Byzantine Fault Tolerance for Nondeterministic Applications[*]

Wenbing Zhao
Department of Electrical and Computer Engineering
Cleveland State University, 2121 Euclid Ave, Cleveland, OH 44115
wenbing@ieee.org

Abstract

All practical applications contain some degree of nondeterminism. When such applications are replicated to achieve Byzantine fault tolerance (BFT), their nondeterministic operations must be controlled to ensure replica consistency. To the best of our knowledge, only the most simplistic types of replica nondeterminism have been dealt with. Furthermore, there lacks a systematic approach to handling common types of nondeterminism. In this paper, we propose a classification of common types of replica nondeterminism with respect to the requirement of achieving Byzantine fault tolerance, and describe the design and implementation of the core mechanisms necessary to handle such nondeterminism within a Byzantine fault tolerance framework.

Keywords: Byzantine Fault Tolerance, Intrusion Tolerance, Replica Nondeterminism, Security, Fault Tolerance Middleware

1. Introduction

Today's society has increasing reliance on services provided over the Internet. These services are expected to be highly dependable, which requires the applications providing such services to be carefully designed and implemented, and rigorously tested. However, considering the intense pressure for short development cycles and the widespread use of commercial-off-the-shelf software components, it is not surprising that software systems are notoriously imperfect. The vulnerabilities due to insufficient design and poor implementation are often exploited by adversaries to cause a variety of damages, e.g., crashing of the applications, leaking of confidential information, modifying or deleting of critical data, or injecting of erroneous information into the application data. These malicious faults are often modeled as Byzantine faults. One approach to tackle such threats is to replicate the server-side applications and employ a Byzantine fault tolerance (BFT) algorithm as described in [7, 8, 9, 10].

Byzantine fault tolerance algorithms require the replicas to operate deterministically, *i.e.,* given the same input under the same state, all replicas produce the same output and transit to the same state. However, all practical applications contain some degree of nondeterminism. When such applications are replicated to achieve fault and intrusion tolerance, their nondeterministic operations must be controlled to ensure replica consistency.

To the best of our knowledge, only the most simplistic types of replica nondeterminism have been dealt with under the Byzantine fault model [7, 8, 9, 10], which we term as wrappable nondeterminism and verifiable pre-determinable nondeterminism. The former assumes that any nondeterministic operations and their side effects can be mapped into some pre-specified abstract operations and state, which are deterministic. The later assumes that any nondeterministic values can be determined prior to the execution of a request, and such values proposed by one replica can be verified by other replicas in a deterministic manner, and the values are accepted only if they are believed to be correct.

The mechanisms designed to handle these types of nondeterminism either are not effective in guaranteeing replica consistency and/or are not effective in masking Byzantine faults, if the application to be replicated exhibits other types of nondeterministic behavior. For example, many online gaming applications contain nondeterminism whose values (*e.g.,* random numbers that determine the state of the applications) proposed by one replica cannot be verified by another replica. It is dangerous to treat this type of nondeterminism the same as the verifiable pre-determinable nondeterminism because a faulty replica could use a predictable algorithm to update its internal state and collude with its clients, without being detected, which defeats the purpose of Byzantine fault tolerance. As another example, multithreaded applications may exhibit nondeterminism whose values (*e.g.,* thread interleaving) cannot be determined prior to the execution of a request (without losing concurrency), which cannot be handled by existing BFT mechanisms.

In this paper, we introduce a classification of common types of replica nondeterminism present in many applications. We propose a set of mechanisms that can be

[*] This work was supported in part by Department of Energy Contract DE-FC26-06NT42853, and by a Faculty Research Development award from Cleveland State University.

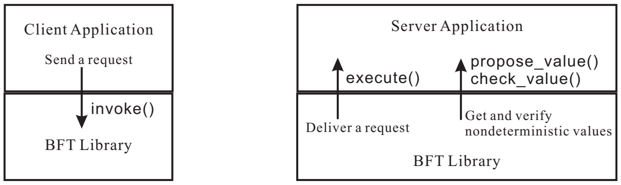


Figure 1. The positioning of the application and the BFT library, and the core interfaces between the two components.

used to control these types of nondeterministic operations. We also describe the implementation of the core mechanisms and their integration with a well-known BFT framework [7, 8, 9, 10]. Our performance evaluation of the integrated framework shows that our mechanisms only introduce moderate runtime overhead.

2. Byzantine Fault Tolerance

This work is built on top of the BFT framework developed by Castro, Rodrigues, and Liskov [7, 8, 9, 10]. We use the same assumptions and system models as those of the BFT framework. For completeness, we briefly summarize the BFT framework here.

The BFT framework supports client-server applications running in an asynchronous distributed environment with a Byzantine fault model, *i.e.,* faulty nodes may exhibit arbitrary behaviors. It requires the use of 3f+1 replicas to tolerate up to f faulty nodes. (In a recent publication [19], Yin et al. proposed a method to reduce the number of replicas to 2f+1 by separating the executing and agreement nodes.)

