention, and (ii) *Chain*, targeted for high-contention conditions without failures/asynchrony. *Quorum* has a very low-latency (like e.g., [23, 44, 1]) and it makes *Aliph* the first BFT protocol to achieve a latency of only 2 message delays with as few as $3f + 1$ servers. *Chain* implements a pipeline message-pattern, and relies on a novel authentication technique. It makes *Aliph* the first BFT protocol with a number of MAC operations at the bottleneck server that tends to 1 in the absence of asynchrony/failures. This contradicts the claim that the lower bound is 2 [67]. Interestingly, each of *Quorum* and *Chain* could be developed independently and required less than 25% of the code needed to develop state-of-the-art BFT protocols.\(^3\)

The rest of the chapter is organized as follows. Section 3.2 presents *Abstract*. After describing our system model in Section 3.3, we describe and evaluate our new BFT protocols: *AZyzyva* in Section 3.4 and *Aliph* in Section 3.5. We presented related works in Section 3.6 and concludes the chapter. For better readability, details are postponed to appendices. Appendix A contains the formal specification of *Abstract*. Appendix B contains protocol details with the correctness proofs given separately in Appendix C.

### 3.2 Abstract

We propose a new approach for the development of BFT protocols. We view a BFT protocol as a composition of instances of *Abstract*. Each instance is itself a protocol that commits clients’ requests, like any state machine replication (SMR) scheme, except if certain conditions are not satisfied, in which case it can abort requests. These conditions, determined by the developer of the particular instance, capture the progress semantics of that instance. They might depend on the design goals and the environment in which a particular instance is to be deployed. Each instance can be developed, proved and tested independently, and this modularity comes from two crucial properties of *Abstract*:

1. **Switching** between instances is idempotent: the composition of two *Abstract* instances yields yet another *Abstract* instance.

2. **BFT** is nothing but a special *Abstract* instance — *one that never aborts*.

A correct implementation of an *Abstract* instance always preserves BFT safety — this extends to any composition thereof. The designer of a BFT protocol only has to make sure that: a) individual *Abstract* implementations are correct, *irrespectively of each other*, and b) the composition of the chosen instances is live: i.e. that every request will eventually be committed. We exemplify this later, in Sections 3.4 and 3.5. In the following, we highlight the main characteristics of *Abstract*. For better readability, precise specification of *Abstract* and our theorem on *Abstract* switching idempotency are postponed to Appendix A.

#### 3.2.1 Switching

Every *Abstract* instance has a unique identifier (instance number) $i$. When an instance $i$ commits a request, $i$ returns a state-machine reply to the invoking client. Like any SMR

\(^3\)Our code counts are in fact conservative since they do not discount for the libraries shared between *ZLight*, *Quorum* and *Chain*, which amount to 10% of a state-of-the-art BFT protocol.
Abstract instance #1
Client A
request #1
commit #1
request #50
abort #50, hist_1, next=2
commit #50

Abstract instance #2
Client A
request #50, hist_1, next=2
commit #51
request #51, hist_1, next=2
abort #51, hist_1, next=2

Abstract instance #3
Client C
abort #130, hist_2, next=3
request #130
commit #130
request #131
commit #131

Figure 3.1: Abstract operating principle.
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scheme, \( i \) establishes a total order on all committed requests according to which the reply is computed for the client. If, however, \( i \) aborts a request, it returns to the client a digest of the history of requests \( h \) that were committed by \( i \) (possibly along with some uncommitted requests); this is called an abort history. In addition, \( i \) returns to the client the identifier of the next instance (\( \text{next}(i) \)) which should be invoked by the client: \( \text{next} \) is the same function across all abort indications of instance \( i \), and we say instance \( i \) switches to instance \( \text{next}(i) \). In the context of this chapter, we consider \( \text{next} \) to be a pre-determined function (e.g., known to servers implementing a given Abstract instance); we talk about deterministic or static switching. However, this is not required by our specification; \( \text{next}(i) \) can be computed “on-fly” by the Abstract implementation (e.g., depending on the current workload, or possible failures or asynchrony) as long as \( \text{next} \) remains a function. In this case, we talk about dynamic switching; this is out of the scope of this chapter.

The client uses abort history \( h \) of \( i \) to invoke \( \text{next}(i) \); in the context of \( \text{next}(i) \), \( h \) is called an init history. Roughly speaking, \( \text{next}(i) \) is initialized with an init history, before it starts committing/aborting clients’ requests. The initialization serves to transfer to instance \( \text{next}(i) \) the information about the requests committed within instance \( i \), in order to preserve total order among committed requests across the two instances.

Once \( i \) aborts some request and switches to \( \text{next}(i) \), \( i \) cannot commit any subsequently invoked request. We impose switching monotonicity: for all \( i, \text{next}(i) > i \). Consequently, Abstract instance \( i \) that fails to commit a request is abandoned and all clients go from there on to the next instance, never re-invoking \( i \).

3.2.2 Illustration

Figure 3.1 depicts a possible run of a BFT system built using Abstract. To preserve consistency, Abstract properties ensure that, at any point in time, only one Abstract instance, called active, may commit requests. Client A starts sending requests to the first Abstract instance. The latter commits requests \#1 to \#49 and aborts request \#50, becoming inactive. Abstract appends to the abort indication an (unforgeable) history (\( \text{hist}_1 \)) and the information about the next Abstract instance to be used (\( \text{next} = 2 \)). Client A sends to the new Abstract instance both its uncommitted request (\#50) and the history returned by the first Abstract instance. Instance \#2 gets initialized with the given history and executes request \#50. Later on, client B sends request \#51 to the first Abstract instance. The latter returns an abort indication with a possibly different history than the one returned to client A (yet both histories must contain previously committed requests \#1 to \#49). Client B subsequently sends request \#51 together with the history to the second abstract instance. The latter being already initialized, it simply ignores the history and executes request \#51. The second abstract instance then executes the subsequent requests up to request \#130 which it aborts. Client B uses the history returned by the second abstract instance to initialize the third abstract instance. The latter executes request \#130. Finally, Client C sends request \#131 to the third instance, that executes it. Note that unlike Client B, Client C directly accesses the currently active instance. This is possible if Client C knows which instance is active, or if all three Abstract instances are implemented over the same set of replicas: replicas can then, for example, ‘tunnel’ the request to the active instance.

3.2.3 A View-Change Perspective

In some sense, an Abstract instance number can be seen as a view number, e.g., in PBFT [27]. Like in existing BFT protocols, which merely reiterate the exact same sub-protocol across the views (possibly changing the server acting as leader), the same Abstract

\footnote{The opposite however does not hold, since multiple views of a given BFT protocol can be captured within a single Abstract instance.}
implementations can be re-used (with increasing instance numbers). However, unlike existing BFT protocols, Abstract compositions allow entire sub-protocols to be changed on a ‘view-change’ (i.e., during switching).

3.2.4 Misbehaving Clients

Clients that fail to comply with the switching mechanism (e.g., by inventing/forging an init history) cannot violate the Abstract specification. Indeed, to be considered valid, an init history of next(i) must be previously returned by the preceding Abstract i as an abort history. To enforce this causality, in practice, our Abstract compositions (see Sec. 3.4 and Sec. 3.5) rely on unforgeable digital signatures to authenticate abort histories in the presence of potentially Byzantine clients. View-change mechanisms employed in existing BFT protocols [27, 67], have similar requirements: they exchange digitally signed messages.

3.3 System Model

We assume a message-passing distributed system using a fully connected network among processes: clients and servers. The links between processes are asynchronous and unreliable: messages may be delayed or dropped (we speak of link failures). However, we assume fairness links: a message sent an infinite number of times between two correct processes will be eventually received. Processes are Byzantine fault-prone; processes that do not fail are said to be correct. A process is called benign if it is correct or if it fails by simply crashing. In our algorithms, we assume that any number of clients and up to f out of 3f + 1 servers can be Byzantine. We assume a strong adversary that can coordinate faulty nodes; however, we assume that the adversary cannot violate cryptographic techniques like collision-resistant hashing, message authentication codes (MACs), and signatures.

We further assume that during synchronous periods (i.e., when there are no link failures) any message m sent between two correct processes is delivered within a bounded delay ∆ (known to sender and receiver) if the sender retransmits m until it is delivered.

Finally, we declare contention in an Abstract instance whenever there are two concurrent requests such that both requests are invoked but not yet committed/aborted.

3.4 Putting Abstract to Work: AZyzzyva

We illustrate how Abstract significantly eases the design, implementation, and proof of BFT protocols with AZyzzyva. This is a full fledged BFT protocol that mimics Zyzzyva [67] in its “common case” (i.e., when there are no link or server failures). In “other cases” we rely on Backup, an Abstract implementation with strong progress guarantees that can be implemented on top of any existing BFT protocol. In our implementation, we chose PBFT [27] for it has been extensively tested and proved correct. We chose to mimic Zyzzyva, for it is known to be efficient, yet very difficult to implement [35]. Using Abstract, we had to write, prove and test less than 24% of the Zyzzyva code to obtain AZyzzyva.

In the “common case”, Zyzzyva executes the fast speculative path depicted in Figure 3.2. A client sends a request to a designated server, called primary (r1 in Fig. 3.2). The primary appends a sequence number to the request and broadcasts the request to all replicas. Each replica speculatively executes the request and sends a reply to the client. All messages in the above sequence are authenticated using MACs rather than (more expensive) digital signatures. The client commits the request if it receives the same reply from all 3f + 1 replicas. Otherwise, Zyzzyva executes a second phase that aims at handling the case with link/server/client failures (“worst-case”). Roughly, this phase (that AZyzzyva avoids to mimic) consists of considerable modifications to PBFT [27], which arise from the “profound
effects” [67], that the Zyzzyva “common-case” optimizations have on its “worst-case”. The second phase is so complex that, as confessed by the authors themselves [35], it is not entirely implemented in the current Zyzzyva prototype. In fact, when this second phase is stressed, due to its complexity and the inherent bugs that it contains, the throughput of Zyzzyva drops to 0.

In the following, we describe how we build AYyzzyva, assess the qualitative benefit of using Abstract and discuss the performance of AYyzzyva.

3.4.1 Protocol Overview

Our goal when building AYyzzyva using Abstract is to show that we can completely separate the concerns of handling the “common-case” and the “worst-case”. We thus use two different Abstract implementations: ZLight and Backup. Roughly, ZLight is a Abstract that guarantees progress in the Zyzzyva “common-case”. On the other hand, Backup is an Abstract with strong progress: it guarantees to commit an exact certain number of requests \( k \) (\( k \) is itself configurable) before it starts aborting.

We then simply construct AYyzzyva such that every odd (resp., even) Abstract instance is ZLight (resp., Backup). ZLight is first executed. When it aborts, it switches to Backup, which commits the next \( k \) requests. Backup then aborts subsequent requests and switches to (a new instance of) ZLight, and so on.

Note that ZLight uses a lightweight checkpointing protocol (shared with Aliph’s Quorum and Chain, Sec. 3.5) triggered every 128 messages to truncate histories (see Sec. B.6.1).

In the following, we briefly describe ZLight and Backup. Details are postponed to Appendix B, whereas correctness proofs can be found in Appendix C.

