Replication for Fault Tolerance

Byzantine Quorums

Pedro F. Souto (pfs@fe.up.pt)

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Roadmap

Byzantine Failures

- A Byzantine process may deviate arbitrarily from its specifications
  - A Byzantine process may send contradictory messages
  - But other processes may not know which processes are Byzantine

Byzantine Generals Problem (BGP) this is reliable broadcast

Agreement All non-faulty processes deliver the same message

Validity If the broadcaster is non-faulty, then all non-faulty processes deliver the message sent by the broadcaster

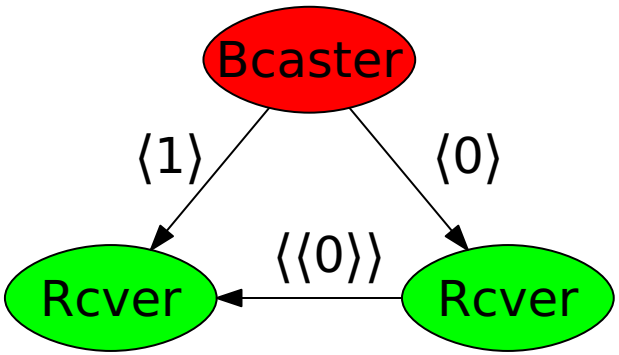
Reliable broadcast can be used as a building block of a solution to the distributed consensus problem.

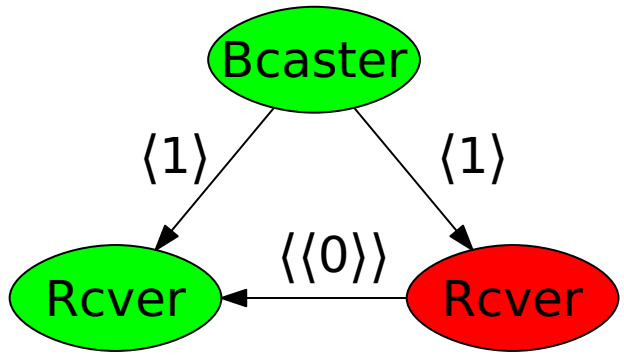
Impossibility There is no solution to the BGP in a system with 3 processes, if one of them may be Byzantine, if messages are not signed

- The general result is that faulty processes must be fewer than a third of all processes

Byzantine Failures and Cryptographic Signatures

Communication without signed messages





- The LHS receiver gets the same messages in both scenarios
  - It should deliver the same message in both scenarios
  - But no message satisfies the desired properties in both cases

Byzantine Failures and Cryptographic Signatures

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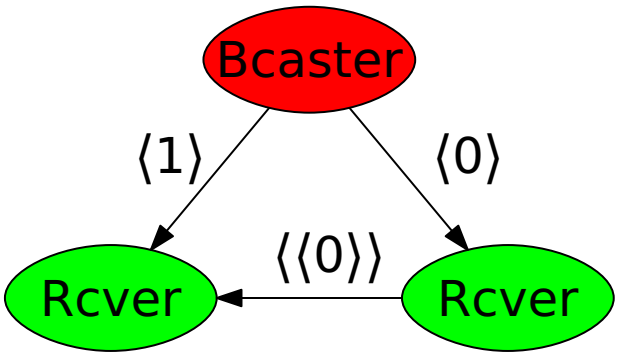

