CSE446: Blockchain & Cryptocurrencies

Lecture – 4: Distributed Systems & Consensus Algorithms

Inspiring Excellence

Agenda

- Distributed system model (Node, process, network)
- Network types
- Various fault models
- Need for consensus
- Atomic broadcast, atomic broadcast properties
- Consensus properties
- FLP Impossibility, CAP Theorem
- Various consensus algorithms

Distributed system model

- A distributed system consists of many computers (nodes)
- These nodes might be geographically located at different places, however, they are connected by a communication network
- All nodes are considered autonomous
  - They behave independently of each other
- They communicate with others using the network

Distributed system model

- Each node contains a processor, communication network, software and non-volatile storage
- Each processor within a node has volatile memory inaccessible by other nodes
- Each node has a network interface (NIC) through which it is connected to the network
- Software is mainly the OS
- The non-volatile is the storage used to store programs (other s/w) and data

Distributed system model

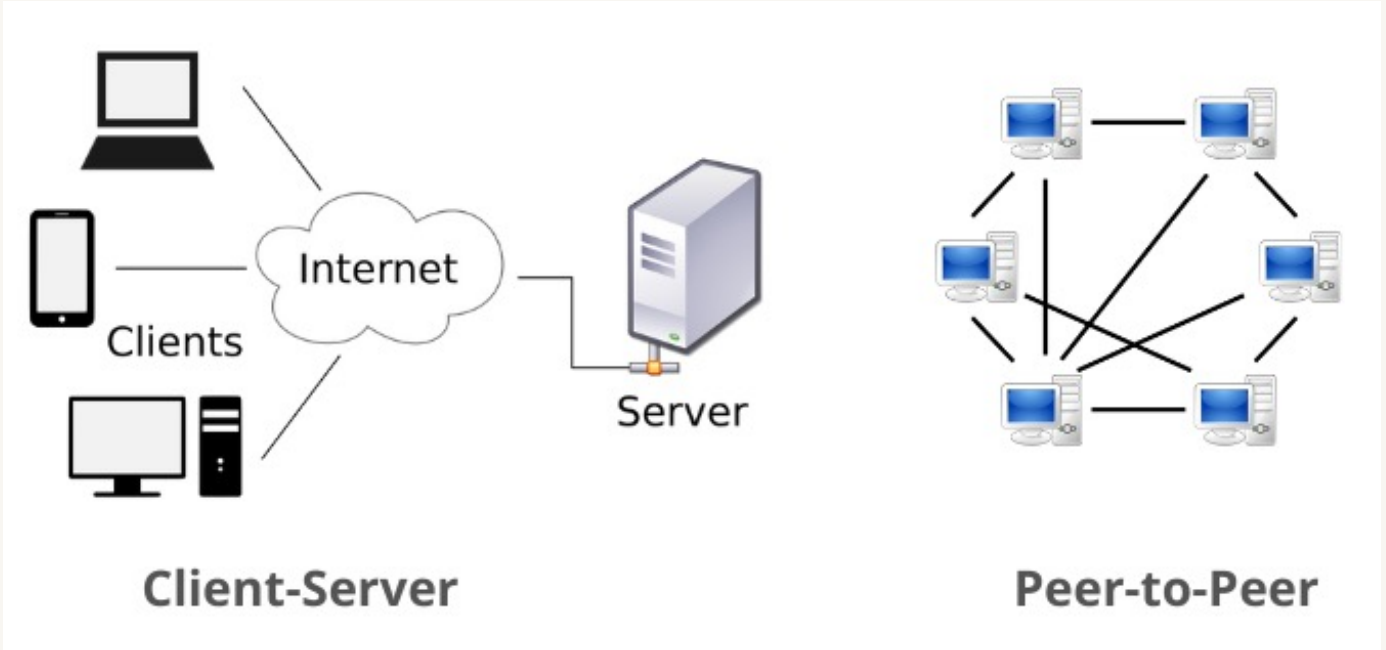
- Often a distributed system can be viewed as a logical construct, from an application viewpoint
- Such applications will be regarded as distributed applications
  - For this course, a distributed system = a distributed application
- A distributed application consists of concurrently executing processes
- A process is the execution of sequential program which is a list of of statements or instructions
- Concurrent processes can be executed in a single processor, each sharing the processor, the *multiprogramming* approach
- However, we are more interested about processes running in parallel in different nodes