3.4.2 ZLight

ZLight implements Abstract with the following progress property which reflects Zyzzyva “common case”: it commits requests when (a) there are no server or link failures, and (b) no client is Byzantine (simple client crash failures are tolerated). When this property holds, ZLight implements Zyzzyva “common-case” pattern (Fig. 3.2), described earlier. Outside the “common-case”, when a client does not receive \( 3f+1 \) consistent replies, the client sends a \textsc{PANIC} message to replicas. Upon reception of this message, replicas stop executing requests and send back a signed message containing their history (replicas will now send the same abort message for all subsequent requests). When the client receives \( 2f+1 \) signed messages containing replica histories, it can generate an abort history and switch to Backup. Client generates abort history \( ah \) such that \( ah[j] \) equals the value that appears at position \( j \geq 1 \) of

![Figure 3.2: Communication pattern of ZLight.](image-url)
$f + 1$ different replica histories (the details of the panic and switching mechanisms are in the appendix, in Sec. B.5 and B.6, respectively).

### 3.4.3 Backup

Backup is an Abstract implementation with a progress property that guarantees exactly $k \geq 1$ requests to be committed, where $k$ is a generic parameter (we explain our configuration for $k$ at the end of this section). We employ Backup in AZyzzyva (and Aliph) to ensure progress outside “common-cases” (e.g., under replica failures).

We implemented Backup as a very thin wrapper (around 600 lines of C++ code) that can be put around any existing BFT protocol. In our C/C++ implementations, Backup is implemented over PBFT [27], for PBFT is the most extensively tested BFT protocol and it is proven correct. Other existing BFT protocols that provide robust performance under failures, like Aardvark [35], are also very good candidates for the Backup basis (unfortunately, the code of Aardvark is not yet publicly available).

To implement Backup, we exploit the fact that any BFT can totally order requests submitted to it and implement any functionality on top of this total order. In our case, Backup is precisely this functionality. Backup works as follows: it ignores all the requests delivered by the underlying BFT protocol until it receives a request containing a valid init history, i.e., an unforgeable abort history generated by the preceding Abstract (ZLight in the case of AZyzzyva). At this point, Backup sets its state by executing all the requests contained in a valid init history it received. Then, it simply executes the first $k$ requests ordered by BFT (neglecting subsequent init histories) and commits these requests. After committing the $k$th request, Backup aborts all subsequent requests returning the signed sequence of executed requests as the abort history (replica digital signature functionality assumed here is readily present in all existing BFT protocols we know of).

The parameter $k$ is generic and is an integral part of the Backup progress guarantees. Our default configuration increases $k$ exponentially, with every new instance of Backup. This ensures the liveness of the composition, which might not be the case with, say, a fixed $k$ in a corner case with very slow clients. More importantly, in the case of failures, we actually do want to have a Backup instance remaining active for long enough, since Backup is precisely targeted to handle failures. On the other hand, to reduce the impact of transient link failures, which can drive $k$ to high values and thus confine clients to Backup for a long time after the transient failure disappears, we flatten the exponential curve for $k$ to maintain $k = 1$ during some targeted outage time. In our implementation, we also periodically reset $k$. Dynamically adapting $k$ to fit the system conditions is appealing but requires further studies and is out of the scope of this chapter.

### 3.4.4 Qualitative Assessment

In evaluating the effort of building AZyzzyva, we focus on the cost of ZLight. Indeed, Backup, for which the additional effort is small (around 600 lines of C++ code), can be reused for other BFT protocols in our framework. For instance, we use Backup in our Aliph protocol as well (Sec. 3.5).

Table 3.1 compares the number of pages of pseudo-code, pages of proofs and lines of code of Zyzzyva and ZLight. The comparison in terms of lines of code is fair, since Zyzzyva and

---

3In short, $k$ requests committed by a single Backup instance $i$ might all be invoked by the same, fast client. A slow client can then get its request aborted by $i$. The same can happen with a subsequent Backup instance, etc. This issue can be avoided by exponentially increasing $k$ (for any realistic load that does not increase faster than exponentially) or by having the replicas across different Abstract instances share a client input buffer.

4For example, using $k = \lceil C \times 2^{m} \rceil$, where $m$ is incremented with every new Abstract instance, with the rough average time of 50ms for switching between 2 consecutive Backup instances in AZyzzyva, we can maintain $k = 1$ during 10s outages with $C = 2^{-200}$. 

---
3.4. PUTTING ABSTRACT TO WORK: AZYZZYVA

all protocols presented in this chapter use the same code base (inherited from PBFT [27]). Notice that, all implementations in the PBFT code base, share about 7500 lines of code implementing cryptographic functions, data structures (e.g. maps, sets), etc. We do not count these lines, which we packaged in a separate library. The code line comparison shows that to build ZLight we needed less than 24% of the Zyzzyva line count (14339 lines). This is, however, conservative since we needed only about 14% to implement ZLight “common case”; the remaining 10% (1391 lines) are due to panicking and checkpointing mechanisms, which are all shared among ZLight, Quorum and Chain (the latter two are used in Aliph, Sec. 3.5). The difference in the ZLight vs. Zyzzyva code size is that ZLight aborts as soon as the system conditions fall outside the “common-case” (in which case A Zyzzya shifts the load to Backup). Hence, we avoid the “common-case”/“worst-case” code dependency that plagued Zyzzva.

Using the same syntax as the one used in the original Zyzzva chapter [67], ZLight requires approximately half a page of pseudo-code, its plain-english proof requires about 1 page (see Sec. C.1). In comparison, the pseudo-code of Zyzzyva (without checkpointing) requires 4.5 pages, making it about 9 times bigger than that of ZLight. Due to the complexity of Zyzzva, the authors first presented a version using signatures and then explained how to modify it to use MACs. The correctness proof of the Zyzzyva signature version requires 4 (double-column) pages, whereas the proof for the MAC version is only sketched.

<table>
<thead>
<tr>
<th></th>
<th>Zyzzyva</th>
<th>ZLight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pages of pseudo-code</td>
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<td>0,5</td>
</tr>
<tr>
<td>Pages of proofs</td>
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<td>1</td>
</tr>
<tr>
<td>Lines of code</td>
<td>14339</td>
<td>3358</td>
</tr>
</tbody>
</table>

Table 3.1: Complexity comparison of Zyzzva and ZLight.

3.4.5 Performance Evaluation

We have compared the performance of A Zyzzya and Zyzzva in the “common-case”, using the benchmarks described in Section 3.5.2. Not surprisingly, A Zyzzya and Zyzzva have the exact same performance in this case. In this section, we do thus focus on the cost induced by Abstract switching mechanism when the operating conditions are outside the common-case (and ZLight aborts a request). We could not compare against Zyzzva. Indeed, as explained above, it has bugs in the second phase in charge of handling faults, which makes its impossible to evaluate the current prototype outside the “common-case”.

To assess the switching cost, we perform the following experiments: we feed the request history of ZLight with $r$ requests of size 1kB. We then issue 10000 successive requests. To isolate the cost of the switching mechanism, we do not execute the ZLight common case; the measured time comprises the time required (1) by the client to send a PANIC message to ZLight replicas, (2) by the replicas to generate and send a signed message containing their history, (3) by the client to invoke Backup with the abort/init history, and (4) by the (next) client to get the abort history from Backup and initialize the next ZLight instance. Note that we deactivate the functions in charge of updating the history of ZLight, so that we ensure that for each aborted request, the history contains $r$ requests. We reproduced each experiment three times and observed a negligible variance.

Figure 3.3 shows the switching time (in ms) as a function of the history size when the number of tolerated faults equals 1. As mentioned above, ZLight uses a checkpointing mechanism triggered every 128 requests. To account for requests that might be received by servers while they are performing a checkpoint, we assume that the history size can grow up to 250 requests. We plot two different curves: one corresponds to the case when replicas do not
miss any request. The other one corresponds to the case when replicas miss requests. More precisely, we assess the performance when 30% of the requests are absent from the history of at least one replica. Not surprisingly, we observe that the switching cost increases with the history size and that it is slightly higher in the case when replicas miss requests (as replicas need to fetch the requests they miss). Interestingly, we see that the switching cost is very reasonable. It ranges between 19.7 ms and 29.2 ms, which is low provided faults are supposed to be rare in the environment for which Zyzzyva has been devised.

![Figure 3.3: Switching time in function of history size and percentage of missing requests in replica histories.]

### 3.5 Putting Abstract to Really Work: Aliph

In this section, we demonstrate how we can build novel, very efficient BFT protocols, using Abstract. Our new protocol, called Aliph, achieves up to 30% lower latency and up to 360% higher throughput than state-of-the-art protocols. The development of Aliph consisted in building two new instances of Abstract, each requiring less than 25% of the code of state-of-the-art protocols, and reusing Backup (Sec. 3.4.3). In the following, we first describe Aliph and then we evaluate its performance.

#### 3.5.1 Protocol Overview

The characteristics of Aliph are summarized in Table 3.2, considering the metrics of [67]. In short, Aliph is the first optimally resilient protocol that achieves a latency of 2 one-way message delays when there is no contention. It is also the first protocol for which the number of MAC operations at the bottleneck replica tends to 1 (under high contention when batching of messages is enabled): 50% less than required by state-of-the-art protocols.

Aliph uses three Abstract implementations: Backup (introduced in Sec. 4.3), Quorum and Chain (both described below). A Quorum instance commits requests as long as there are no: (a) server/link failures, (b) client Byzantine failures, and (c) contention. Quorum implements a very simple communication pattern and gives Aliph the low latency flavor when its progress conditions are satisfied. On the other hand, Chain provides exactly the same progress guarantees as ZLight (Sec. 3.4.2), i.e., it commits requests as long as there are no
Table 3.2: Characteristics of state-of-the-art BFT protocols. Row 1 is the number of replicas. Row 2 is the throughput in terms of number of MAC operations at the bottleneck server (assuming batches of b requests). Row 3 is the latency in terms of number of 1-way messages in the critical path. Bold entries denote protocols with the lowest known cost.

server/link failures or Byzantine clients. Chain implements a pipeline pattern and, as we show below, allows Aliph to achieve better peak throughput than all existing protocols. Both Quorum and Chain share the panicking mechanism with ZLight, which is invoked by the client when it fails to commit the request.

Aliph uses the following static switching ordering to orchestrate its underlying protocols: Quorum-Chain-Backup-Quorum-Chain-Backup—etc. Initially, Quorum is active. As soon as it aborts (e.g., due to contention), it switches to Chain. Chain commits requests until it aborts (e.g., due to asynchrony). Aliph then switches to Backup, which executes k requests (see Sec. 3.4.3). When Backup commits k requests, it aborts, switches back to Quorum, and so on.

In the following, we first describe Quorum (Sec. 3.5.1.1) and Chain (Sec. 3.5.1.2) (full details and correctness proofs can be found in Appendix B and C, respectively). Then, we discuss some system-level optimizations of Aliph (Sec. 3.5.1.3).

3.5.1.1 Quorum

Quorum implements a very simple communication pattern (see Fig. 3.4); it requires only one round-trip of message exchange between a client and replicas to commit a request. Namely, the client sends the request to all replicas that speculatively execute it and send a reply to the client. As in ZLight, replies sent by replicas contain a digest of their history. The client checks that the histories sent by the 3f + 1 replicas match. If that is not the case, or if the client does not receive 3f + 1 replies, the client invokes a panicking mechanism. This is the same as in ZLight (Sec. 3.4.2): (i) the client sends a PANIC message to replicas, (ii) replicas stop executing requests on reception of a PANIC message, (iii) replicas send back a signed message containing their history. The client collects 2f + 1 signed messages containing replica histories and generates an abort history. Note that, unlike ZLight, Quorum does not tolerate contention: concurrent requests can be executed in different orders by different replicas. This is not the case in ZLight, as requests are ordered by the primary.