The BFT framework is implemented as a library to be linked to the application code (both the server and the client sides), as shown in Figure 1. In general, on the server side, we use the term *replica* to refer to the combined entity of the server application and the BFT library. On the client side, we use the term *client* to refer to the combined entity of the client application and the client-side BFT library. Sometimes, however, it is necessary to distinguish the two parts explicitly. As shown in Figure 1, the client-server application and the BFT mechanisms (residing in the BFT library) interact via a set of Application Programming Interfaces (APIs). The APIs contain a number of downcalls to be invoked by the application for a number of purposes, for example, to initialize the BFT library with appropriate parameters and callback functions, to send requests to the server replicas, and to start the event loop managed by the BFT library. The APIs also contain a number of upcalls to be implemented and supplied by the application, so that the BFT mechanisms can deliver a request to the server application, retrieve and verify nondeterministic values (if applicable), and retrieve and restore application state. Figure 1 includes a subset of the APIs directly related to this work.

In the BFT framework, a replica is modeled as a state machine. The replica is required to run (or rendered to run) deterministically. The state change is triggered by remote invocations on the methods offered by the replica. In general, the client first sends its request to the primary replica. The primary replica then broadcasts the request message to the backup replicas and also determines the execution order of the message. All correct replicas must agree on the same set of request messages with the same execution order. In other words, the request messages must be delivered to the server application at all replicas reliably in the same total order.

In the BFT framework, a very efficient Byzantine agreement algorithm, often referred to as the BFT algorithm, is used to ensure the total ordering of the requests received from different clients. The normal operations of the BFT algorithm involve three phases. The first phase is called the pre-prepare phase, where the primary replica multicasts a `PRE_PREPARE` message containing the ordering information, the client's request, and the nondeterministic values that can be determined prior to the execution of the request (if any) to all backup replicas. A backup replica then verifies the ordering information, the nondeterministic values, and the validity of the request message. If the backup replica accepts the `PRE_PREPARE` message, it multicasts to all other replicas a `PREPARE` message containing the ordering information and the digest of the request message being ordered. This starts the second phase, *i.e.,* the prepare phase. When a replica has collected 2f valid `PREPARE` messages for the request from other replicas, it multicasts a `COMMIT` message. This is the start of the third phase. When a replica has received 2f matching `COMMIT` messages from other replicas, the request message has been totally ordered and it is ready to be delivered to the server application. This concludes the third phase, *i.e.,* the commit phase, of the BFT algorithm. In the BFT framework, all messages are protected by a digital signature, or an authenticator [6] to ensure their integrity.

3. Classification of Replica Nondeterminism

We distinguish replica nondeterminism into the following three major categories:

- *Wrappable nondeterminism*. This type of replica nondeterminism can be easily controlled by using an infrastructure-provided or application-provided wrapper function, *without explicit inter-replica coordination*. For example, information such as hostnames, process ids, file descriptors, etc. can be determined group-wise. Another situation is when all replicas are implemented according to the same abstract specification, in which case, a wrapper function can be used to translate between the local state and the group-wise abstract state, as described in [10].

- *Pre-determinable nondeterminism*. This is a type of replica nondeterminism whose values can be known *prior to* the execution of a request and it requires inter-replica coordination to ensure replica consistency.

- *Post-determinable nondeterminism*. This is a type of replica nondeterminism whose values can only be recorded *after* the request is submitted for execution and the nondeterministic values won't be complete until the end of the execution. It also requires inter-replica coordination to ensure replica consistency.

In this paper, we will not have further discussion on the wrappable replica nondeterminism because it can be dealt with using a deterministic wrapper function without inter-replica coordination, and also because it has been thoroughly studied in [10]. Instead, we will focus on the rest of two types of replica nondeterminism.

Based on if a replica can verify the nondeterministic values proposed (or recorded) by another replica, replica nondeterminism can be further classified into the following types:

- *Verifiable nondeterminism*. The type of replica nondeterminism whose values can be verified by other replicas.

- *Non-verifiable nondeterminism*. The type of replica nondeterminism whose values cannot be completely verified by other replicas. Note that a replica might be able to partially verify some nondeterministic values proposed by another replica. This would help reduce the impact of a faulty replica.

Overall, our classification gives four types of replica nondeterminism of our interest:

- *Verifiable pre-determinable nondeterminism (VPRE)*. In the past, clock-related operations have been treated as this type operations. However, strictly speaking, it is not possible for a replica to verify deterministically another replica's proposal for the current clock value without imposing stronger restriction on the synchrony of the distributed system (e.g., bounds on message propagation and request execution).

- *Non-verifiable pre-determinable nondeterminism (NPRE)*. Online gaming applications, such as Blackjack [1] and Texas Hold'em [18], exhibit this type of nondeterminism. The integrity of services provided by such applications depends on the use of good secure random number generators. For best security, it is essential to make one's choice of a random number unpredictable, let alone verifiable by other replicas.