Distributed system model

- There are three different types of concurrent processes: independent, competing and cooperating
- Concurrent processes are considered independent if the sets of objects accessed by them are disjoint
- Concurrent processes are considered competing if they share resources but they do not exchange information between them
- Cooperating processes exchange information between them either using shared data objects or via message passing

Distributed system model: network

- P2P and client/server Network



https://www.networkstraining.com/wp-content/uploads/2021/06/Client-Server-p2p.png

Even though, we only show nodes here, there could be processes underneath

Network type

- Dwork et al.* categorised three types of networks exhibiting different properties: synchronous, asynchronous, and partially/eventually synchronous
- The latency involved in delivering a message to all nodes in a synchronous network is bound by some time denoted as Δ
  - Any message sent at time T will be delivered by T + Δ
- On the other hand, the latency in an asynchronous network cannot be reliably bound by any Δ, message will eventually be delivered

*C. Dwork, N. Lynch, and L. Stockmeyer "Consensus in the presence of partial synchrony". Journal of the ACM (JACM), 35(2):288323, 1988.

Network type

- In a partially/eventually synchronous network, it is assumed that
  - the network will eventually act as a synchronous network
  - even though it might be asynchronous over some arbitrary period of time

Fault model

- In a distributed system, a node (process) might behave differently for various reasons (e.g. intentional or unintentional corruption)
- When this happens, we call these nodes as faulty nodes
- Up to f nodes out of N (total number) may fail
  - f is usually a function of N, like $f < N/2$ or $f < N/3$
- We mostly look at two types of faults:
  - Crash failure
  - Byzantine failure
- Nodes that do not fail are called “honest” or “correct” nodes

Fault model: crash failure

- The crash failure model deals with nodes that simply fail to respond due to some hardware or software failure
  - E.g. Hardware crash, hard disk bad sector, software crash, etc.
- It may happen any time without any prior warning
- The corresponding faulty node remains unresponsive until further actions are taken

Fault model: BGP

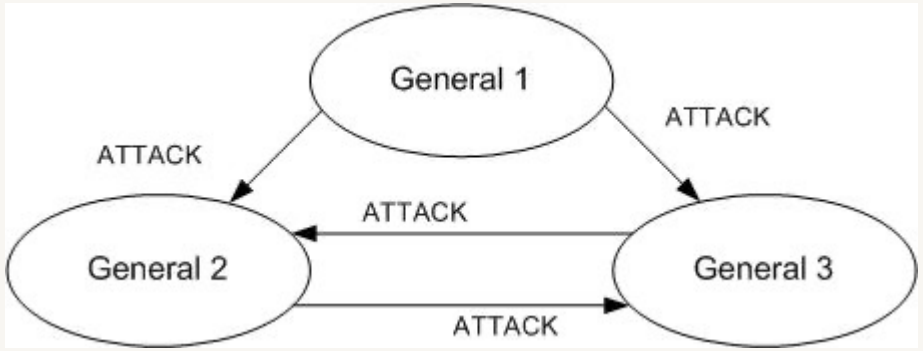
- The Byzantine Generals Problem, by Leslie Lamport, Robert Shostak, and Marshall Pease. ACM TOPLAS 1982
- Byzantine army divisions camped outside the walls of an enemy city
- Each division is led by a general
- Generals decide on a common plan of action

Fault model: byzantine fault

- There are two types of generals: Loyal or Traitor
- Conditions needed to be met:
  - Loyal generals decide upon the same plan of action
  - Small number of traitors should not be able to lead the loyal generals make a bad decision

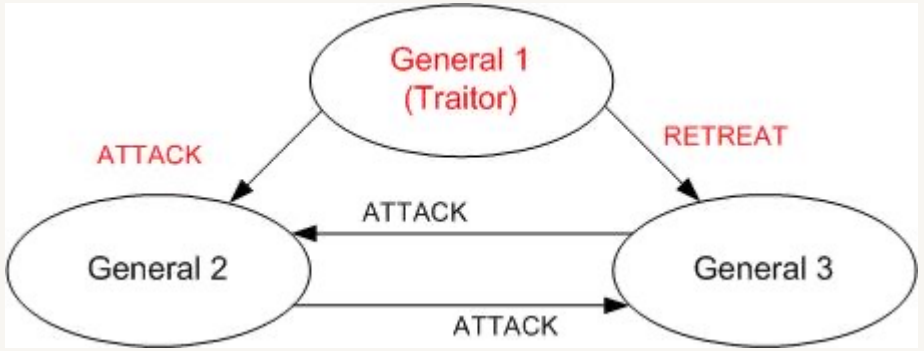
Fault model: byzantine fault

- General 2 receives ATTACK, ATTACK
- General 3 receives ATTACK, ATTACK
- So ATTACK is Not a Bad Decision