The implementation of Quorum is very simple. It requires 3200 lines of C code (including panicking and checkpoint libraries). Quorum makes Aliph the first BFT protocol to achieve a latency of 2 one-way message delays, while only requiring 3f + 1 replicas (Q/U [1] has the same latency but requires 5f + 1 replicas). Given its simplicity and efficiency, it might seem surprising not to have seen it published earlier. We believe that Abstract made that possible because we could focus on weaker (and hence easier to implement) Abstract specifications, without caring about (numerous) difficulties outside the Quorum “common-case”.

3.5.1.2 Chain

Chain organizes replicas in a pipeline (see Fig. 3.5). All replicas know the fixed ordering of replica IDs (called chain order); the first (resp., last) replica is called the head (resp., the tail). Without loss of generality we assume an ascending ordering by replica IDs, where the head (resp., tail) is replica r_1 (resp., r_{3f+1}).
3.5. PUTTING ABSTRACT TO REALLY WORK: ALIPH

Figure 3.4: Communication pattern of *Quorum*.

Figure 3.5: Communication pattern of *Chain*.
In Chain, a client on invoking a request, sends the request req to the head, who assigns sequence numbers to requests. Then, each replica \( r_i \) forwards the message to its successor \( r_i' \), where \( r_i' = r_{i+1} \). The exception is the tail whose successor is the client: upon receiving the message, the tail sends the reply to the client. Similarly, replica \( r_i \) in Chain accepts a message only if sent by its predecessor \( r_i' \), where \( r_i' = r_{i-1} \); the exception is the head, which accepts requests only from the client.

The behavior of Chain, as described so far, is very similar to the protocol described in [93]. That protocol, however, did only tolerate crash faults. We tolerate Byzantine failures by ensuring: (1) that the content of a message is not modified by a malicious replica before being forwarded, (2) that no replica in the chain is bypassed, and (3) that the reply sent by the tail is correct. To provide those guarantees, our Chain relies on a novel authentication method we call chain authenticators (CAs). CAs are lightweight MAC authenticators, requiring processes to generate (at most) \( f + 1 \) MACs (in contrast to 3\( f + 1 \) in traditional authenticators). CAs guarantee that, if a client commits request \( req \), every correct replica executed \( req \). CAs, along with the inherent throughput advantages of a pipeline pattern, are key to Chain's dramatic throughput improvements over other BFT protocols. We describe below how CAs are used in Chain.

Replicas and clients generate CAs in order to authenticate the messages they send. Each CA contains MACs for a set of processes called successor set. The successor set of clients consists of the \( f + 1 \) first replicas in the chain. The successor set of a replica \( r_i \) depends on its position \( i \): (a) for the first \( 2f \) replicas, the successor set comprises the next \( f + 1 \) replicas in the chain, whereas (b) for other replicas \( (i > 2f) \), the successor set comprises all subsequent replicas in the chain, as well as the client. Dually, when process \( p \) receives a message \( m \) it verifies \( m \), i.e., it checks whether \( m \) contains a correct MAC from the processes from \( p \)’s predecessor set (a set of processes \( q \) such that \( p \) is in \( q \)’s successor set). For instance, process \( p_1 \) verifies that the message contains a valid MAC from process \( p_0 \) and the client, whereas the client verifies that the reply it gets contains a valid MAC from the last \( f + 1 \) replicas in the chain. Finally, to make sure that the reply sent by the tail is correct, the \( f \) processes that precede the tail in the chain append a digest of the response to the message.

When the client receives a correct reply, it commits it. On the other hand, when the reply is not correct, or when it does not receive any reply (e.g., due to the Byzantine tail which discards the request), the client broadcasts a PANIC message to replicas. As in ZLight and Quorum, when replicas receive a PANIC message, they stop executing requests and send back a signed message containing their history. The client collects \( 2f + 1 \) signed messages containing replica histories and generates an abort history.

Chain’s implementation requires 3300 lines of code (with panic and checkpoint libraries). Moreover, it is the first protocol in which the number of MAC operations at the bottleneck replica tends to 1. This comes from the fact that, under contention, the head of the chain can batch requests. Head and tail do thus need to read (resp. write) a MAC from (resp. to) the client, and write (resp. read) \( f + 1 \) MACs for a batch of requests. Thus for a single request, head and tail perform \( 1 + \frac{f+1}{f} \) MAC operations. Note that all other replicas process requests in batch, and have thus a lower number of MAC operations per request. State-of-the-art protocols [67, 27] do all require at least 2 MAC operations at the bottleneck server (with the same assumption on batching). The reason why this number tends to 1 in Chain can be intuitively explained by the fact that these are two distinct replicas that receive the request (the head) and send the reply (the tail).

### 3.5.1.3 Optimizations

When a Chain instance is executing in Aliph, it commits requests as long as there are no server or link failures. In the Aliph implementation we benchmark in the evaluation, we slightly modified the progress property of Chain so that it aborts requests as soon as
replicas detect that there is no contention (i.e. there is only one active client since at least 2s). Moreover, Chain replicas add an information in their abort history to specify that they aborted because of the lack of contention. We slightly modified Backup, so that in such case, it only executes one request and aborts. Consequently, Aliph switches to Quorum, which is very efficient when there is no contention. Finally, in Chain and Quorum we use the same checkpoint protocol as in ZLight.

3.5.2 Evaluation

This section evaluates the performance of Aliph. For lack of space, we focus on experiments without failures (of processes or links), since we compare to protocols that are known to perform well in the common-case — PBFT [27], Q/U [1] and Zyzzyva [67].

We first study latency, throughput, and fault scalability using Castro’s microbenchmarks [27, 67], varying the number of clients. Clients invoke requests in closed-loop (meaning that a client does not invoke a new request before it commits a previous one). In the x/y microbenchmark, clients send x kB requests and receive y kB replies. We also perform an experiment in which the input load dynamically varies.

We evaluate PBFT and Zyzzyva because the former is considered the “baseline” for practical BFT implementations, whereas the latter is considered state-of-the-art. Moreover, Zyzzyva systematically outperforms HQ [67]; hence, we do not evaluate HQ. Finally, we benchmark Q/U as it is known to provide better latency than Zyzzyva under certain condition. Note that Q/U requires 5f + 1 servers, whereas other protocols we benchmark only require 3f + 1 servers.

PBFT and Zyzzyva implement two optimizations: request batching by the primary, and client multicast (in which clients send requests directly to all the servers and the primary only sends ordering messages). All measurements of PBFT are performed with batching enabled as it always improves performance. This is not the case in Zyzzyva. Therefore, we assess Zyzzyva with or without batching depending on the experiment. As for the client multicast optimization, we show results for both configurations every time we observe an interesting behavior.

PBFT code base underlies both Zyzzyva and Aliph. To ensure that the comparison with Q/U is fair, we evaluate its simple best-case implementation described in [67].

We ran all our experiments on a cluster of 17 identical machines, each equipped with a 1.66GHz bi-processor and 2GB of RAM. Machines run the Linux 2.6.18 kernel and are connected using a Gigabit ethernet switch.

3.5.2.1 Latency

<table>
<thead>
<tr>
<th></th>
<th>0/0 benchmark</th>
<th>4/0 benchmark</th>
<th>0/4 benchmark</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>f=1</td>
<td>f=2</td>
<td>f=3</td>
</tr>
<tr>
<td>Q/U</td>
<td>8%</td>
<td>14,9%</td>
<td>33,1%</td>
</tr>
<tr>
<td>Zyzzyva</td>
<td>31,6%</td>
<td>31,2%</td>
<td>34,5%</td>
</tr>
<tr>
<td>PBFT</td>
<td>49,1%</td>
<td>48,8%</td>
<td>44,5%</td>
</tr>
</tbody>
</table>

Table 3.3: Latency improvement of Aliph for the 0/0, 4/0, and 0/4 benchmarks.

We first assess the latency in a system without contention, with a single client issuing requests. The results for all microbenchmarks (0/0, 0/4 and 4/0) are summarized in Table 3.3 demonstrating the latency improvement of Aliph over Q/U, PBFT, and Zyzzyva. We show results for a maximal number of server failures f ranging from 1 to 3. Our results show that Aliph consistently outperforms other protocols, since Quorum is active when there is
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no contention. These results confirm the theoretical expectations (see Table 3.2, Sec. 3.5.1). The results show that Q/U also achieves a good latency with \( f = 1 \), as Q/U and Quorum use the same communication pattern. Nevertheless, when \( f \) increases, performance of Q/U decreases significantly. The reason is that Q/U requires \( 5f + 1 \) replicas and both clients and servers perform additional MAC computations compared to Quorum. Moreover, the significant improvement of Aliph over Zyzzyva (31% at \( f = 1 \)) can be easily explained by the fact that Zyzzyva requires 3-one-way message delays in the common case, whereas Aliph (Quorum) only requires 2-one-way message delays.

3.5.2.2 Throughput

In this section, we present results obtained running the 0/0, 0/4, and 4/0 microbenchmarks under contention. We do not present the results for Q/U since it is known to perform poorly under contention. Notice that in all the experiments presented in this section, Chain is active in Aliph. The reason is that, due to contention, there is always a point in time when a request sent to Quorum reaches replicas in a different order, which results in a switch to Chain. As there are no failures in the experiments presented in this section, Chain executes all the subsequent requests.

Our results show that Aliph consistently and significantly outperforms other protocols starting from a certain number of clients that depends on the benchmark. Below this threshold, Zyzzyva achieves higher throughput than other protocols.

0/0 benchmark. Figure 3.6 plots the throughput achieved in the 0/0 benchmark by various protocols when \( f = 1 \). We ran Zyzzyva with and without batching. For PBFT, we present only the results with batching, since they are substantially better than results without batching. We observe that Zyzzyva with batching performs better than PBFT, which itself achieves higher peak throughput than Zyzzyva without batching (this is consistent with the results of [67, 87]).

Moreover, Figure 3.6 shows that with up to 40 clients, Zyzzyva achieves the best throughput. With more than 40 clients, Aliph starts to outperform Zyzzyva. The peak throughput achieved by Aliph is 21% higher than that of Zyzzyva. The reason is that Aliph executes Chain, which uses a pipeline pattern to disseminate requests. This pipeline pattern brings
two benefits: reduced number of MAC operations at the bottleneck server, and better network usage: servers send/receive messages to/from a single server.

Nevertheless, the Chain is efficient only if its pipeline is fed, i.e. the link between any server and its successor in the chain must be saturated. There are two ways to feed the pipeline: using large messages (see the next benchmark), or a large number of small messages (this is the case of 0/0 benchmark). Moreover, as in the microbenchmarks clients invoke requests in closed-loop, it is necessary to have a large number of clients to issue a large number of requests. This explains why Aliph starts outperforming Zyzzyva only with more than 40 clients.

Figure 3.7 plots the response-time of Zyzzyva (with and without batching), PBFT and Aliph as a function of the achieved throughput. We observe that Aliph achieves consistently lower response-time than PBFT. This stems from the fact that the message pattern of PBFT is a very complex one, which increases the response time and limits the throughput of PBFT. Moreover, up to the throughput of 37Kops/sec, Aliph has a slightly higher response-time than Zyzzyva. The reason is the pipeline pattern of Chain that results in a higher response time for low to medium throughput, which stays reasonable nevertheless. Moreover, Aliph scales better than Zyzzyva: from 37Kops/sec, it achieves lower response time, since the messages are processed faster due to the higher throughput ensured by Chain. Hence, messages spend less time in waiting queues. Finally, we observe that for very low throughput, Aliph has lower response time than Zyzzyva. This comes from the fact that Aliph uses Quorum when there is no contention, which significantly improves the response-time of the protocol.