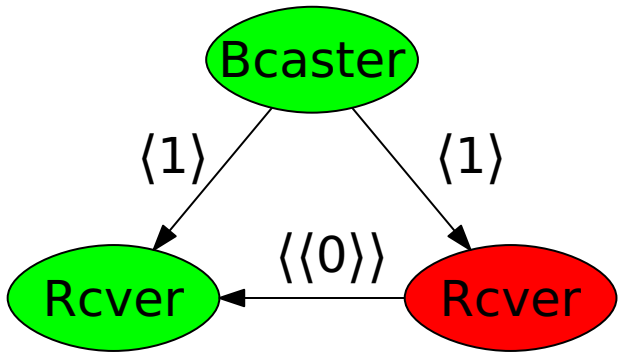

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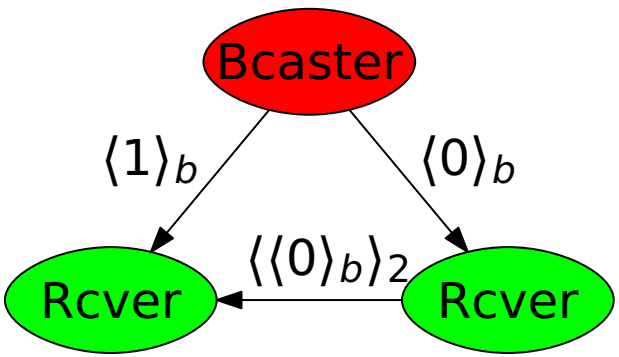
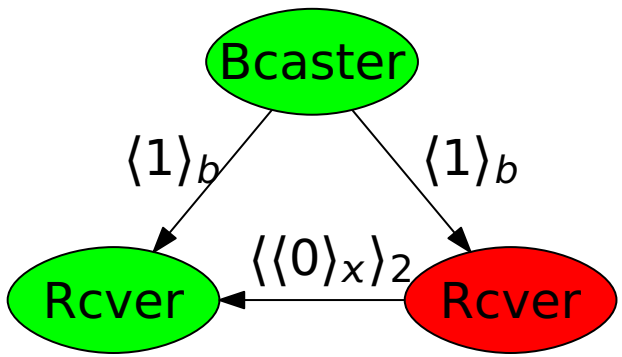
Communication with signed messages





- Byzantine receiver cannot properly sign a modified message
  - Of course, the protocol must prevent replay attacks

Roadmap

Quorum Consensus

- Each (replicated) operation (e.g. read/write) requires a **quorum**
  - This is a set of replicas
- The fundamental property of these quorums is that
  - If the result of one operation depends on the result of another, then their quorums must overlap, i.e. have common replicas
- A simple way to define quorums is to consider all replicas as peers.
  - In this case quorums are determined by their size, i.e. the number of replicas in the quorum
  - This is equivalent to assign 1 vote to each replica
- More generally:

  Set of servers, U
  A quorum system $\mathcal{Q} \subseteq 2^U$ is a non-empty set of subsets of U, every pair of which intersect
  - Each set $Q \in \mathcal{Q}$ is a **quorum**

Byzantine Quorums: Model

Processes some servers in U may exhibit **byzantine** failures, i.e. they may deviate from their specification arbitrarily

- E.g., may report random version numbers

Let $\mathcal{B} \subseteq 2^U$ a non-empty set of subsets of U such that:

- None of which is contained in another
- Some $B \in \mathcal{B}$ contains all faulty servers

Note This is a more general way of characterizing failure scenarios

- Rather than bounding the number of faulty servers (as usual)
- E.g. can be used to model correlated failures

Clients are assumed not to fail

- But the paper also considers their failure

Network any two processes (clients or servers) can communicate over an authenticated and reliable point-to-point channel

- This is meaningless, if some channel end-point is faulty
- Communication is **asynchronous**
  - There are no known bounds on message delays

Problem Definition

- Clients perform read and write operations on a variable x replicated at all servers (in U)
- Each server stores a replica (copy) of x and a timestamp t
- Timestamps are assigned by clients when the client writes the replica
  - Each client, c, chooses its timestamps from a set of timestamps, T_c that does not overlap the sets of all other clients
    - E.g. by appending the client id to an integer

Safety any read that is not concurrent with writes returns the last value written in some serialization of the preceding writes

- Operations are assumed to have **begin** and **end** events that determine a partial order
- Essentially, this means **linearizability** of read/write operations

Access Protocol

Write of value v by a client c

1. c queries all servers of some quorum Q to obtain a set of timestamps $A = \{t_u : u \in Q\}$
2. c chooses a timestamp $t \in T_c$ greater than
   - the highest timestamp value in A
   - any timestamp it has chosen previously
3. c sends the update $\langle v, t \rangle$ to servers until it has received an acknowledgement from every server in some quorum Q'