Fault model: byzantine fault

- General 2 receives ATTACK, ATTACK
- General 3 receives RETREAT, ATTACK
- Now, ATTACK or RETREAT?



Fault model: byzantine fault

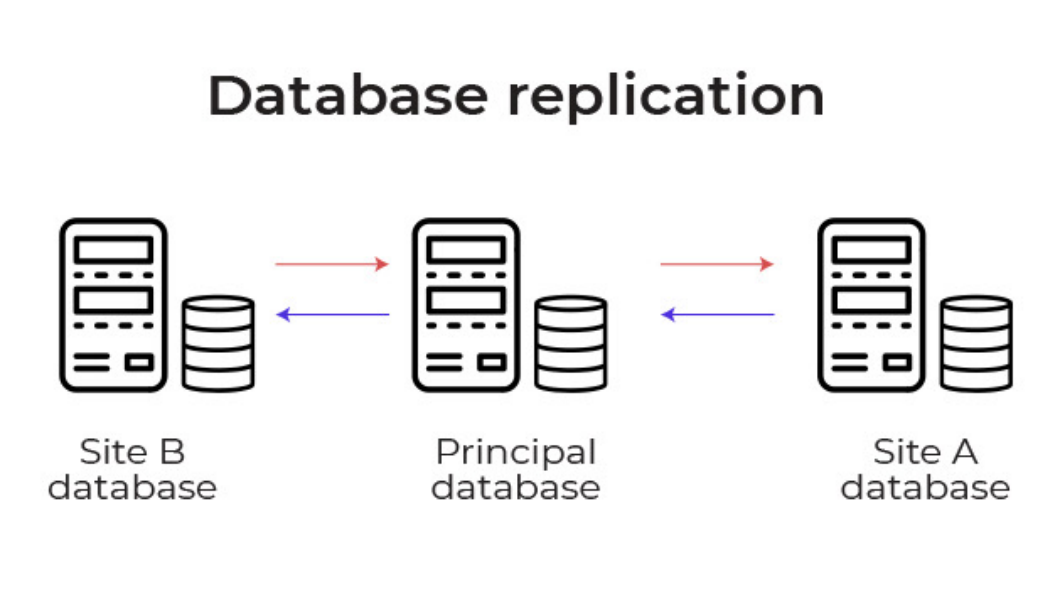
- Coping with failures in nodes not related to crash
- A (faulty) byzantine node sends conflicting information to different parts of system (the byzantine behavior)
  - Non-malicious: Software bugs
  - Malicious reasons: Machine compromised
- P2P Networks:
  - Faulty nodes generate corrupted and misleading messages
  - Good nodes have to “agree to do the same thing” (agreement)
- Agreement in the presence of faults is challenging

Fault model: byzantine failure

- Byzantine failure deals with nodes that misbehave due to some software bugs or because of the nodes being compromised by an adversary
- A Byzantine node can behave maliciously by arbitrarily sending deceptive messages to others
  - This might affect the security of distributed systems
- Hence, such nodes are mostly relevant in application with security implications