0/4 benchmark. Figure 3.8 shows the throughput of the various protocols for the 0/4 microbenchmark when $f = 1$. PBFT and Zyzzyva are using the client multicast optimization. We observe that with up to 15 clients, Zyzzyva outperforms other protocols. Starting from 20 clients, Aliph outperforms PBFT and Zyzzyva. Nevertheless, the gain in peak throughput (7.7% over PBFT and 9.8% over Zyzzyva) is lower than the gain we had with the 0/0 microbenchmark. This can be explained by the fact that the dominating cost is now sending replies to clients, partly masking the effect of request processing and request/sequence number forwarding. In all protocols, there is only one server sending a full reply to the client (other servers send only a digest of the reply). We were expecting PBFT and Zyzzyva to out-
perform *Aliph* (which executes *Chain* when there is load), since the server that sends a full reply in PBFT and Zyzzyva changes on a per-request basis. Nevertheless, this is not the case. We again attribute this result to the fact that *Chain* uses a pipeline pattern: the last process in the chain replies to clients at the throughput of about 391MB/sec.

Figure 3.8: Throughput for the 0/4 benchmark (f=1).

**4/0 benchmark.** Figure 3.9 shows the results of *Aliph*, PBFT and Zyzzyva for the 4/0 microbenchmark with *f* = 1. Notice the logarithmic scale for the *X* axis, that we use to better highlight the behavior of various protocols with small numbers of clients. For PBFT and Zyzzyva, we plot curves both with and without client multicast optimization. The graph shows that with up to 3 clients, Zyzzyva outperforms other protocols. With more than 3 clients, *Aliph* significantly outperforms other protocols. Its peak throughput is about 360% higher than that of Zyzzyva. The reason why *Aliph* is very efficient under high load and when requests are large was explained earlier in the context of the 0/0 benchmark.

Notice also the interesting drop in the performance of Zyzzyva and PBFT when client multicast optimization is used (Fig. 3.9). This is to be contrasted with the case when the primary forwards requests, where the performance of PBFT and Zyzzyva remain almost constant after the peak throughput has been reached. These results may seem surprising given that [67, 27] recommend to use the client multicast optimization when requests are large, in order to spare the primary of costly operations request forwarding. Nevertheless, these results can be explained by the fact that simultaneous multicasts of large messages by different clients result in collisions and buffer overflows, thus requiring many message retransmissions\(^7\) (there is no flow control in UDP). This explains why enabling the concurrent client multicasts drastically reduces performance. On the other hand, when the primary forwards messages, there are fewer collisions, which explains the better performance we observe.

**Impact of the request size.** In this experiment we study how protocols are impacted by the size of requests. Figure 3.10 shows the peak throughput of *Aliph*, PBFT and Zyzzyva

\(^7\)Note that similar performance drops with large UDP packets have already been observed in the context of broadcast protocols. For instance, a recent study made by the authors of the JGroups toolkit showed that with 5K messages, their TCP stack achieves up to 5 times the throughput of their UDP stack, even if the latter includes some flow control mechanisms.
as a function of the request size for $f = 1$. To obtain the peak throughput of PBFT and Zyzzyva, we benchmarked both protocols with and without client multicast optimization and with different batching sizes for Zyzzyva. Interestingly, the behavior we observe is similar to that observed using simulations in [87]: differences between PBFT and Zyzzyva diminish with the increase in payload. Indeed, starting from 128B payloads, both protocols have almost identical performance. Figure 3.10 also shows that Aliph sustains high peak throughput with all message sizes, which is again the consequence of Chain being active under contention.

Fault scalability. One important characteristic of BFT protocols is their behavior when the number of tolerated server failures $f$ increases. Figure 3.11 depicts the performance of Aliph for the 4/0 benchmark when $f$ varies between 1 and 3. We do not present results for PBFT
and Zyzzyva as their peak throughput is known to suffer only a slight impact [67]. Figure 3.11 shows that this is also the case for Aliph. The peak throughput at \( f = 3 \) is only 3.5% lower than that achieved at \( f = 1 \). We also observe that the number of clients that Aliph requires to reach its peak throughput increases with \( f \). This can be explained by the fact that Aliph uses Chain under contention. The length of the pipeline used in Chain increases with \( f \). Hence, more clients are needed to feed the Chain and reach the peak throughput.

![Figure 3.11: Impact of the number of tolerated failures \( f \) on the Aliph throughput.](image)

### 3.5.2.3 Performance in Case of Faults

As mentioned in Section 3.4.3, when Aliph switches to Backup, it executes \( k \) requests, and then switches back to Quorum. To assess the impact of \( k \) on system’s performance, we compared performance for two different values of \( k \) – in the first case, \( k = 1 \), and in the second case, \( k = 2^i \), where \( i \) is the number of invocations of Backup since beginning.

In this experiment, we skip execution in Chain, and focus only on Quorum and Backup. There is one client, which issues 15,000 requests in total. If run just under Quorum, system would process these requests in 7s. After client sends 2,000 requests, one of the replicas goes down, and remains down for 10s. During this time, only three replicas are active. Hence, as Quorum protocol requires all replicas to respond, it will not execute any request. Figure 3.12 shows the throughput of the system, when Aliph switches to Backup for a single request. As discovery of replica failure in Quorum is done with timers, only handful of requests will be serviced (by Backup) while one replica is down. On the other hand, Figure 3.13 shows the behavior of the system if it stays in Backup for \( 2^i \) requests. Although it takes less time to finish the experiment, system may stay for too long in Backup. Replica came back up at \( t = 11s \) in the experiment, but switch from Backup to Quorum occurred around \( t = 14s \), because Backup had to process 8192 requests.

### 3.5.2.4 Dynamic Workload

Finally, we study the performance of Aliph under dynamic workload (i.e., fluctuating contention). We compare its performance to that achieved by Zyzzyva and by Chain alone. We do not present results for Quorum alone as it does not perform well under contention. The experiments consists in having 30 clients issuing requests of different sizes, namely, 0k,
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Figure 3.12: Throughput under faults, when system switches to Backup for one request.

Figure 3.13: Throughput under faults, when system switches to Backup for $2^i$ requests.
related work

0.5k, 1k, 2k, and 4k. Clients do not send requests all at the same time: the experiment starts with a single client issuing requests. Then we progressively increase the number of clients until it reaches 10. We then simulate a load spike with 30 clients simultaneously sending requests. Finally, the number of clients decreases, until there is only one client remaining in the system.

Figure 3.14 shows the performance of Aliph, Zyzzyva, and Chain. For each protocol, clients were invoking the same number of requests. Moreover, requests were invoked after the preceding clients had completed their bursts. First, we observe that Aliph is the most efficient protocol: it completes the experiment in 42s, followed by Zyzzyva (68.1s), and Chain (77.2s). Up to time \( t = 15.8s \), Aliph uses Quorum, which performs much better than Zyzzyva and Chain. Starting at \( t = 15.8s \), contention becomes too high for Quorum, which switches to Chain. At time \( t = 31.8s \), there is only one client in the system. After 2s spent with only one client in the system, Chain in Aliph starts aborting requests due to the low load optimization (Sec. 3.5.1.3). Consequently, Aliph switches to Backup and then to Quorum. This explains the increase in throughput observed at time \( t = 33.8s \). We also observe on the graph that Chain and Aliph are more efficient than Zyzzyva when there is a load spike: they achieve a peak throughput about three times higher than that of Zyzzyva. On the other hand, Chain and Aliph have slightly lower performance than Zyzzyva under medium load (i.e. from 16s to 26s on the Aliph curve). This suggests an interesting BFT protocol that would combine Quorum, Zyzzyva, Chain and Backup. However, this requires smart choices for dynamic switching, e.g., between Zyzzyva and Chain. We believe that building such a protocol is an interesting research topic.

![Figure 3.14: Throughput under dynamic workload.](image)

### 3.6 Related Work

Several BFT protocols have been proposed in the last ten years with practical motivations in mind: PBFT [27] was the first to make a convincing argument for the practical potential of BFT. PBFT was in particular the first to use MAC vectors (instead of signatures) to improve performance. Q/U [1] was the first to implement the idea of a single communication round to expedite a decision in the absence of contention or timeouts. It required however \( 5f + 1 \)
servers to tolerate $f$ Byzantine server failures, unlike our Quorum protocol which enables the same communication pattern with only $3f + 1$ servers.

Several examples of speculative protocols, distinguishing an optimistic phase from a recovery one, were discussed in the survey of Pedone [83]. These speculation ideas were used in the context of Byzantine state machine replication, e.g., in HQ [38] and Zyzzyva [67]. We are however the first to clearly separate the phases and encapsulate them within first class, well-specified, modules, that can each be designed, tested and proved independently. In a sense, Abstract enables to build a BFT protocol as the composition of as many (gracefully degrading) phases as desired, each with a “standard” interface. This allows for an unprecedented flexibility in BFT protocol design that we illustrated with Aliph, a BFT protocol that combines three different phases. In retrospect, and with Abstract in mind, one can obtain a modular protocol that mimics Zyzzyva (or HQ) in favorable cases for which it was optimized, by adding less than 24% to the code of a black-box BFT protocol (e.g. PBFT).

The idea of aborting if “something goes wrong” is almost as old as distributed computing. It underlies for instance the seminal two-phase commit protocol (2PC) [57]: abort can be decided if there is a failure or some database server votes negatively. Interestingly, our decomposition of a BFT protocol into several BFT sub-protocols with various progress semantics can be be viewed as way to obtain an effective non-blocking commit protocol [18], by combining several 2PC protocols (each optimized for a specific operating condition) together with a backbone 3PC protocol [88].

Two forms of abortable agreement were proposed in [32] and [22]. In the first case, a process can abort if a majority of processes cannot be reached whereas, in the second, a process can abort if there contention. The latter idea was generalized for arbitrary shared objects in [9] and then [2]. In particular, in [2], a process can abort and then query the object to seek whether the last query of the process was performed. This query can however abort if there is contention. Our abstraction is different in two senses. First, the condition under which Abstract can abort is a generic parameter: it can express for instance contention, synchrony or failures. Second, in case of abort, Abstract returns (without any further query) an information needed for recovery. This, in turn, can be used to invoke another, possibly stronger, Abstract. This ability is key to the composability of Abstract.

Several abstractions were proposed to deconstruct BFT protocols. In [45], a BFT protocol is viewed as a series of weak-interactive consistency instances. In [25], a BFT protocol is built using the abstraction of multi-valued Byzantine agreement with external validity. These abstractions are orthogonal to our and can, we believe, implement instances of Abstract. Neither of those tackle however the problem of composing several BFT protocols. The optimistically terminating consensus (OTC) framework proposed in [98] captures the notion of a round of communication and allows the deconstruction of single-instance agreement protocols. OTC seeks latency-optimal BFT protocols whereas Abstract is oblivious to any particular complexity metric. We indeed illustrated the benefits of Abstract with latency as well as throughput efficient BFT protocols.

Finally, let us note that there have been research works aiming at preserving what we call “common circumstances”, even in the presence of attacks. Notably, some protocols [36, 34] have been devised by means of distributed systems models and architectures that limit, by construction, the attack model, that is to say, the potential of hackers to create deviations from “common circumstances”. These works are complementary to the work presented in this chapter. One might devise Abstract instances following the principles described in these papers.
3.7 Conclusion

Progress in computer science comes with the design and implementation of abstractions that encapsulate specific aspects of a computation problem within a well-defined interface. Seminal examples include data structures like records and arrays for sequential programming, as well as synchronization primitives like semaphores and monitors for concurrent programming. Distributed programming abstractions do exist, such as sockets or signatures, but these are low-level and the difficulty of building and maintaining distributed systems calls for higher level abstractions. State machine replication might be viewed as one such high-level abstraction: it seeks to entirely hide distribution by providing the single, immortal, sever illusion. Yet, in some sense, once state machine replication is achieved, the job is over. What is lacking is a suite of abstractions to simplify the implementation and maintenance of state machine replication itself. We presented one such abstractions in this chapter [58, 95], with the aim to simplify the construction of the most resilient form of state machine replication protocols, namely BFT (Byzantine Fault-Tolerant) protocols.