- *Verifiable post-determinable nondeterminism (VPOST)*. We have yet to identify a commonly used application that exhibits this type of nondeterminism. We include this type for completeness.

- *Non-verifiable post-determinable nondeterminism (NPOST)*. In general, all multithreaded applications exhibit this type of nondeterminism. For such applications, it is virtually impossible to determine which thread ordering should be used prior to the execution of a request without losing concurrency.

4. Controlling Replica Nondeterminism

In this section, we present core mechanisms for controlling replica nondeterminism for Byzantine fault tolerance, and provide a brief informal proof of the correctness of our mechanisms. Our mechanisms rely on the same set of APIs as those in the original BFT library to retrieve from, upload to, and verify by applications of the nondeterministic values, albeit with some modifications to the parameter list. The most relevant APIs have been shown in Figure 1. Due to space limitation, we omit the detailed explanation of these APIs.

Our mechanisms work in the following ways. When the primary receives a client's request, if it is ready to order the message, it invokes the `propose_value()` callback function registered by the application layer. The application supplies the type of nondeterminism that would be involved in the execution of the request, and if applicable, the nondeterministic values. Depending on the type of nondeterminism returned by the application, the modified BFT algorithm operates differently according to the mechanisms described from Section 4.1 through Section 4.4.

In practical applications, the execution of a request often involves with more than one type of nondeterminism, for example, both time-related nondeterminism (which is of verifiable pre-determinable type) and multithreading-related nondeterminism (which is of non-verifiable post-determinable type). To accommodate this complexity, a bitmask should be used instead of an integer value to capture the nondeterminism type information in the `propose_value()` and `check_value()` upcalls. However, the data structure used to store the nondeterministic values does not need to be made more sophisticated because it is the application's duty to generate and interpret them. Our algorithm can readily cope with this complexity. Using the same example, the time-related nondeterministic values can be determined during the pre-prepare-update phase. The multithreading-related nondeterminism can be resolved in the post-commit phase.

4.1. Controlling VPRE nondeterminism

If the nondeterminism for the operation at the primary is of type `VPRE`, the application provides the nondeterministic values in the `ndet` parameter. The obtained information is

