

Dynamic Scalable State Machine Replication

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Abstract. State machine replication (SMR) is a well-known technique for providing a fault-tolerant, high availability service, by having clients commands executed in the same order on all replicas, following the deterministic execution, producing same state of all replica for each client command. The original SMR model was not quite efficient since adding replica to the system doesn't increase the performance or throughput, since all replicas still have to execute same number of commands. Scalable SMR (S-SMR) then was introduced to address that problem by partitioning the application state, that allow client commands go through a combination of replicas, but not necessary all the replicas, while still maintain the consistency of the system. However (S-SMR) TODO: complete abstract

1 Introduction

TODO: add content

2 Model and definitions

A distributed system is considered as a system consisting of an unbounded set of client processes $C = \{c_1, c_2, \dots\}$ and a bounded set of server processes $S = \{s_1, \dots, s_n\}$. Set S is divided into P disjoint groups of servers, s_1, \dots, s_P . Processes are either *correct*, if they never fail, or *faulty*, otherwise. In either case, processes do not experience arbitrary behavior (i.e., no Byzantine failures). Processes communicate by message passing, using either one-to-one or one-to-many communication, as defined next. The system is asynchronous: there is no bound on message delay or on relative process speed.

We consider a scalable state machine replication system. One-to-one communication uses primitives $send(p, m)$ and $receive(m)$, where m is a message and p is the process m is addressed to. If sender and receiver are correct, then every message sent is eventually received. One-to-many communication relies on atomic multicast, defined by the primitives $multicast(\gamma, m)$ and $deliver(m)$, where γ is a set of server groups. Let relation \prec be defined such that $m \prec m'$ if there is a server that delivers m before m' . Atomic multicast ensures that (i) if a server delivers m , then all correct servers in γ deliver m (*agreement*); (ii) if a correct process multicasts m to groups in γ , then all correct servers in every

group in γ deliver m (*validity*); and (iii) relation \prec is acyclic (*order*).¹ The order property implies that if s and r deliver messages m and m' , then they deliver them in the same order. Atomic broadcast is a special case of atomic multicast in which there is a single group with all servers.

3 Background and motivation

State-machine replication is a fundamental approach to implement a fault-tolerant service by replicating servers and coordinating the execution of client commands against server replicas [10, 17]. State-machine replication ensures strong consistency (i.e., linearizability [1]) by coordinating the execution of commands in the different replicas: Every replica has a full copy of the service state $V = \{v_1, \dots, v_m\}$ and executes commands submitted by the clients in the same order. A command is a program consisting of a sequence of operations, which can be of three types: *read*(v), *write*(v , val), or a deterministic computation.

3.1 Scaling state-machine replication

By starting in the same initial state and executing the same sequence of deterministic commands, servers make the same state changes and produce the same reply for each command. To guarantee that servers deliver the same sequence of commands, SMR can be implemented with atomic broadcast: commands are atomically broadcast to all servers, and all correct servers deliver and execute the same sequence of commands [2, 4].

Despite its simple execution model, classical SMR does not scale: adding resources (e.g., replicas) will not translate into sustainable improvements in throughput. This happens for a few reasons. First, the underlying communication protocol needed to ensure ordered message delivery may not scale itself (i.e., a communication bottleneck). Second, every command must be executed sequentially by each replica (i.e., an execution bottleneck).

Several approaches have been proposed to address SMRs scalability limitations. To cope with communication overhead, some proposals have suggested to spread the load of ordering commands among multiple processes (e.g., [16, 12, 15]), as opposed to dedicating a single process to determine the order of commands (e.g., [3, 11]).

Two directions of research have been suggested to overcome execution bottlenecks. One approach (scaling up) is to take advantage of multiple cores to execute commands concurrently without sacrificing consistency [8, 13, 9, 7]. Another approach (scaling out) is to partition the service's state and replicate each partition (e.g., [6, 14]). In the following section, we review Scalable State-Machine Replication (S-SMR), a proposal in the second category.

¹ Solving atomic multicast requires additional assumptions [3, 5]. In the following, we simply assume the existence of an atomic multicast oracle.

3.2 Scalable State-Machine Replication

TODO: talk about SSMR

SSMR implementation brings into use the concept of *Oracle*, the core of partitioning algorithms, which runs a static deterministic algorithm to return the combination of involved partitions of a command; all clients and partitions have their own version of Oracle, and assumed to be identical. By doing that way, SSMR can ensure Oracle return same results for query from both clients and partitions. However, this implementation leads to some limitations: (i) the Oracles on all parties are not synchronized, thus they need to have the knowledge of all $v \in V$ during the life-cycle of the system, and (ii) a change in V on one Oracle will not be recognized by the others. Therefore, SSMR doesn't support creating state variable v_n on the fly, and has to initialize the whole V on the starting phase.