The idea underlying our abstraction echoes Lampson’s recommendation to build practically effective protocols by handling common and worst cases separately [71]. Clearly, what might be considered the common case for a given application and environment might not be considered common for another one. Even for the same application, what might be considered common might well change over time: the load that is considered normal for Amazon servers right before thanksgiving is not the same as the one that is considered normal during the early morning of January 5th. Our abstraction seeks to simplify the implementation of separate BFT sub-protocols, each intended to be executed under a specific common case. The key to simplicity is the observation that, precisely because many of those normal cases are favorable ones (e.g., no timeout, no failures or even sometimes no contention), there is no reason a BFT sub-protocol that needs to be executed only during those cases need to be as hard to implement, test and prove than a full-fledged BFT protocol, supposed to be performed under all conditions. The challenge to make that simplification possible was however to precisely define what needs to be ensured under a normal case and what exactly happens when the operating conditions are not those expected anymore: this is exactly what Abstract encapsulates. The genericity of Abstract captures the diversity of the very notion of a “normal case”. Not surprisingly, certain Abstract instances are simple to implement and prove as they only need to guarantee progress under favorable circumstances. Yet, although simple to implement, some of those instances, such as our Chain sub-protocol, can drastically boost the peak throughput of a BFT protocol.

Needless to say, Abstract does not trivialize the problem of building effective BFT protocols. It does however give back to Caesar what belongs to Caesar. BFT experts can focus on building libraries of Abstract instances, whereas system experts can focus on analyzing which BFT protocol is best suited to a specific environment. Several directions can be interesting to explore. It would be interesting to devise efficient Abstract implementations for other interesting definitions of the progress property, e.g., implementations that perform well despite failures. It would be also interesting to explore possibilities for signature-free switching, to obtain practical BFT protocols that do not rely on signatures [37]. Moreover, we believe that an interesting research challenge is to define and evaluate effective heuristics for dynamic switching among Abstract instances. While we described Aliph and showed that, albeit simple, it outperforms existing BFT protocols, Aliph is simply the starting point for Abstract. The idea of dynamic switching depending on the system conditions seems very promising.
Chapter 4

Conclusion

This chapter concludes the thesis. We start by a brief summary of the contributions presented in this document. We then give some research directions for future work.

4.1 Summary of Contributions

This thesis makes two contributions to state machine replication, a software technique aiming at building fault-tolerant systems using commodity hardware. The operating principle of state machine replication is very simple: the service to be made fault-tolerant is replicated on different machines. A state machine replication protocol ensures that all replicas receive the same set of requests in the same order.

The first contribution is LCR [60, 61, 73], a uniform total order broadcast protocol that can be used to implement a state machine replication protocol in an environment where nodes only fail by crashing, and where crashes can be accurately detected (using a failure detector). When executed on a set of homogeneous machines interconnected by a LAN, LCR ensures optimal throughput during failure-free periods. To the best of our knowledge, LCR is the first total order broadcast protocol to achieve optimal throughput in this environment. Contrarily to most existing protocols, LCR does not rely on a native multicast primitive, but rather uses point-to-point communication channels. More precisely, LCR organizes processes in a ring topology: each node has only one successor in the ring to which it forwards messages. We show both theoretically and experimentally that this ring topology yields optimal throughput. Moreover, we benchmark an implementation of LCR and we show that it outperforms the two most widely used total order broadcast protocols.

The second contribution presented in this thesis is Abstract [58, 95], a novel abstraction that simplifies the design, implementation, testing and verification of state machine replication protocols. In particular, Abstract focuses on state machine replication protocols tolerating arbitrary (also called Byzantine) faults. In a sense, Abstract is an abortable state machine that enables to build a state machine replication protocol as the composition of as many (gracefully degrading) phases as desired, each with a “standard” interface. These phases are Abstract instances and each of them can be designed, implemented, tested and proved independently. This allows for an unprecedented flexibility in state machine replication protocol design that we illustrated with the development of two protocols. The first one mimics a state of the art protocol, but requires writing much less code (only 24% of the legacy code size). This is due to the fact that Abstract’s modularity allows easily reusing and factorizing code. The second protocol we developed using Abstract is called Aliph. It illustrates the ability to develop very efficient protocols using this modular approach. In particular, we evaluated Aliph using microbenchmarks and showed that it outperforms state of the art protocols both
4.2 Future Work

State machine replication has been a very active research topic for more than 20 years. Yet, we believe that many works remain to be done. In the remainder of this section we discuss three of them.

**Wide-area Byzantine-resilient state machine replication.** Services are increasingly migrating to data centers geographically spread across the Internet. This is the so-called “cloud” architecture. The benefits of cloud architectures are numerous. Let us mention, for instance, the ability for users to access services from any host or the possibility to automate both service upgrades and data backups.

Unfortunately, a whole data center can be rendered unavailable by a catastrophic event, a loss of power, or simply a loss of connectivity. For reliability reasons, it is thus not a good idea to execute a service on a single data center. Moreover, it is often desired to decrease the latency perceived by clients. This can be achieved by locating a service on several data centers geographically spread around the world in order to decrease the probability to encounter network congestion between clients and the service.

It is thus becoming necessary to devise state machine replication protocols for services hosted on multiple clouds. We believe that it is important that these protocols tolerate Byzantine faults as it does not seem reasonable to assume only crash failures in large-scale environments, where nodes are hosted on different clouds and administered by different entities. BFT protocols studied in Chapter 3 are not good candidates for such environments. Indeed, they do either not tolerate contention [38, 1], or they rely on a leader to allocate sequence numbers [67, 27]. Requests generated by clients close to the leader might be favored by such protocols. Moreover, leader-based protocols have unbalanced communication patterns that limit the utilization of the available bandwidth. Finally, these protocols rely on IP multicast, which is known to perform poorly in large-scale settings.

To the best of our knowledge, only two BFT protocols have been specifically devised for wide-area networks. The first one, called Steward [6], is a hierarchical BFT protocol that combines a BFT protocol running on each site (or cloud) and a Paxos-like protocol between the different sites. The main drawback of this protocol is that it requires a minimum of 3f+1 machines running in each cloud. Another weakness is that the Paxos-like protocol running between the different sites is not optimized for wide-area networks. The second protocol is proposed by Amir et al. [5]. The paper describes a mechanism that allows establishing a reliable virtual communication link between sets of machines located in different sites. The goal of this mechanism is to have all machines of a given site appear as being a single machine. A traditional replication protocol can then be used between the different sites. This replication protocol needs to deal with a reduced number of nodes (only one virtual node per site). Like Steward, the protocol used for inter-site replication is not optimized for wide-area networks.

We would like to propose BFT protocols optimized for wide-area communications. Such protocols must provide both high throughput under high client load and low latency under low client load. They must also be able to face changing network conditions and varying client load. Finally, they must be able to leverage asymmetric network link performance. A path we would like to explore is the use of multiple leaders to assign distinct sets of sequence numbers. This idea has been initially proposed by Mao et al. [78] to tolerate benign failures. We believe that it could be adapted to tolerate Byzantine failures. Another path we envision is the combination of multiple communication patterns (e.g. tree, multicast, pipe-line) in order to deal with the heterogeneity of environments comprising multiple clouds. For instance, one
might combine the pipelining pattern used in the Chain protocol presented in Chapter 3 with the multicast-based pattern used in Zyzzyva [67].

**Parallel state machine replication.** Hardware technology trends indicate that processor clock rates are stalling and that future performance improvements are likely to come from increased parallelism rather than raw speed improvements. As hardware parallelism increases, services are expected to become more and more parallel in order to provide better performance.

Unfortunately, state machine replication systems have traditionally required deterministic execution achieved through sequential state machine execution. This means that current techniques for state machine replication are only applicable to single-threaded applications and cannot safely leverage hardware parallelism. This is a real and major performance penalty considering that it is now admitted that the performance bottleneck in replicated state machines is the execution of the state machine rather than the coordination of replicas.

There have been proposals to avoid the limitations of sequential state machine execution. For instance, it has been suggested to weaken reliability guarantees in order to allow replica states to temporarily diverge [79, 90]. This approach can nevertheless not be applied to services, such as databases, that require strong consistency. Another approach is to enforce determinism at the operating system level. Recently, an operating system called Determinator [10], has been proposed. Determinator enforces determinism on both multi-threaded and multi-process computations. It can run parallel applications deterministically both on multi-core PCs and across nodes in a cluster. This approach works well for applications exhibiting coarse-grained parallelism, but it induces a high overhead for fine-grained parallel applications. Finally, a third approach has been described in [68], where authors propose to use application-specific information to identify and concurrently execute independent requests. They design an architecture in three stages responsible for agreement on request order, request parallelization, and request execution, respectively. The parallelization stage uses rules supplied by the application designer to identify the set of requests that can be executed in parallel without compromising safety. This approach has a major drawback: it requires rules to be correct, otherwise, safety is not ensured. Writing correct rules might not be trivial. Consider for instance a database that implements row-level locking. In order to achieve the highest level of parallelism, rules should be based on the set of rows that each database query will update, which can be extremely hard to know at design time.

We believe that state machine determinism is not necessarily exclusive with parallel execution. We plan to study the possibility to design an architecture that let replicas optimistically execute requests and then verify whether or not they have produced equivalent results. This is in contrast with current state machine replication architectures that, even when speculative [67], first agree on the order in which requests will be executed and then rely on deterministic execution to guarantee that all replicas reach the same state. Embracing the mantra of “trust but verify” should allow leveraging benign parallelism, but it will introduce additional cost and complexity for higher degrees of parallelism. Specifically, two replicas that execute requests in parallel may produce different outputs based on differences in local thread scheduling. When replicas diverge, it will be necessary to invoke repair mechanisms in order to maintain consistency. In order for repair to be efficient, we will need to implement various mechanisms such as incremental state rollback, fast checkpoint generation and comparison, and fast incremental state transfer.

**Single-node Byzantine-resilient state machine replication.** The number of standard processing cores per chip doubles with every semi-conductor process generation. Unfortunately, the increase in computing power has not been followed by an increase in software and hardware reliability. Zhenmin Li et al. have recently presented a study of around 29,000 bugs in Mozilla and Apache Web Server [74]. They observe that around 10% of Apache bugs lead to
a crash and that bugs related to the security of the application are increasingly present over the years. On the hardware side, core failures such as manufacturing defects and soft errors are becoming a concern. This comes from the fact that the number of transistors put into a processor drastically increases, but not the reliability of each individual transistor.

We have seen in this thesis that one way to improve the reliability of software systems is to use replication. We have studied various protocols that allow running several (possibly different) copies of a state machine on different machines. We believe that an interesting research topic is to study the possibility to implement state machine replication on a single-machine. The idea is to collocate the different replicas of the state machine on the same physical machine in order to take advantage of the increasing power of modern computers to improve the resilience of software systems. Note that the idea of considering a single computer as a distributed system is a current research trend. For instance, Baumann et al. argue that modern computers resemble a distributed system and propose Barrelfish [17], an operating system designed as a distributed system. Note also that implementing state machine replication on a single machine has been studied by Chun et al. in a position paper [33]. This paper does nevertheless not propose a solution. It only describes challenges that need to be solved and a few potential designs.