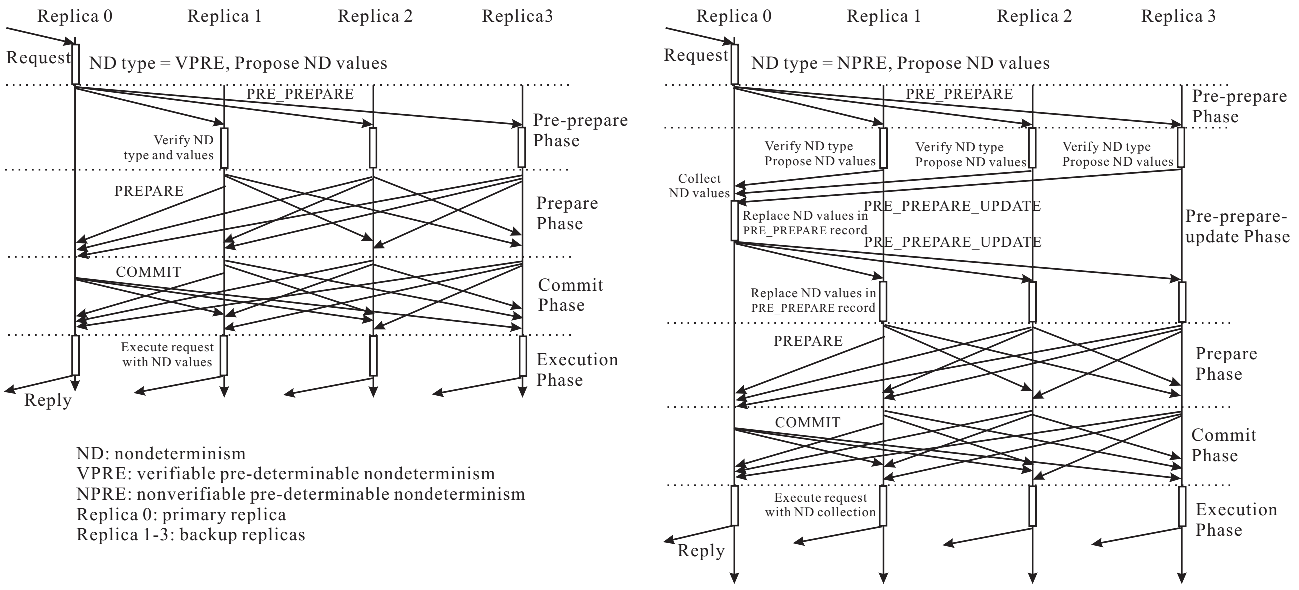

Replica 0
Replica 1
Replica 2
Replica3
Request
ND type = VPRE, Propose ND values
PRE_PREPARE
Pre-prepare Phase
Verify ND type and values
PREPARE
Prepare Phase
COMMIT
Commit Phase
Execute request with ND values
Execution Phase
Reply
ND: nondeterminism
VPRE: verifiable pre-determinable nondeterminism
NPRE: nonverifiable pre-determinable nondeterminism
Replica 0: primary replica
Replica 1-3: backup replicas
Replica 0
Replica 1
Replica 2
Replica 3
Request
ND type = NPRE, Propose ND values
PRE_PREPARE
Pre-prepare Phase
Verify ND type Propose ND values
Verify ND type Propose ND values
Verify ND type Propose ND values
Collect ND values
Replace ND values in PRE_PREPARE record
PRE_PREPARE_UPDATE
PRE_PREPARE_UPDATE
Pre-prepare-update Phase
Replace ND values in PRE_PREPARE record
PREPARE
Prepare Phase
COMMIT
Commit Phase
Execute request with ND collection
Execution Phase
Reply

Figure 2. Normal operation of the modified BFT algorithm in handling verifiable (left) and nonverifiable (right) pre-determinable nondeterminism.

included in the PRE_PREPARE message, and it is multicast to the backup replicas.

On receiving the PRE_PREPARE message, a backup replica invokes the check_value() callback function. The replica passes the information received regarding the nondeterminism type and data values to the application layer so that the application can verify (1) the type of nondeterminism for the client's request is consistent with what is reported by the primary, and (2) the nondeterministic values proposed by the primary is consistent with its own values. If either check turns out to be false, the check_value() call returns an error code, the backup replica then suspects the primary. Otherwise, the backup replica accepts the client's request and the ordering information specified by the primary, logs the PRE_PREPARE message and multicasts a PREPARE message to all other replicas. From now on, the algorithm works the same as that of the original BFT framework, with the exception that the PREPARE and COMMIT messages also carry the digest of the nondeterministic values. The normal operations of the modified BFT algorithm is illustrated in Figure 2.

4.2. Controlling NPRE nondeterminism

If the nondeterminism for the operation at the primary is of type NPRE, the application at the primary proposes its share of nondeterministic values. The type of nondeterminism and the nondeterministic values are included in the PRE_PREPARE message, and it is multicast to all backup replicas.

On receiving the PRE_PREPARE message, a backup replica invokes the check_value() callback function to verify the nondeterminism type information supplied by the primary replica (after it has verified the client's request and the ordering information). If the verification is successful, the backup replica invokes the propose_value() function to obtain its share of nondeterministic values. It then builds a PRE_PREPARE_UPDATE message including its own nondeterministic values, and sends the message to the primary.

When the primary receives 2f PRE_PREPARE_UPDATE messages from different backup replicas (for the same client's request), it builds a PRE_PREPARE_UPDATE message, including the 2f+1 sets of nondeterministic values, each protected by the proposer's digital signature or authenticator. The PRE_PREPARE_UPDATE message itself is further protected by the primary's signature or authenticator. The primary then multicasts the message to all backup replicas. From now on, the BFT algorithm operates according to the original algorithm, except that the PREPARE and COMMIT messages also carry the digest of the nondeterministic values, and the 2f+1 sets of nondeterministic values are delivered to the application layer as part of the execute() upcall. The normal operations of the modified BFT algorithm for this type of nondeterminism is illustrated in Figure 2.

4.3. Controlling VPOST nondeterminism

The normal operations of the modified BFT algorithm in handling this type of replica nondeterminism is shown in Figure 3. The primary includes the nondeterminism type (*i.e.*, VPOST) information in the PRE_PREPARE message without any nondeterministic values and multicasts the message to the backup replicas.