The need for consensus algorithm

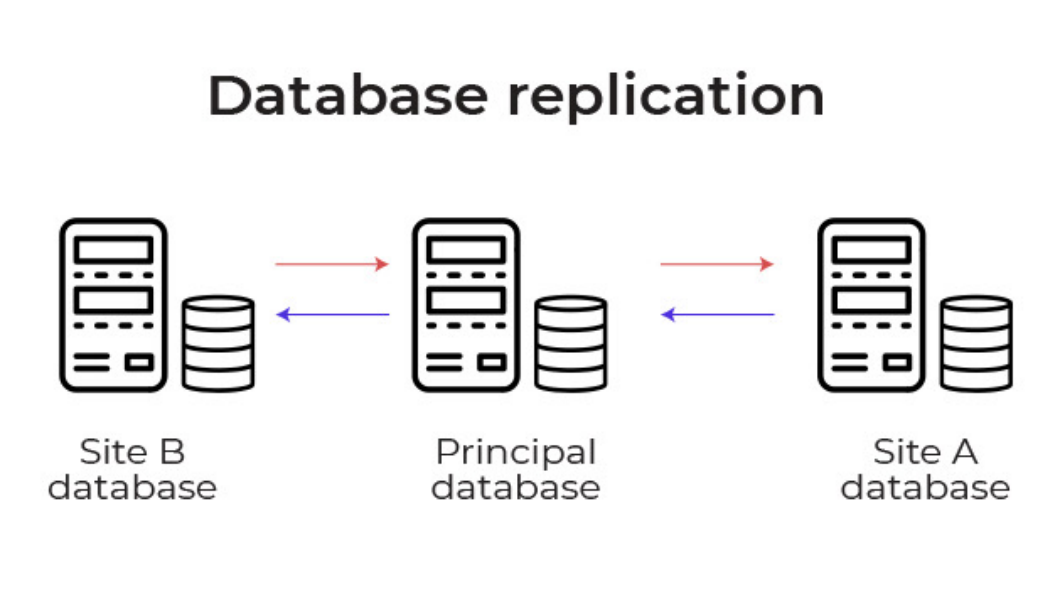
- Consensus is a fundamental problem in distributed applications
  - One use-case is database replication (aka Replicated Database)
- Database replication is the process of storing data in more than one site or node
- It is useful in ensuring resilience against node failures within a network
  - E.g. data are not lost when one or more nodes fail to function in an excepted fashion
  - This improves the availability of data



https://databand.ai/blog/data-replication-the-basics-risks-and-best-practices/

The need for consensus algorithm

- It is simply copying data from one server to another server
  - So that all the users can share the same data without any inconsistency
- To ensure synchronisation across multiple nodes
  - The mechanism of consensus is used
- Consensus enables all nodes agree to a certain shared state/data among a set of distributed nodes



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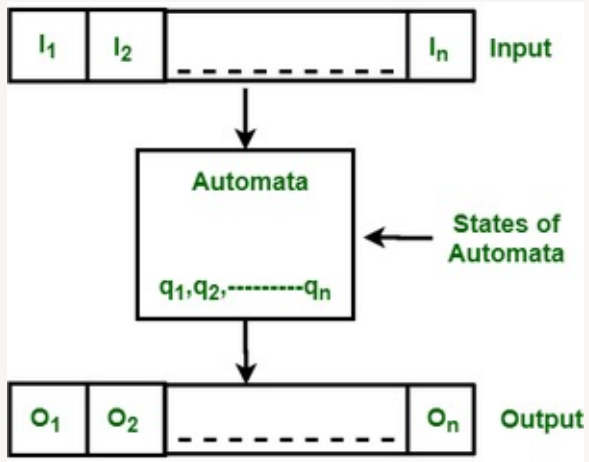
State machine

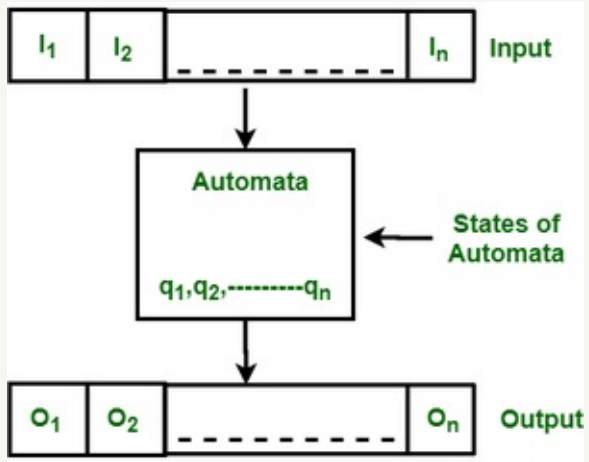
- The finite automata or finite state machine is an abstract machine
  - Simply, it is an abstract model of a digital computer
- It has a set of states
- It contains rules for moving from one state to another but it depends upon the applied input symbol
- It can be deterministic or non-deterministic



https://www.geeksforgeeks.org/introduction-of-finite-automata/

State machine

- A deterministic finite automata is a 5-tuple, (Q, Σ, δ, q_0, F), consisting of
  - a finite set of states Q
  - a finite set of input symbols called the alphabet Σ
  - a transition function $\delta : Q \times \Sigma \rightarrow Q$
  - an initial or start state $q_0 \in Q$
  - a set of accept states $F \subseteq Q$