Implementing state machine replication on a single machine will open new perspectives for the design of replication protocols and underlying communication mechanisms. Indeed, if current BFT replication protocols can easily run on a multi-core machine, they will most probably not achieve the best possible performance. The reasons are twofold. First, these protocols have been designed for asynchronous systems. On a multicore machine, it is maybe possible to make some synchrony assumption on processing time and communications. More precisely, if we assume that memory and I/O buses are fault-free and that replicas are equally fast, it is possible to assume a synchronous system model. Second, current BFT protocols rely on existing communication mechanisms, such as Inet sockets, that have been designed for communications between remote machines. These mechanisms can be used by processes running on the same machine. Nevertheless, their performance will not be as good as what could be achieved by customized mechanisms. We believe that it will thus be necessary to design a new communication mechanism implementing a very efficient and robust multicast primitive for single-machine communications. This mechanism cannot be implemented using shared memory techniques (as done in Barrelfish [17]) since it needs to be robust, i.e. to ensure that messages cannot be forged by erroneous replicas.
Bibliography


Appendix A

Abstract: specification

Before diving into the precise specification of Abstract, we first introduce some notations and definitions. We denote the output function of the (replicated) state machine by $\text{rep}(h)$, where $h$ is a sequence of requests called commit history: the initial state is an implicit argument of $\text{rep}()$. Basically, $\text{rep}(h)$ represents replies that state machine outputs to clients. We assume that every Abstract instance has its own unique id $i$ (a natural number) that uniquely determines the implementation and the set of underlying servers.

Abstract $i$ exports one operation: $\text{Invoke}_i(m, [h])$, where $m$ is a request, and $h$ a (optional) sequence of requests called init history; we say the client invokes request $m$ (with init history $h$). By convention, when $i = 1$, the invocation never contains an init history. Abstract $i$ returns two indications to the client:

1. Commit($i(m, \text{rep}(h))$, where commit history $h$ contains $m$;
2. Abort($i(m, h, \text{next}(i))$, where the sequence of requests $h$ is called an abort history and $\text{next}$ is a function that returns an integer.

Respectively, we say that a client commits aborts the request $m$. In the case of an abort, we also say that instance Abstract $i$ switches to instance next($i$). We also define a valid init history (VIH) as follows: init history $h$ is a VIH if there is an Abstract $j$ that returned Abort$_j(s, h, i)$ (i.e., such that next($j$) = $i$). Similarly, we define a valid init request (VIR) as follows: (1) if $i = 1$, any invoked request is a VIR; (2) if $i \neq 1$, $m$ is a VIR if and only if $m$ is invoked with a VIH. We say that an instance $i > 1$ is initialized upon it commits or aborts some VIR. Finally, we say that a request $m$ is valid if (1) $m$ is a VIR, or (2) $m$ is invoked after $i$ gets initialized.

We are now ready to specify the properties of Abstract (parametrized by a predicate $P$). In the following, “prefix” refers to a non-strict prefix.

1. (Validity) In every commit/abort history, no request appears twice and every request is a valid request, or an element of a valid init history.
2. (Termination) If a correct client $c$ invokes a valid request $m$, then $c$ eventually commits or aborts $m$.
3. (Progress) If a correct client $c$ invokes a valid request $m$ and some predicate $P$ holds, then $c$ commits $m$.
4. (Init Order) The longest common prefix of all valid init histories is a prefix of any commit or abort history.
5. **(Commit Order)** Let \( h \) and \( h' \) be any two commit histories: either \( h \) is a prefix of \( h' \) or vice versa.

6. **(Abort Order)** Every commit history is a prefix of every abort history.

7. **(Switching Monotonicity)** For every Abstract instance \( i, i < next(i) \).

   It is important to see that Abstract is a strict generalization of BFT. Namely, BFT is precisely an Abstract (with \( i = 1 \)) that never aborts. In this case, Abort Order and Switching Monotonicity become irrelevant, and Init Order trivially holds.

   We build BFT protocols by composing Abstract instances. At the heart of the composition lies a simple scheme (we refer to as Abstract composition algorithm (ACA)), given in Figure A.1, where: a) correct clients use an abort history of an aborting Abstract instance (e.g., \( i \)) as the init history for the next instance (\( next(i) \)), and b) a given client invokes \( next(i) \) with an init history included only once (with its first invocation of \( next(i) \): subsequently, it invokes \( next(i) \) without any init history.

   ![Figure A.1: Abstract composition algorithm (ACA). Invocations/indications of the composed Abstract are in uppercase.](image)

   The key invariant in the Abstract framework is idempotence: a composition of any two Abstract instances is, itself, an Abstract instance. More precisely:

   **Theorem 1** Given any two Abstract instances \( i \) and \( i' \) and integer \( i'' \), such that \( i' = next(i) \) and \( next(i') = i'' \), ACA implements a single Abstract instance with the instance id \( i \), such that \( next(i) = i'' \).

   By induction, the theorem extends to a composition of any number of Abstract instances, which yields again an Abstract instance.
Appendix B

Abstract: detailed protocol descriptions

In this Appendix, we give the details of ZLight, Quorum, Chain and their shared panicking mechanism (Sec. B.2 - B.5). For ease of presentation, we first give details about handling invocations without init histories and then (Sec. B.6) we show how we handle init histories and switch between Abstract instances in AZyzyva and Aliph. Finally, we give the details of our checkpointing subprotocol in Section B.6.1. Correctness proofs can be found in Appendix C.

B.1 Notations

A message $m$ sent by process $p$ to the process $q$ and authenticated with a MAC is denoted by $\langle m \rangle_{\mu_{p,q}}$. A process $p$ can use vectors of MACs (called authenticators [27]) to simultaneously authenticate the message $m$ for multiple recipients belonging to the set $S$; we denote such a message, which contains $\langle m \rangle_{\mu_{p,q}}$ for every $q \in S$, by $\langle m \rangle_{\alpha_{p,S}}$. In addition, we denote the digest of the message $m$ by $D(m)$, whereas $\langle m \rangle_{\sigma_p}$ denotes a message that contains $D(m)$ signed by the private key of process $p$ and the message $m$. All processes are assumed to own the public key of every other process. Finally, we denote the set of all $(3f + 1)$ replicas by $\Sigma$.

| $i$ | current Abstract id |
| $c/r_j$ | client (resp., replica) ID |
| $t_c$ | local timestamp at client $c$ |
| $t_j[c]$ | the highest $t_c$ seen by replica $r_j$ |
| $o$ | operation invoked by the client |
| $LH_j$ | a local history at replica $r_j$ |
| $\text{reply}_j$ | $\text{rep}(LH_j)$ (application reply in function of $LH_j$) |
| $sn_j$ | sequence number at replica $r_j$ (not used in Quorum) |

Figure B.1: Message fields and local variables.

Notation for message fields and client/replica local variables used in ZLight, Quorum and Chain is shown in Figure B.1. To help distinguish clients’ requests for the same operation $o$, we assume that client $c$ calls $\text{Invoke}_c(req)$, where $req = \langle o, t_c, c \rangle$ and where $t_c$ is a unique, monotonically increasing client’s timestamp. A replica $r_j$ executes $req$ by appending it to $LH_j$. 

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B.2 ZLight Details

Step Z1. On Invoke$(req)$, client $c$ sends the message $m' = \langle\text{REQ}, req, i\rangle_{\alpha_{c, \Sigma}}$ to the primary (say $r_1$) and triggers timer $T$.

Step Z2. The primary $r_1$ on receiving $m' = \langle\text{REQ}, req, i\rangle_{\alpha_{c, \Sigma}}$, if:
- $req.t_c$ is higher than $t_1[c]$,
then it:
- updates $t_1[c]$ to $req.t_c$,
- increments $sn_1$, and
- sends $\langle\langle\text{ORDER}, req, i, sn\rangle_{\mu_{r_1, r_j}}, MAC\rangle_j$ to every replica $r_j$, where $MAC_j$ is the MAC entry for $r_j$ in the client’s authenticator for $m'$.

Step Z3. Replica $r_j$ on receiving (from primary $r_1$) $\langle\langle\text{ORDER}, req, i, sn\rangle_{\mu_{r_1, r_j}}, MAC\rangle_j$, if:
- $MAC_j$ authenticates $req$ and $i$,
- $sn' = sn_j + 1$, and
- $t_j[c] < req.t_c$,
then it:
- updates $sn_j$ to $sn'$ and $t_j[req.c]$ to $req.t_c$,
- executes $req$, and
- sends $\langle\text{RESP}, reply_j, D(LH_j), i, req.t_c, r_j\rangle_{\mu_{r_j, c}}$ to $c$.

Moreover, if $MAC_j$ verification fails, $r_j$ stops executing Step Z3 in instance $i$.

Step Z4. If client $c$ receives $3f + 1 \langle\text{RESP}, reply_j, LH\text{Digest}, i, req.t_c, *\rangle_{\mu_{c, \Sigma}}$ messages from different replicas before expiration of $T$, with identical digests of replicas’ local history ($LH\text{Digest}$) and identical replies (or digests thereof), then the client commits $req$ with $reply$. Otherwise, the client triggers the panicking mechanism explained in Section B.5 (Step P1).

B.3 Quorum Details

Step Q1. On Invoke$(req)$, client $c$ sends message $\langle\text{REQ}, req, i\rangle_{\mu_{c, \Sigma}}$ to all replicas and triggers timer $T$.

Step Q2. Replica $r_j$ on receiving $\langle\text{REQ}, req, i\rangle_{\mu_{c, \Sigma}}$ from client $c$, if:
- $req.t_c$ is higher than $t_j[c]$
then it:
- updates $t_j[c]$ to $req.t_c$,
- executes $req$, and
- sends $\langle\text{RESP}, reply_j, D(LH_j), i, req.t_c, r_j\rangle_{\mu_{r_j, c}}$ to $c$.

Step Q3. Identical to Step Z4 of ZLight.

\footnote{As an optimization (which also applies to Step Q2 of Quorum), all but one designated replica can send reply digests $D(reply_j)$ instead of $reply_j$.}
B.4 Chain Details

In the following, we assume that every CHAIN message sent by process $p$ contains its respective chain authenticator (CA), as well as MACs $p$ received from its predecessor $\overset{\leftarrow}{p}$ destined to processes in $p$’s successor set (see Sec. 3.5.1.2).

**Step C1.** On $\text{Invoke}_{i}(\text{req})$, client $c$ sends the message $m' = \langle \text{CHAIN}, \text{req}, i \rangle$ to the head (say $r_1$) and triggers the timer $T$.

**Step C2.** The head $r_1$, on receiving $m = \langle \text{CHAIN}, \text{req}, i \rangle$ from client $c$, if:

- $\text{req}.t_c$ is higher than $t_1[c]$, and
- the head can verify client’s MAC (otherwise the head discards $m$),

then the head:

- updates $t_1[c]$ to $\text{req}.t_c$,
- increments $sn_1$, and
- sends $\langle \text{CHAIN}, \text{req}, i, sn_1, \bot \rangle$ to $\overset{\leftarrow}{r_1} = r_2$.

**Step C3.** Replica $r_j$ on receiving $m = \langle \text{CHAIN}, \text{req}, i, sn, \text{REPLY} \rangle$ from $\overset{\leftarrow}{r_j}$, if

- it can verify MACs from all processes from its predecessor set against the content of $m$,
- $sn = sn_j + 1$, and
- $\text{req}.t_c$ is higher than $t_j[c]$,

then it:

- updates $sn_j$ to $sn$ and $t_j[c]$ to $\text{req}.t_c$,
- (ii) executes $\text{req}$, and
- (iii) sends $\langle \text{CHAIN}, \text{req}, i, sn, \text{REPLY}, LH\text{Digest} \rangle$ to $\overset{\leftarrow}{r_j}$, where $\text{REPLY} = LH\text{Digest} = \bot$ in case of the first $2f$ replicas, $\text{REPLY} = D(\text{reply}_j)$ and $LH\text{Digest} = D(LH_j)$ in case $i \in \{2f+1 \ldots 3f\}$, or $\text{REPLY} = \text{reply}_j$ and $LH\text{Digest} = D(LH_j)$ in case $r_j$ is tail.