On receiving the PRE_PREPARE message, a backup

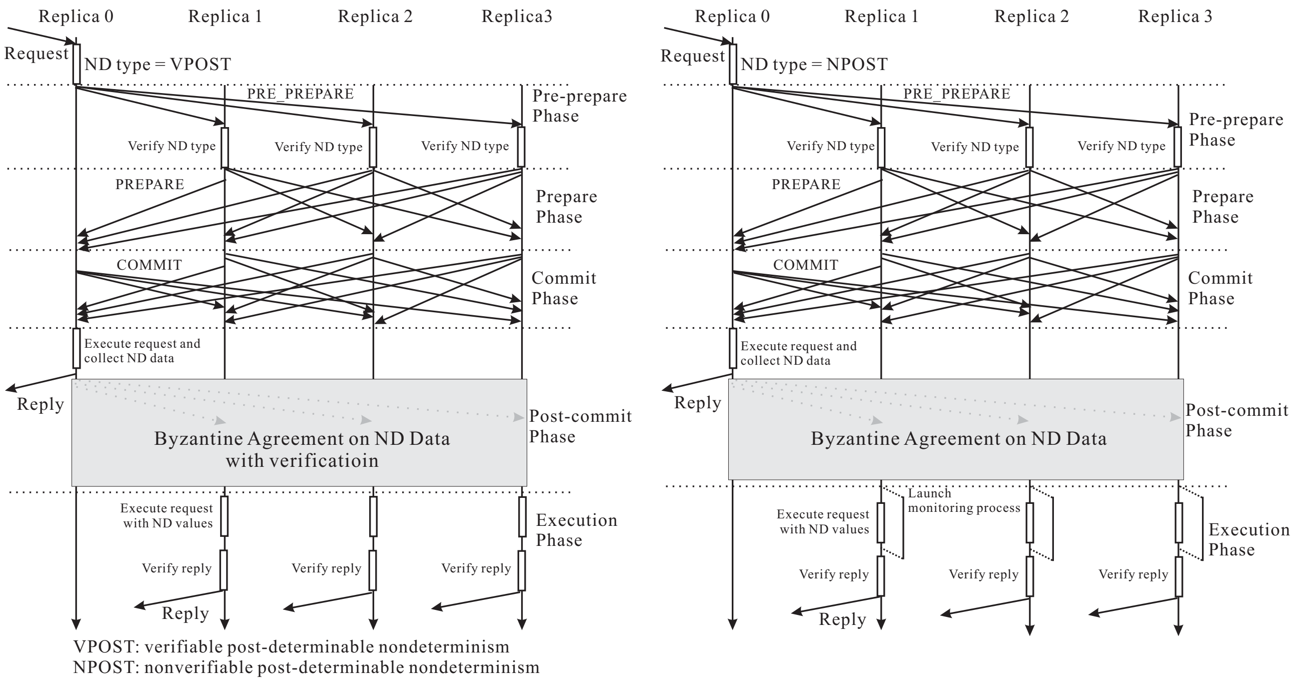


Figure 3. Normal operations of the modified BFT algorithm in handling verifiable (left) and nonverifiable (right) post-determinable nondeterminism.

replica performs the `check_value()` upcall if it has verified the client's request and the ordering information. If the backup replica confirms the type of nondeterminism, the BFT algorithm proceeds to the commit phase as usual. Otherwise, the backup replica suspects the primary.

When the primary is ready to deliver the request message, it proceeds to performing the `execute()` upcall and expects to receive both the reply message and the recorded nondeterministic values. Once the upcall returns, the primary stores the retrieved post-determined nondeterministic values, together with the digest of the reply, into a `postnd` log, and sends the reply message to the client. The digest of the reply is included so that a backup replica can verify if the primary has actually used the nondeterministic values to generate the reply.

A post-commit phase is needed for the primary to disseminate the data in the `postnd` log to backup replicas and for all correct replicas to be sure they have received the same set of values for the corresponding request. Unlike the pre-prepare-update phase for controlling `NPRE`, the post-commit phase involves with all the steps needed for correct replicas to reach an agreement on the nondeterministic values, which requires three rounds of message exchanges similar to those used to determine the ordering of the requests under normal operations. For `NPRE`, the prepare and commit phases needed for the correct replicas to reach a Byzantine agreement on the nondeterministic values are integrated with those for the corresponding request message. We could not do so for post-determinable nondeterminism types because the ordering for the corresponding request has already been decided.

A backup replica does not deliver a request message until a Byzantine agreement has been reached on the nondeterministic values for the request. If the Byzantine agreement could not be reached, or the verification of the nondeterministic values fails, a replica suspects the primary. Furthermore, when the replica produces a reply for the request, the digest of the reply is compared with that supplied by the primary. If the two do not match, the backup replica suspects the primary. Regardless of the comparison result, the backup replica sends the reply message to the client. It is safe to do so because if all correct backup replicas produce the same reply using the same set of nondeterministic values (even if they might be different from the set actually used by the primary, which implies that the primary is lying and will be suspected), the result is valid.

4.4. Controlling NPOST nondeterminism

The handling of non-verifiable post-determinable nondeterminism involves with the same steps as those described in the previous subsection until a backup replica is ready to deliver the request with the post-determined nondeterministic values, as shown in Figure 3.

The concern here is that a faulty primary could disseminate a wrong set of nondeterministic values hoping to either confuse the backup replicas, or to block them from providing useful services to their clients. For example, if the nondeterministic values contain thread ordering information, a faulty primary can arrange the ordering in such a way that it leads to the crash of the backup replicas (e.g., if the primary knows the existence of a software bug that leads to a segmentation fault), or it may cause a deadlock at the backup replicas (it is possible for a replica to perform a deadlock analysis before it follows the primary's ordering to prevent this from happening).

Because in general the replica cannot completely verify the correctness of the nondeterministic values until it actually executes the request, it is important for a backup replica to launch a separate monitoring process prior to invoking the `execute()` call. Should the replica run into a deadlock or a crash failure, the monitoring process can restart the replica and suspect the primary.