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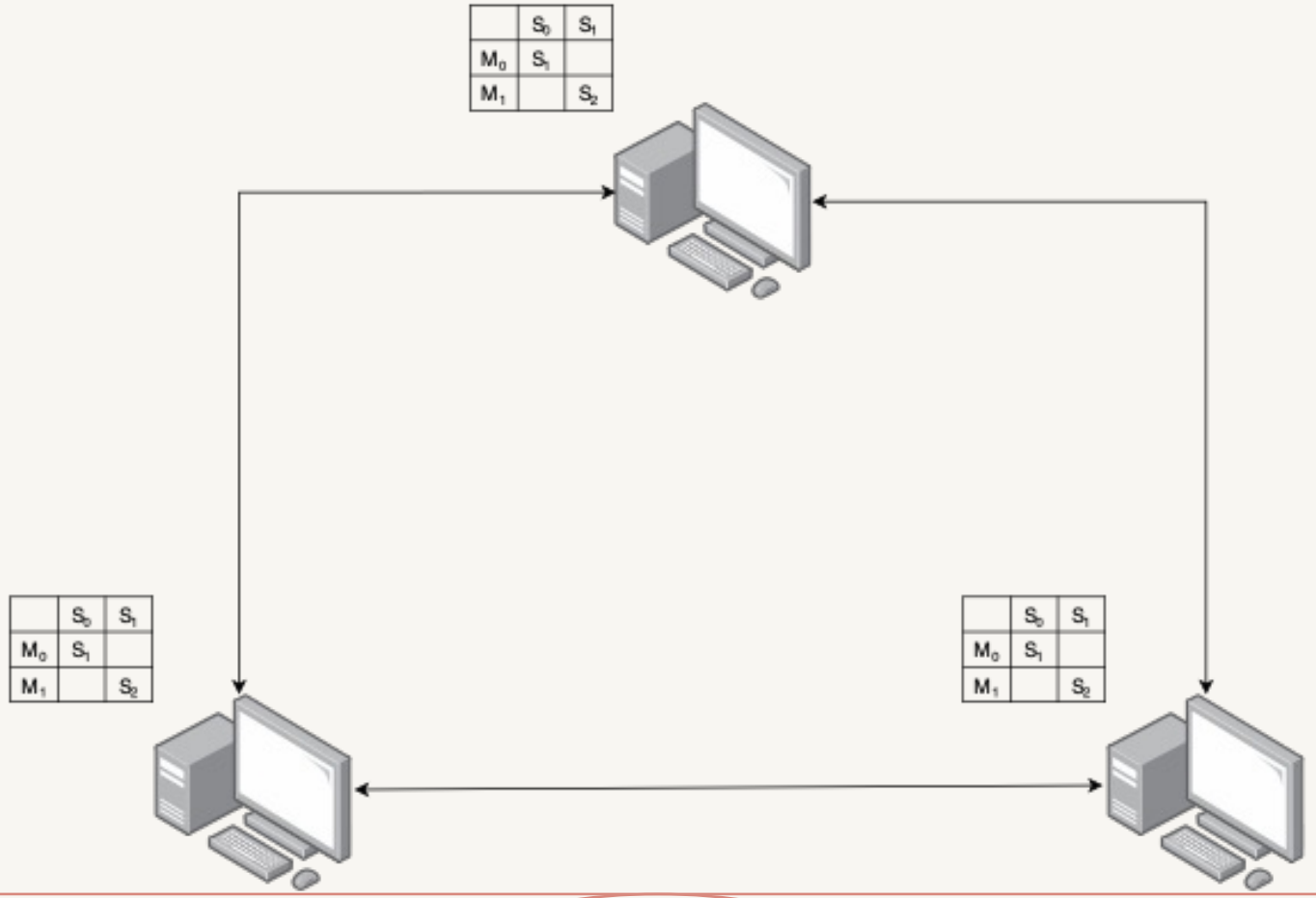
Atomic broadcast