In case MAC verification mentioned above fails, replica stops executing Step C3 in instance $i$.

**Step C4.** If client $c$ receives $\langle \text{CHAIN}, \text{req}, i, *, \text{reply}, LH\text{Digest} \rangle$ from the tail before expiration of $T$, and with MACs from last $f+1$ replicas that authenticate $\text{req}, i, LH\text{Digest}$ and $D(\text{reply})$ (or $\text{reply}$ itself), then $c$ commits $\text{req}$ with $\text{reply}$. Otherwise, the client triggers the panicking mechanism explained in the following section (Step P1, Sec. B.5).
B.5 Panicking Mechanism

This is the mechanism through which we initiate the switching from ZLight (resp., Quorum, Chain) in Step Z4 (resp., Q3, C4).

Step P1. If the client does not commit request \( req \) by the expiration of timer \( T \) (triggered in Steps Z1/Q1/C1), \( c \) panics, i.e., it sends a \( \langle \text{PANIC}, req.t_c \rangle_{\mu_c.r_j} \) message to every replica \( r_j \). Since messages may be lost, client periodically PANIC messages, until it aborts the request.

Step P2. Replica \( r_j \), on receiving a \( \langle \text{PANIC}, req.t_c \rangle_{\mu_c.r_j} \) message, stops executing new requests (i.e., stops executing Step Z3/Q2/C3) and sends \( \langle \text{ABORT}, req.t_c, LH_j, \text{next}(i) \rangle_{\sigma_{r_j}} \) to \( c \).

Step P3. When client \( c \) receives \( 2f + 1 \) \( \langle \text{ABORT}, req.t_c, *, \text{next}(i) \rangle \) messages with correct signatures from different replicas and the same value for \( \text{next}(i) \), the client collects these messages into the set \( \text{Proof}_{AH_i} \), and extracts the abort history \( AH_i \) from \( \text{Proof}_{AH_i} \) as follows:

- First, \( c \) generates history \( h \) such that \( AH_i[j] \) equals the value that appears at position \( j \geq 1 \) of \( f + 1 \) different histories \( LH_j \) that appear in \( \text{Proof}_{AH_i} \);
- If such a value does not exist for position \( x \) then \( h \) does not contain a value at position \( x \) or higher.
- Finally, \( AH_i \) is the longest prefix of \( h \) in which no request appears twice.

B.6 Handling Init Histories and Switching

To switch from ZLight, Quorum or Chain instance \( i \), client invokes instance \( i' = \text{next}(i) \) by accompanying \( req \) with init history \( IH_{i'} = AH_i \) and \( \text{Proof}_{AH_i} \). Then a replica running instance \( i' \), executing its first request in \( i' \) (e.g., in Step C3 of Chain), simply makes the library call to verify \( IH_{i'} \) against \( \text{Proof}_{AH_i} \), following the algorithm given in Sec. B.5 and verifies that ABORT messages in \( \text{Proof}_{AH_i} \) indeed declare \( i' \) as \( \text{next}(i) \). In the case of switching to Backup, this check is simply a part of the functionality implemented on top of the underlying BFT.

To switch from Backup\(^2\), Backup replicas must provide the client with \( f + 1 \) different signatures of the identical abort history and the next Abstract instance id \( i' \). This is a reasonable requirement on the BFT that underlies Backup, since any BFT protocol must anyway provide an identical reply from at least \( f + 1 \) replica; in the case of Backup abort history, we just require this particular reply to be signed (we trivially implemented this in PBFT). Then, the client includes these signatures with \( req \) in its invocations of an Abstract \( i' \) (e.g., ZLight) and replicas running \( i' \), before executing the request (e.g., in Step Z3 of ZLight), simply verify the signatures against the submitted init history to find \( f + 1 \) matching ones.

In all cases of switching, a replica running instance \( i' \) executes all the requests contained in the first verified init history \( IH_{i'} \) before executing the invoked request itself. Replicas simply ignore all subsequent init histories. Below we summarize the additional init history related actions performed by processes in steps of ZLight, Quorum and Chain. In the following, we assume that the verification of init histories is performed as described above.

\(^2\)In AZyzzyva, Backup switches to ZLight, whereas in Aliph it switches to Quorum.
B.6. HANDLING INIT HISTORIES AND SWITCHING

**Step Z1/Q1/C1.** On $Invoke_{i'}(req, IH)$, the message(s) sent by the client contain also $IH$ and the set of signatures $Proof_{IH}$ returned by the preceding $Abstract_i$, where $i' = next(i)$.

**Step Z2/C2.** If its local history $LH_1$ is empty, the primary/head $r_1$ executes the step only if $IH$ can be verified against $Proof_{IH}$.

**Step Z3/Q2/C3.** If its local history $LH_j$ is empty, the replica $r_j$ executes the step only if it receives $IH$ that can be verified against $Proof_{IH}$. If so, then (before executing $req$) $r_j$ executes all the requests contained in $IH$ (i.e., $r_j$ sets $LH_j$ to $IH$); then $r_j$ executes $req$ unless $req$ was already in $IH$.

**Step P1.** On sending PANIC messages for a request that was invoked with an init history, client also includes $IH$ and the set of signatures $Proof_{IH}$ returned by the preceding $Abstract_i$ within a PANIC message.

**Step P2.** If its local history $LH_j$ is empty, replica $r_j$, executes the step only if $IH$ can be verified against $Proof_{IH}$. Then, before executing the step as described in Section B.5, $r_j$ first sets $LH_j$ to $IH$.

B.6.1 Lightweight Checkpointing Subprotocol

In ZLight, Quorum and Chain we use a lightweight checkpoint subprotocol (LCS) to truncate histories every $CHK$ requests (in our evaluations, $CHK = 128$), similarly to checkpoint protocols used in [27, 67]. Here, we explain our simple LCS and its impact on our implementations as presented earlier in this appendix.

LCS consists in the following:

1. every replica $r_j$ increments the checkpoint counter $cc$ and sends it along with the digest of its local state to every other replica (using simple point-to-point MACs), when its (non-checkpointed suffix of) local history reaches $CHK$ requests. Then, $r_j$ triggers a checkpoint timer.

2. if the timer expires and there is no checkpoint, the replica stops executing all requests.

3. If replica $r_j$ receives the digest of the same state $st$ with the same checkpoint counter number $cc$ greater than $lastcc$ (initially $lastcc = 0$) from all replicas, $r_j$: (a) truncates its local history and checkpoints its state to $st$ and (b) stores $cc$ to variable $lastcc$. Such a checkpointed state (referred to as $st_{cc}$) becomes a prefix of replicas' local histories to which new requests are appended and is treated as such in all operations on local histories in our algorithms. Moreover, every abort or commit history of length at most $cc \times CHK$ is considered to be a prefix of $st_{cc}$.

LCS has no impact on ZLight, Quorum and Chain as described earlier in this appendix, with a single exception, related to client extraction of abort histories from the received ABORT messages (see Step P3, Sec. B.5). Namely, if the client receives a history from some replica $r_j$ consisting of a checkpointed state followed by $CHK$ requests, the client will first collapse all such histories into the single checkpointed state (i.e., the client will perform the checkpoint on behalf of the replica). Only in case the client cannot retrieve $t+1$ confirmations of (some) checkpointed state when executing Step P3 in this way, the client will repeat the procedure described in this step with replica histories as received from replicas, i.e., precisely as described in Step P3, Section B.5.
Appendix C

Abstract: correctness proofs

In this Section, we give the correctness proofs of ZLight, Quorum, and Chain. Moreover, we omit the correctness proof of Backup which is straightforward due to the properties of the underlying BFT. Finally, the proofs of liveness of our compositions trivially rely on the assumption of an exponentially increasing Backup configuration parameter $k$ (Sec. 3.4.3). Since ZLight and Quorum share many similarities, we give their correctness proof together. This is followed by the proof of Chain.

C.1 ZLight and Quorum

In this Section, we prove that ZLight and Quorum implements Abstract. We first prove the common properties of the two implementations and then focus on the only different property (Progress).

Well-formed commit indications. It is easy to see that the reply returned by a commit indication always equals $\text{rep}(h)$, where (commit history) $h$ is a uniquely defined sequence of requests. Indeed, by Step Z4/Q3, in order to commit a request a client needs to receive identical digests of some history $h'$ and identical reply digests from all $3f + 1$ replicas including at least $2f + 1$ correct ones. By Step Z3 of ZLight (reps., Q2 of Quorum), a digest of the reply sent by a correct replica is $D(\text{rep}(h'))$. Hence, $h'$ is exactly a commit history $h$ and is uniquely defined due to our assumption of collision-free digests.

Moreover, since a correct replica executes an invoked request before sending a RESP message in Step Z3 (resp., Q2), it is straightforward to see that if $req$ is committed with a commit history $h_{\text{req}}$, then $req$ is in $h_{\text{req}}$.

Validity. For any request $req$ to appear in a commit or abort history, at least $f + 1$ replicas must have sent a history (or a digest of a history) containing $req$ to the client (see Step Z4/Q3 for commit histories, and Step P3 for abort histories). Hence, at least one correct replica appended $req$ to its local history. By Step Z3/Q2, the correct replica $r_j$ appends $req$ to its local history only if $r_j$ receives a REQ message with a valid MAC from a client. This is, in turn, present only if some client invoked $req$, or if $req$ is contained in some verified (valid) init history.

Moreover, by Step Z3/Q2, no replica executes the same request twice (since every replica maintains $t_j[c]$). Hence, no request appears twice in any local history of a correct process, and consequently, no request appears twice in any commit history. In the case of abort histories, no request appears twice by construction (see Step P3 Sec. B.5).
Termination. By assumption of a quorum of $2f+1$ correct replicas and fair-loss links: (1) correct replicas eventually receive the \textsc{panic} message sent by correct client $c$ (in Step P1) and (2) $c$ eventually receives $2f+1$ abort messages from correct replicas (sent in Step P2). Hence, if correct client $c$ panics, it eventually aborts invoked request $req$, in case $c$ does not commit $req$ beforehand.

To prove Commit and Abort Ordering we first prove the following Lemma.

Lemma 1 Let $r_j$ be a correct replica and $LH_j^{req}$ the state of $LH_j$ upon $r_j$ executes $req$. Then, $LH_j^{req}$ remains a prefix of $LH_j$ forever.

A correct replica $r_j$ modifies its local history $LH_j$ only in Step Z3/Q2 by sequentially appending requests to $LH_j$. Hence, $LH_j^{req}$ remains a prefix of $LH_j$ forever.

Commit Order. Assume, by contradiction, that there are two committed requests $req$ (by benign client $c$) and $req' \neq req$ (by benign client $c'$) with different commit histories $h_{req}$ and $h_{req'}$ such that neither is the prefix of the other. Since a benign client commits a request only if it receives in Step Z4/Q3 identical digests of replicas’ local histories from all $3f+1$ replicas, there must be a correct replica $r_j$ that sent $D(h_{req})$ to $c$ and $D(h_{req'})$ to $c'$ such that $h(req)$ is not a prefix of $h_{req}$ nor vice versa. A contradiction with Lemma 1.