If it can successfully complete the `execute()` upcall, the backup replica performs the same reply verification procedure as that described in the previous subsection, and sends the reply to the client.

4.5. Proof of Correctness

We now provide an informal proof of correctness of our mechanisms. Due to space limitation, we only argue for the correctness of the safety property of our mechanisms and omit the proof for liveness. Since we do not have space to elaborate the view change mechanisms, the proof is further limited to the safety property within a single view.

Theorem 1. If a correct replica delivers a request m with a set of nondeterministic data in view v, then no other correct replica delivers m with a different set of nondeterministic data, and all such correct replicas use, or record (at the primary), the same set of nondeterministic data during its execution for m.

For `VPRE` type, the nondeterministic data is proposed by the primary and the agreement on the data is carried out together with the request message itself. At the end of the three-phase BFT algorithm, if some correct replicas agree on the ordering of the request message, they reach an agreement on the nondeterministic data as well. For `NPRE` type, the nondeterministic data is collectively determined by the pre-prepare-update phase, and it is followed by the three-phase BFT agreement. Again, if some correct replicas commit the request m, they also agree on the associated nondeterministic data. For both `VPRE` and `NPRE` types, when the request m is delivered at a correct replica, the nondeterministic data that have been agreed-upon are also delivered and used for execution.

For `VPOST` and `NPOST` types, the agreement on the nondeterministic data among correct replicas are guaranteed by the three-phase BFT algorithm executed during the post-commit phase. When the request m is delivered at a correct backup, the nondeterministic data associated with m is also delivered. The primary, if it is correct, must have recorded the nondeterministic data during its execution of m, and have disseminated the data to the backups during the post-commit phase. Therefore, the same nondeterministic data are used for execution at the primary (if it is correct) and other correct replicas.

5. Implementation and Performance

We implemented the core mechanisms described in the previous section in C++ and integrated them into the BFT framework [7, 8, 9, 10]. The experiments described below are focused on the evaluation of the cost for providing Byzantine fault tolerance to nondeterministic applications in the BFT layer. The cost associated with recording nondeterministic values, verifying such values, and replaying such values in the application layer is not studied in this work.

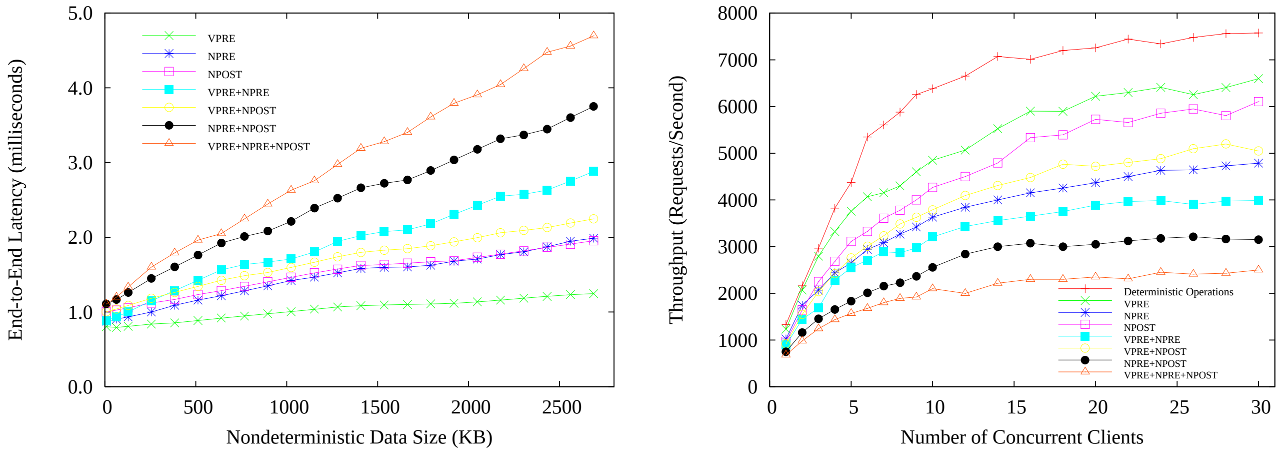
The development and test platform consists of 14 nodes running RedHat 8.0 Linux. Of the 14 computers, 4 of them are equipped with Pentium-4 2.8GHz processors and the rest have pentium-3 1GHz processors. The computers are connected via a 16-port Netgear 100Mbps switch. The server replicas run on the four Pentium-4 nodes and the clients are distributed across the rest of the nodes.

Figure 4 shows the summary of the end-to-end latency and throughput measurements for a client-server application under normal operations for different types of replica nondeterminism, including composite types. In each iteration, each client issues a request to the server replicas and waits for the corresponding reply. There is no waiting time between consecutive iterations. The size of each request and reply is kept fixed at 1KB. In each run, we measure the total elapsed time for 10,000 consecutive iterations at each client. From the measured time, we derive the average end-to-end latency for each request-reply iteration and the system throughput.