- In fault-tolerant distributed computing, an atomic broadcast or total order broadcast is a broadcast where
  - all nodes receive the same set of input messages in the same order (i.e. the same sequence of messages)

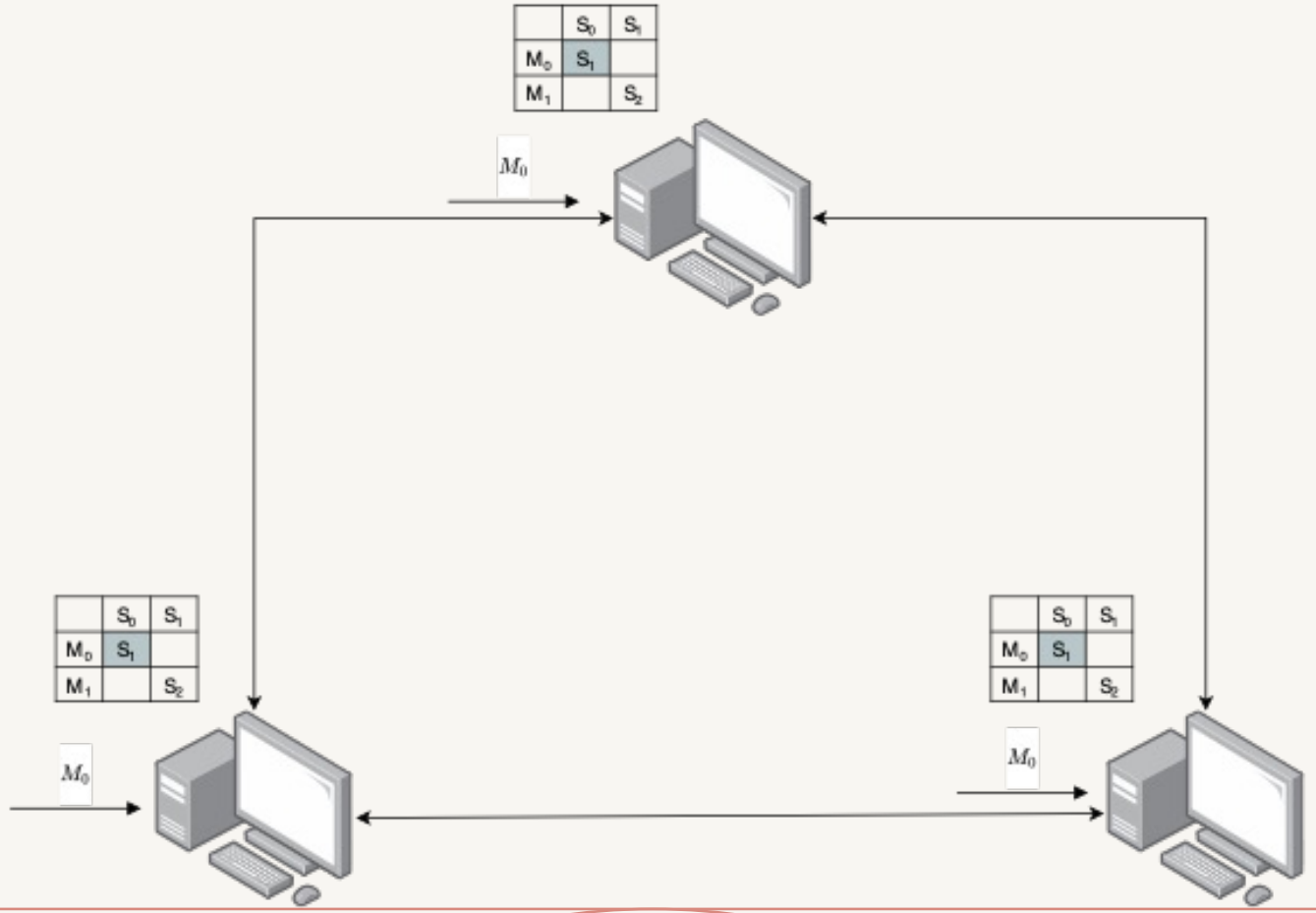
State machine replication

- The notion of the replicated database can be generalised with the concept of State Machine Replication (SMR)
- The core idea behind SMR is that a computing machine can be expressed as a deterministic state machine
- The machine accepts an input message, performs its predefined computation, and might produce an output/response
  - These actions essentially change its state
- SMR conceptualises that such a state machine, with an initial state, can be replicated among different nodes