Abort Order. First, we show that for every committed request $req$ with the commit history $h_{req}$ and any \textsc{abort} message $m$ sent by a correct replica $r_j$ containing local history $LH_j^m$, $h_{req}$ is a prefix of $LH_j^m$. Assume, by contradiction, that there are request $req'$, correct replica $r_j'$ and \textsc{abort} message $m'$ such that the above does not hold. Then, since a benign client needs to receive identical history digests from all replicas to commit a request (Step Z4/Q3), and since $r_j'$ stops executing new requests before sending any \textsc{abort} message (Step P2), $r_j'$ executed $req$ before sending $m'$. However, by Lemma 1, $h_{req}$ is a prefix of $LH_j^{m'}$ — a contradiction.

By Step P3, a client that aborts a request waits for $2f+1$ \textsc{abort} messages including at least $f+1$ from correct replicas. Since any commit history $h_{req}$ is a prefix of every history sent in an \textsc{abort} message by any correct replica (as shown above), at least $f+1$ received histories will contain $h_{req}$ as a prefix, for any committed request $req$. Hence, by construction of abort histories (Step P3 Sec. B.5) every commit history $h_{req}$ is a prefix of every abort history.

Init Order. By the clarifications of Step Z3/Q2 and Step P2 given in Section B.6, every correct replica must initialize its local history (with some valid init history) before sending any RESP or \textsc{abort} message. Since any common prefix $CP$ of all valid init histories is a prefix of any particular init history $I$, $CP$ is a prefix of every local history sent by a correct replica in an RESP or \textsc{abort} message. Init Order for commit histories immediately follows. In the case of abort histories, notice that at least out of $2f+1$ \textsc{abort} messages received by a client on aborting a request in Step P3, at least $f+1$ are sent by correct processes and contain local histories that have $CP$ as a prefix. Hence, by Step P3, $CP$ is a prefix of any abort history.

ZLight Progress. Recall that ZLight guarantees to commit clients’ requests if: there are no replica/link failures and Byzantine client failures. We assume that the message processing at processes takes negligible time and that clients set the timer $T$ triggered in Step Z1 to $3\Delta$. Then, to prove Progress, we prove a stronger property that no client executes Step P1 and panics (consequently no client ever aborts and Progress follows from Termination).

Assume by contradiction that there is a client $c$ that panics and denote the first such time by $t_{\text{panic}}$. Since no client is Byzantine, $c$ must be benign and $c$ invoked request $req$ at
t = t_{PANIC} - 3\Delta. Since no client panics by t_{PANIC} all replicas execute all requests they receive by t_{PANIC}. Then, it is not difficult to see, since there are no link failures, that: (i) by t + \Delta the primary receives req and take Step Z2 and (ii) by time t + 2\Delta < t_{PANIC} the replicas take Step Z3 for req. Since the primary is correct all replicas execute all requests received before t_{PANIC} in the same order (established by the sequence numbers assigned by the primary). Hence, by t + 3\Delta = t_{PANIC}, c receives 3f + 1 identical replies (Step Z4), commits req and never panics. A contradiction.

**Quorum Progress.** Recall that Quorum guarantees to commit clients’ requests only if:

- there are no replica/link failures,
- no client is Byzantine, and
- there is no contention.

We assume that the message processing at processes takes negligible time and that the timer T triggered in Step Z1 to 2\Delta. Like in the proof of ZLight Progress, we prove a stronger property that no client executes Step P1 and panics.

Assume by contradiction that there is a client c that panics and denote the first such time by t_{PANIC}. Since no client is Byzantine, c must be benign and c invoked request req at $t = t_{PANIC} - 2\Delta$. Since no client panics by $t_{PANIC}$ all replicas execute all requests they receive by $t_{PANIC}$. Then, it is not difficult to see, since there are no link failures, that by time $t + \Delta < t_{PANIC}$ all replicas receive req and take Step Q2. Since there is no contention and all replicas are correct, all replicas order all requests in the same way and send identical histories to the clients. Hence, by $t + 2\Delta = t_{PANIC}$, c receives 3f + 1 identical replies (Step Q3), commits req and never panics. A contradiction.

### C.2 Chain

In this Section, we prove that Chain implements Abstract with Progress equivalent to that of ZLight. We denote the predecessor (resp., successor) set of the replica $r_j$, by $\overline{R}_j$ (resp., $R_j$). We also denote by $\Sigma_{last}$ the set of the last $f + 1$ replicas in the chain order, i.e., $\Sigma_{last} = \{r_j \in \Sigma : i > 2t\}$. In addition, we say that correct replica $r_j$ executes req at position $pos$ if $sn_j = pos$ when $r_j$ executes req.

Before proving Abstract properties, we first prove two auxiliary lemmas. Notice also that Lemma 1, Section C.1, extends to Chain as well.

**Lemma 2** If correct replica $r_j$ executes req (at position $sn$, at time $t_1$), then all correct replicas $s_j$, $1 \leq j < i$ execute req (at position $sn$, before $t_1$).

By contradiction, assume the lemma does not hold and fix $r_j$ to be the first correct replica that executes req (at position $sn$), such that there is a correct replica $r_x$ ($x < j$) that never executes req (at position $sn$); we say $r_j$ is the first replica for which req skips. Since CHAIN messages are authenticated using CAs, $r_j$ executes req at position $sn$ only if $r_j$ receives a CHAIN message with MACs authenticating req and $sn$ from all replicas from $\overline{R}_j$ authenticate req and $sn$, i.e., only after all correct replicas from $\overline{R}_j$ execute req at position $sn$. If $r_x \in R_j$, $r_x$ must have executed req at position $sn$ — a contradiction. On the other hand, if $r_x \notin R_j$, then $r_j$ is not the first replica for which req skips, since req skips for any correct replica (at least one) from $\overline{R}_j$ — a contradiction.

**Lemma 3** If benign client c commits req with history $h$ (at time $t_1$), then all correct replicas in $\Sigma_{last}$ execute req (before $t_1$) and the state of their local history upon executing req is $h$. 

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To prove this lemma, notice that correct replica \( r_j \in \Sigma_{\text{last}} \) generates a MAC for the client authenticating \( \text{req} \) and \( D(h') \) for some history \( h' \) (Step C3): (1) only after \( r_j \) executes \( \text{req} \) and (2) only if the state of \( LH_j \) upon execution of \( \text{req} \) equals \( h' \). Moreover, by Step C3, no correct replica executes the same request twice. By Step C4, a benign client (resp., replica) cannot commit \( \text{req} \) with \( h \) unless it receives a MAC authenticating \( \text{req} \) and \( D(h') \) from every correct replica in \( \Sigma_{\text{last}} \). Hence the lemma.

**Well-formed commit indications.** By Step C4, in order to commit a request a client needs to receive MACs authenticating \( LH \)Digest = \( D(h') \) for some history \( h' \) and the reply digest from all replicas from \( \Sigma_{\text{last}} \), including at least one correct replica. By Step C3, a digest of the reply sent by a correct replica is \( D(\text{rep}(h')) \). Hence, \( h' \) is exactly a commit history \( h \) and is uniquely defined due to our assumption of collision-free digests.

Moreover, since a correct replica executes an invoked request before sending a CHAIN message in Step C3, it is straightforward to see that if \( \text{req} \) is committed with a commit history \( h_{\text{req}} \), then \( \text{req} \) is in \( h_{\text{req}} \).

**Validity.** For any request \( \text{req} \) to appear in a abort (resp., commit) history \( h \), at least \( f + 1 \) replicas must have have sent \( h \) (resp., a digest of \( h \) in Step P2 (resp., Step C3)) such that \( \text{req} \in h \). Hence, at least one correct replica executed \( \text{req} \).

Now, we show that correct replicas execute only requests invoked by clients. By contradiction, assume that some correct replica executed a request not invoked by any client and let \( r_j \) be the first correct replica to execute such a request \( \text{req}' \) in Step C3 of Chain. In case \( j < f + 1 \), \( r_j \) executes \( \text{req}' \) only if \( r_j \) receives a CHAIN message with a MAC from the client, i.e., only if some client invoked \( \text{req} \), or if \( \text{req} \) is contained in some valid init history. On the other hand, if \( j > f + 1 \), Lemma 2 yields a contradiction with our assumption that \( r_j \) is the first correct replica to execute \( \text{req}' \).

Moreover, by Step C3, no replica executes the same request twice (every replica maintains \( t_j[c] \)). Hence, no request appears twice in any local history of a correct process, and consequently, no request appears twice in any commit history. In the case of abort histories, no request appears twice by construction (see Step P3(ii) Sec. B.5).

**Termination.** See the proof of Termination for ZLight/Quorum (Sec. C.1).

Moreover, to see that a committed request \( \text{req} \) must be in its commit \( h_{\text{req}} \), notice that a client needs to receive the MAC for the same local history digest \( D(h_{\text{req}}) \) from all \( f + 1 \) from \( \Sigma_{\text{last}} \) including at least one correct replica \( r_j \). By Step C3, \( r_j \) executes \( \text{req} \) and appends it to its local history \( LH_j \) before authenticating the digest of \( LH_j \); hence, \( \text{req} \in h_{\text{req}} \).

**Commit Order.** Assume, by contradiction, that there are two committed request \( \text{req} \) (by benign client \( c \)) and \( \text{req}' \neq \text{req} \) (by benign client \( c' \)) with different commit histories \( h_{\text{req}} \) and \( h_{\text{req}}' \) such that neither is the prefix of the other. By Lemma 3, there is correct replica \( r_j \in \Sigma_{\text{last}} \) that executed \( \text{req} \) and \( \text{req}' \) such that the state of \( LH_j \) upon executing these requests is \( h_{\text{req}} \) and \( h_{\text{req}}' \), respectively. A contradiction with Lemma 1 (recall that this lemma extends to Chain as well).

**Abort Order.** Assume, by contradiction, that there is committed request \( \text{req}_C \) (by some benign client) with commit history \( h_{\text{req}_C} \) and aborted request \( \text{req}_A \) (by some benign client) with commit history \( h_{\text{req}_A} \), such that \( h_{\text{req}_A} \) is not a prefix of \( h_{\text{req}_A} \). By Lemma 3 and the assumption of at most \( f \) faulty replicas, all correct replicas (at least one) from \( \Sigma_{\text{last}} \) execute \( \text{req}_C \) and their state upon executing \( \text{req}_C \) is \( h_{\text{req}_C} \). Let \( r_j \in \Sigma_{\text{last}} \) be a correct replica with the highest index \( \text{ind} \) among all replicas in \( \Sigma_{\text{last}} \). By Lemma 2, all correct replicas execute all the requests in \( h_{\text{req}_C} \) at the same positions these requests have in \( h_{\text{req}_C} \). In addition, a correct replica executes all the requests belonging to \( h_{\text{req}_C} \) before sending any ABORT message in
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Step P2; indeed, before sending any ABORT message, a correct replica must stop further execution of requests. Therefore, for every local history $LH_j$ that a correct replica sends in an ABORT message, $h_{req_c}$ is a prefix of $LH_j$.

Finally, by Step P3, a client that aborts a request waits for $2f + 1$ ABORT messages including at least $f + 1$ from correct replicas. By construction of abort histories (Step P3) every commit history, including $h_{req_c}$, is a prefix of every abort history, including $h_{req_a}$, a contradiction.

Init Order. The proof is identical to the proof of ZLight/Quorum Init Order.

Progress. Chain guarantees to commit clients’ requests under the same conditions as ZLight, i.e., if: there are no replica/link failures and Byzantine client failures. Assuming that the message processing at processes takes negligible time, it is sufficient that clients set the timer $T$ triggered in Step C1 to $(3f + 2)\Delta$. Then, Progress of Chain is very simple to show, along the lines of ZLight Progress (Sec. C.1).