4 Dynamic Scalable State Machine Replication

In this section, we introduce Dynamic SSMR, discuss performance optimizations, and argue about D-SSMR's correctness.

4.1 General idea

S-SSMR divides the state variables v into P partitions p_1, \dots, p_P , where for each p_i , $p_i \subseteq V$, and each variable v in V has to be assigned to at least one partition and define $part(v)$ as the partitions that hold v . Each partition p_i is replicated by servers in group s_i . For brevity, the server s belongs to p_i with the meaning that $s \in S_i$, and say that client c multicasts command C to partition P_i means that c multicasts C to group S_i .

To execute command C , the client multicasts C to all partitions that hold a variable read or updated by C . Consequently, the client must be able to determine the partitions accessed by C , denoted by $part(C)$. If the client cannot accurately estimate which partitions are accessed by C , it must determine a superset of these partitions, in the worst case assuming all partitions. In order for clients to provide a close approximation to the command's actually accessed partitions, there is an oracle that tells the client which partitions should receive each command.

Dynamic SSMR improves on SSMR implementation by adding a central Oracle which has the information of all state variables V , as well as provides a mechanism of controlling the access to those variable that ensure linearizability.

We distinguish between three operation types: $read(v)$, an operation that reads the value of a state variable, v , $create(v, P)$, an operation that create a state variable at a specific partition P , and $move(v, p_n)$, an operation that move v to partition p_n ,

Consider the execution depicted in Figure 1 (a), where state variables x is created on partition p_1 in the middle of the execution of SSMR. Command $C_1(x)$

and $C_3(x)$ reads the value of x , $C_2(x, p_1)$ create x on partition p_1 . Client a first multicasts query to the *Oracle* for location of x , which is not available at that time, hence *Oracle* return empty result, which tell client a to end the execution. Client b then wants to create variable x on p_1 , before sending actual creating command, client b also multicasts query to *Oracle* to get the involved partition (eg., p_1), then multicasts $C_2(x, p_1)$ to both *Oracle* and p_1 . *Oracle* will update information of x , and p_1 will execute create x command. From then, for every read command to x (eg., $C_3(x)$), *Oracle* could answer with partition p_1 which is the one holds x .

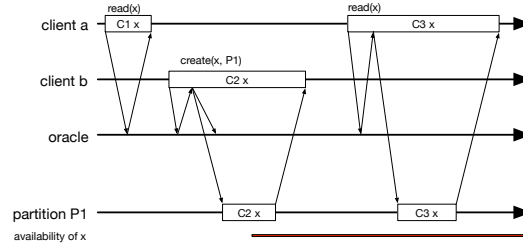


Fig. 1. Execution flow of D-SSMR with *create* command

In the following figures (2b, 2c), where read command $C_1(x)$ comes in the middle of the execution of create command $C_2(x, p_1)$, while the query of $C_1(x)$ comes after multicasts command of $C_2(x, p_1)$. With the knowledge of x , *Oracle* response to the query with a positive answer, therefore there are possibilities that the read command either comes during (eg., fig. 2b) or before (eg., fig. 2c) the execution of actual write command. The SSMR model avoid the problem described in figure 2 (b) by ensuring that the execution of every command is atomic (eg., for every server s in partition P that executes C , there is a server r in every $P' \in \text{part}(C)$ such that $\text{delivery}(C, r) < \text{end}(C, s)$. Intuitively, this condition guarantees that the execution of C at P and P' overlap in time.) With the problem figure 2 (c) TODO: explain

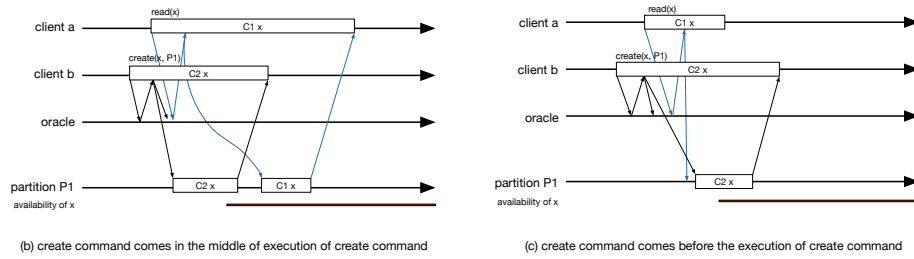


Fig. 2. Execution flow of D-SSMR with overlapping commands

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