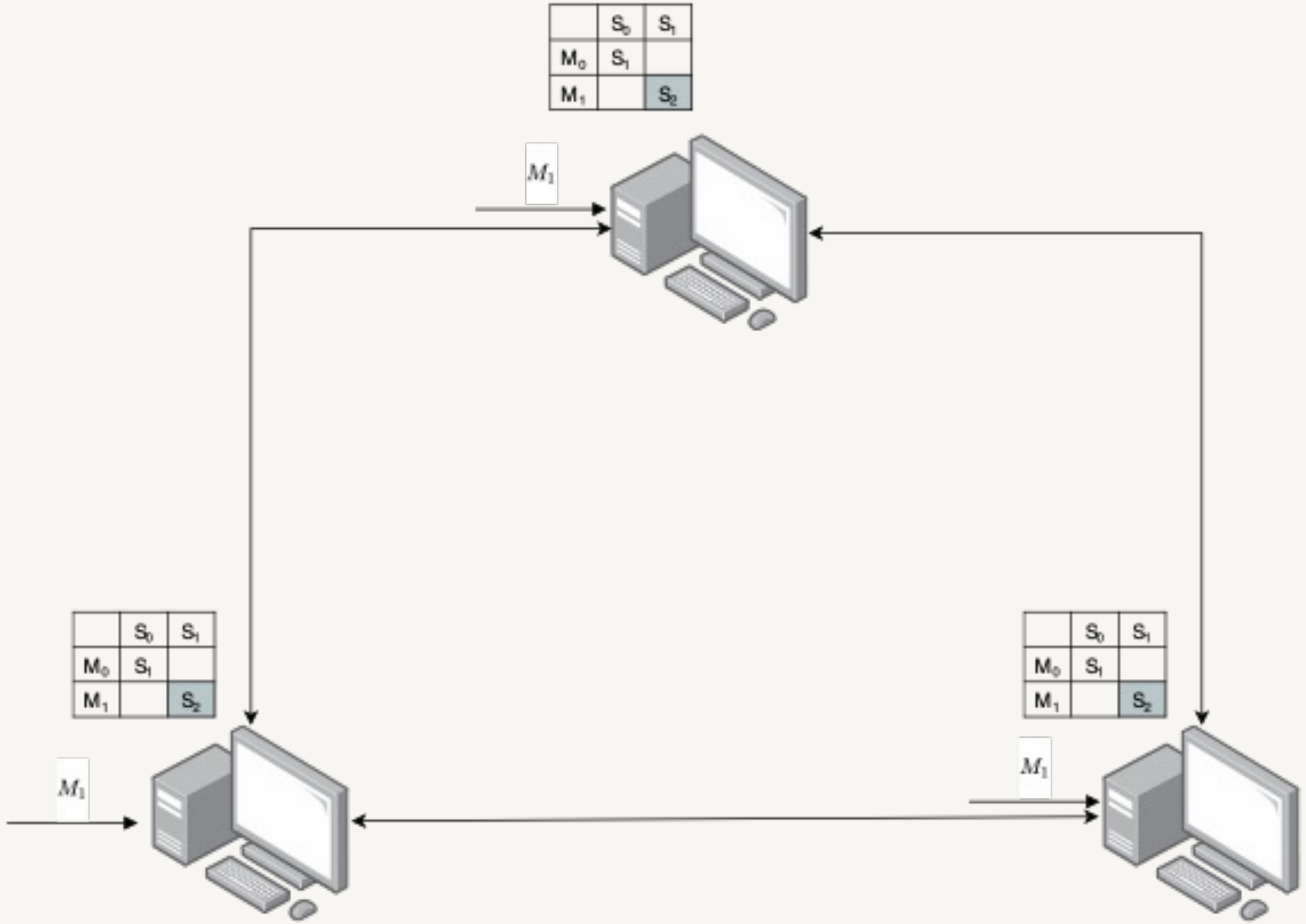
State machine replication



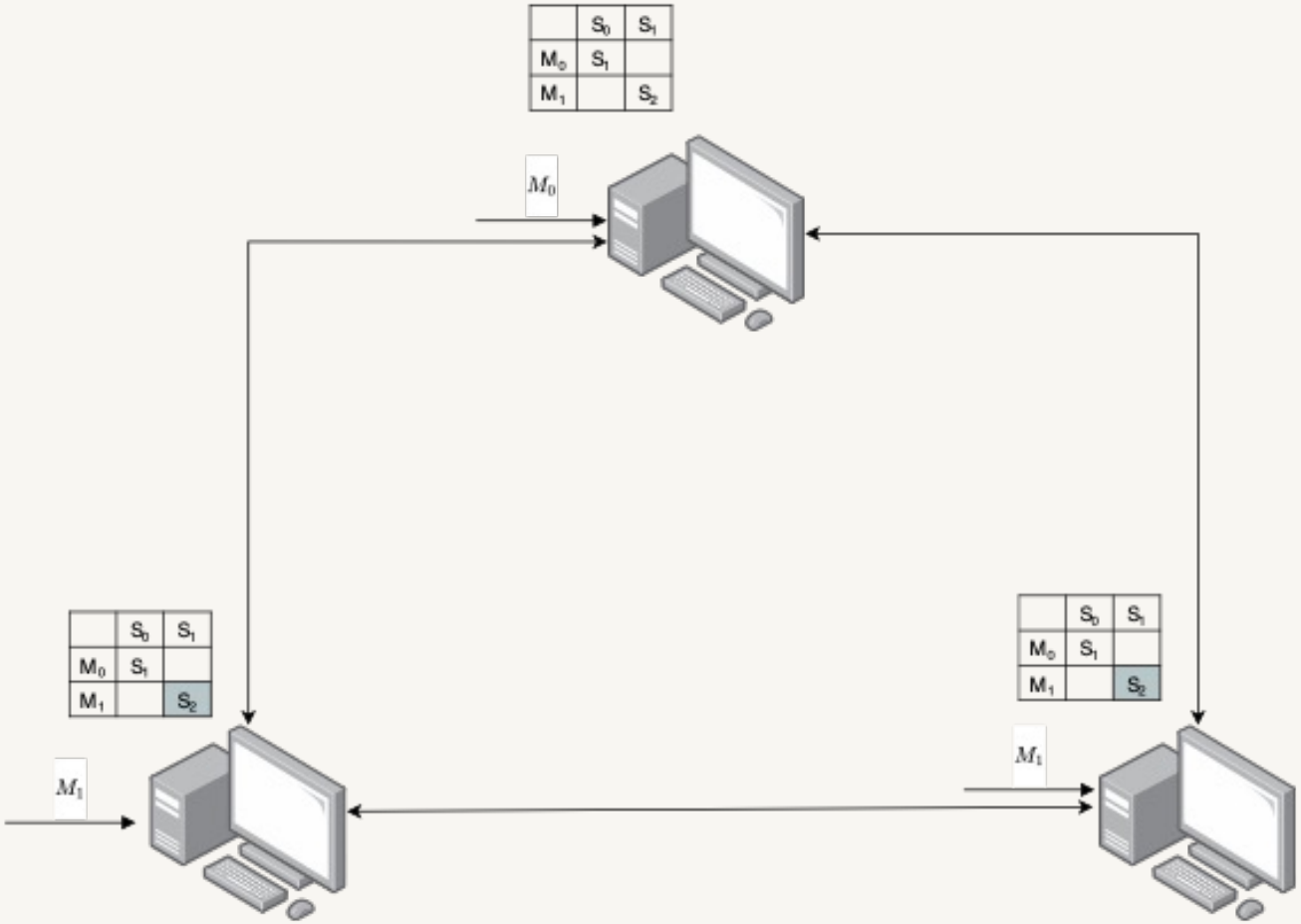
State machine replication



State machine replication



State machine replication



State machine replication

- If we can ensure an atomic broadcast of messages then each node would be able to evolve the states of its state machine individually in exactly the same fashion
  - All nodes behave similarly even though they are different
- This can guarantee consistency and availability regarding the state of the machine (as well as data it holds)
  - For example, if a node fails, other nodes can be used to recover its states or the data
- Once this occurs, it can be said that a distributed consensus has emerged among the participating nodes

State machine replication

- To make this happen, a protocol is required
- The protocol needs to ensure the timely dissemination and atomic broadcast of input messages among the nodes
- Such a protocol is called a consensus protocol


THANK YOU
QUESTIONS?