The type of nondeterminism and the size of nondeterministic values vary in different experiments, except during the throughput measurements, where the nondeterministic values are kept at 256 Bytes for each type. Note that the sizes of nondeterministic values shown in the horizontal axis in Figure 4(a) are for *each* type. That means, for composite types, the total size of nondeterministic values is twice or three-times as large as those displayed.

Except for `VPRE`, the handling of other types of nondeterminism involves with one or more phases of message exchanges for correct replicas to reach an agreement on the nondeterministic values. As such, as shown in Figure 4, the end-to-end latency is noticeably larger, and the throughput is smaller, than that of `VPRE` nondeterministic operations. The end-to-end latency difference is more significant as the size of nondeterministic values involved with each operation increases.

The results shown in Figure 4 are obtained after a number of optimizations to the mechanisms described previously. Without these optimizations, the latency is signifi-



(a) (b)

Figure 4. End-to-end latency (a) and throughput (b) for requests with different types of replica nondeterminism under normal operations. In (b), throughput for deterministic requests is included as a reference.

cantly larger and the throughput is much lower, except those for VPRE nondeterministic operations.

In the pre-prepare-update phase, which is needed to handle NPRE nondeterminism and other composite types involving with NPRE nondeterminism, each backup replica multicasts its contribution of the nondeterministic values to all other replicas, and the primary decides on the collection (must include the contributions from 2f+1 replicas, including its own) to be used to calculate the final nondeterministic values. Instead of multicasting the collection of nondeterministic values, the primary replica disseminates the collection of the *digests* of the values proposed by each replica. This sharply reduces the message size if the size of nondeterministic values is large. Since each replica can log the nondeterministic values received from other replicas, a (backup) replica can verify the digests provided by the primary using its local copies. A backup replica might not have received the values proposed by one or more replicas included in the primary's message, in which case, the replica asks for retransmission of the values.

During the post-commit phase, which is needed to handle NPOST nondeterminism, The data in the postn log is piggybacked with the PRE_PREPARE message for the next request. This way, the Byzantine agreement for the nondeterministic values is reached together with that for the ordering of the that request, which reduces the number of messages needed to handle this type of nondeterminism. Even though the end-to-end latency for a request increases slightly as a result, the system throughput is significantly improved. To avoid waiting indefinitely for the next request, the primary sets a timer. When the timer expires, the primary initiates the Byzantine agreement phases for the nondeterministic values in conjunction with a null request so that the existing mechanisms can be reused.

It may be surprising to see that the end-to-end latency for a request with NPRE nondeterminism is similar to, or slightly larger than, that for a request with NPOST nondeterminism when there are large quantity of nondeterministic values. With the above optimization, the pre-prepare-update phase (needed to handle NPRE) involves with at least two large messages (one message per backup replica on its proposed nondeterministic values) while the post-commit phase (needed to handle NPOST) involves with only one large message (sent by the primary). Due to the same reason, the throughput for requests with NPOST nondeterminism is higher for those with NPRE nondeterminism when sufficient number of concurrent clients are present (so that virtually all post-determinable nondeterministic values are piggybacked with the PRE_PREPARE messages for other requests, rather than being sent as separate messages).

6. Related Work

Replica nondeterminism has been studied extensively under the benign fault model [2, 3, 4, 5, 12, 13, 14, 15, 16, 17, 20]. However, there is a lack of systematic classification of the common types of replica nondeterminism, and even less so on the unified handling of such nondeterminism. [4, 5, 16] did provide a classification of some types of replica nondeterminism. However, they largely fall within the types of wrappable nondeterminism and verifiable predeterminable nondeterminism, with the exception of nondeterminism caused by asynchronous interrupts, which we do not address in this work.

The replica nondeterminism caused by multithreading has been studied separately from other types of nondeterminism, again, under the benign fault mode only, in [2, 3, 12, 13, 14, 15]. However, these studies provided valuable insight on how to approach the problem of ensuring consistent replication of multithreaded applications. It is realized that what matters in achieving replica consistency is to control the ordering of different threads on access of shared data. The mechanisms to record and to replay such ordering have been developed. So do those for checkpointing and restoring the state of multithreaded applications (for example, [11]). Even though these mechanisms alone are not sufficient to achieve Byzantine fault tolerance for multithreaded applications, they can be adapted and used towards this goal. In this paper, we have shown when to record and (partially) verify the ordering, how to propagate the ordering, and how to provision for problems encountered when replaying the ordering, all under the Byzantine fault model.

Under the Byzantine fault model, the main effort on the subject of replica nondeterminism control so far is to cope with wrappable and verifiable pre-determinable replica nondeterminism [7, 8, 9, 10]. In [7], Castro and Liskov provided a brief guideline on how to deal with the type of nondeterminism that requires collective determination of the nondeterministic values. The guideline is very important and useful, as we have followed in this work. However, the guideline is applicable to only a subset of the problems we have addressed.

7. Conclusion and Future Work

In this paper, we presented a classification of common types of replica nondeterminism, and the mechanisms necessary to handle them in the context of Byzantine fault tolerance. We also described how to integrate our mechanisms into a well-known BFT framework [7, 8, 9, 10]. Furthermore, we conducted extensive experiments to evaluate the performance of the BFT framework extended with our mechanisms. We show that our mechanisms only incur moderate runtime overhead.

Future work will focus on the development of modules and tools that help applications record, verify (if applicable), and replay nondeterministic values.

References

[1] B. Arkin, F. Hill, S. Marks, M. Schmid, and T. J. Walls. How we learned to cheat at online poker: A study in software security. http://www.developer.com/java/other/ article.php/10936_616221_1, September 1999.

[2] C. Basile, K. Whisnant, and R. Iyer. A preemptive deterministic scheduling algorithm for multithreaded replicas. In *Proceedings of the IEEE International Conference on Dependable Systems and Networks*, pages 149–158, San Francisco, CA, June 2003.

[3] C. Basile, K. Whisnant, Z. Kalbarczyk, and R. Iyer. Loose synchronization of multithreaded replicas. In *Proceedings of the International Symposium on Reliable Distributed Systems*, pages 250–255, Suita, Japan, October 2002.

[4] T. Bressoud. TFT: A software system for application-transparent fault tolerance. In *Proceedings of the IEEE 28th International Conference on Fault-Tolerant Computing*, pages 128–137, Munich, Germany, June 1998.

[5] T. Bressoud and F. Schneider. Hypervisor-based fault tolerance. *ACM Transactions on Computer Systems*, 14(1):80–107, February 1996.

[6] M. Castro and B. Liskov. Authenticated Byzantine fault tolerance without public-key cryptography. Technical Report MIT-LCS-TM-589, MIT, June 1999.

[7] M. Castro and B. Liskov. Practical Byzantine fault tolerance. In *Proceedings of the Third Symposium on Operating Systems Design and Implementation*, New Orleans, USA, February 1999.

[8] M. Castro and B. Liskov. Proactive recovery in a Byzantine-fault-tolerant system. In *Proceedings of the Third Symposium on Operating Systems Design and Implementation*, San Diego, USA, October 2000.

[9] M. Castro and B. Liskov. Practical Byzantine fault tolerance and proactive recovery. *ACM Transactions on Computer Systems*, 20(4):398–461, November 2002.

[10] M. Castro, R. Rodrigues, and B. Liskov. BASE: Using abstraction to improve fault tolerance. *ACM Transactions on Computer Systems*, 21(3):236–269, August 2003.

[11] W. R. Dieter and J. E. Lumpp. User-level checkpointing for LinuxThreads programs. In *Proceedings of the USENIX Technical Conference*, Boston, Massachusetts, June 2001.

[12] R. Jimenez-Peris, M. Patino-Martinez, and S. Arevalo. Deterministic scheduling for transactional multithreaded replicas. In *Proceedings of the IEEE 19th Symposium on Reliable Distributed Systems*, pages 164–173, Nurnberg, Germany, October 2000.

[13] L. Moser and M. Melliar-Smith. Transparent consistent semi-active and passive replication of multithreaded application programs. US Patent Application No. 20040078618, 2004.

[14] L. Moser and M. Melliar-Smith. Consistent asynchronous checkpointing of multithreaded application programs based on semi-active or passive replication. US Patent Application No. 20050034014, 2005.

[15] P. Narasimhan, L. E. Moser, and P. M. Melliar-Smith. Enforcing determinism for the consistent replication of multithreaded CORBA applications. In *Proceedings of the IEEE 18th Symposium on Reliable Distributed Systems*, pages 263–273, Lausanne, Switzerland, October 1999.

[16] D. Powell. *Delta-4: A Generic Architecture for Dependable Distributed Computing*. Springer-Verlag, 1991.

[17] J. Slember and P. Narasimhan. Living with nondeterminism in replicated middleware applications. In *Proceedings of the ACM/IFIP/USENIX 7th International Middleware Conference*, pages 81–100, Melbourne, Australia, 2006.

[18] J. Viega and G. McGraw. *Building Secure Software*. Addison-Wesley, 2002.

[19] J. Yin, J.-P. Martin, A. Venkataramani, L. Alvisi, and M. Dahlin. Separating agreement from execution for byzantine fault tolerant services. In *Proceedings of the ACM Symposium on Operating Systems Principles*, pages 253–267, Bolton Landing, NY, USA, 2003.

[20] W. Zhao, L. E. Moser, , and P. M. Melliar-Smith. Deterministic scheduling for multithreaded replicas. In *Proceedings of the IEEE International Workshop on Object-oriented Real-time Dependable Systems*, pages 74–81, Sedona, Arizona, February 2005.