   A server updates its local copy and timestamp to the received values $\langle v, t \rangle$, only if t is greater than the timestamp of its current copy
   - In both cases, it returns an acknowledgement to the client

Read of variable x by client c

1. c queries all servers of some quorum Q to obtain a set of value/timestamp pairs $A = \{(v_u, t_u) : u \in Q\}$
2. c applies a **deterministic function** $Result()$ to A to obtain the result $Result(A)$ of the read operation

Access Protocol (Gifford)

Read

1. Collect a read quorum, to find out the current version
2. Read the object state from an up-to-date replica.
   - If the size of the object is small, it can be read as the read quorum is assembled

Write

1. Collect a read quorum, to find out the current version
2. Write the new value with the new version to a write quorum
   - We are assuming that writes modify the entire object, not parts of it

Access Protocol: Missing Details

Quorums which quorums should be used to tolerate byzantine servers

***Result*()** what should *Result*() be to ensure safety

Access Protocol: Asynchrony

- Both in the read and write operations, a client has to get replies from **all** servers in a quorum
  - This is the only way to ensure that it gets the reply from all non-faulty servers, given that the network is **asynchronous**
  - Quorums are defined such that there is one quorum of **non-faulty** servers at any time
    - Note that Byzantine servers may also fail by not responding.
    - By attempting the operation at multiple quorums, a client can eventually make progress

Access Protocol: Beginning and End Events

write of value v with timestamp t

- begin when the client initiates the operation
- end when all correct servers in some quorum have processed the update $\langle v, t \rangle$

read

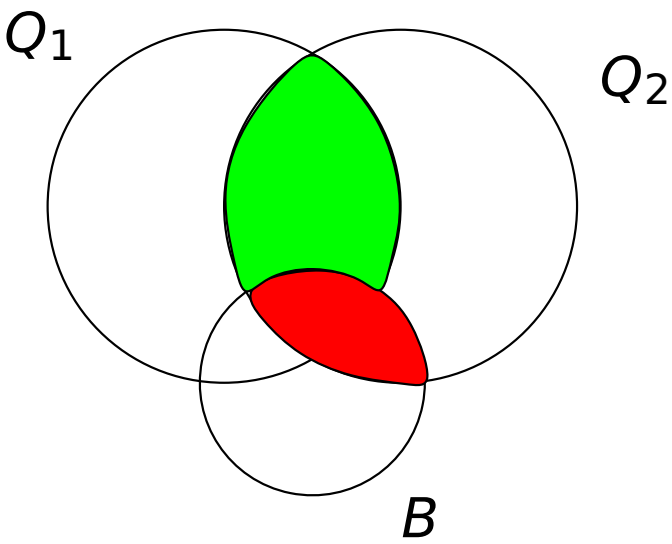
- begin when the client initiates the operation
- end when the *Result*() function returns, thus determining the read result

op_1 precedes op_2 if op_1 ends before op_2

op_1 and op_2 are concurrent if neither op_1 precedes op_2, nor op_2 precedes op_1

Roadmap

Byzantine Masking Quorums



Q_1 latest write quorum

B set of byzantine nodes

Q_2 read quorum

$(Q_1 \cap Q_2) \setminus B$ servers with up-to-date values

$Q_2 \setminus (Q_1 \cup B)$ servers with stale values

$Q_2 \cap B$ arbitrary values

Masking Quorum System, $\mathcal{Q}$ for a fail-prone system $\mathcal{B}$ if:

M-consistency

$$\forall Q_1, Q_2 \in \mathcal{Q}, \forall B_1, B_2 \in \mathcal{B} : (Q_1 \cap Q_2) \setminus B_1 \not\subseteq B_2$$

M-availability

$$\forall B \in \mathcal{B} : \exists Q \in \mathcal{Q} : B \cap Q = \emptyset$$

Size-based Byzantine Masking Quorums (1/2)

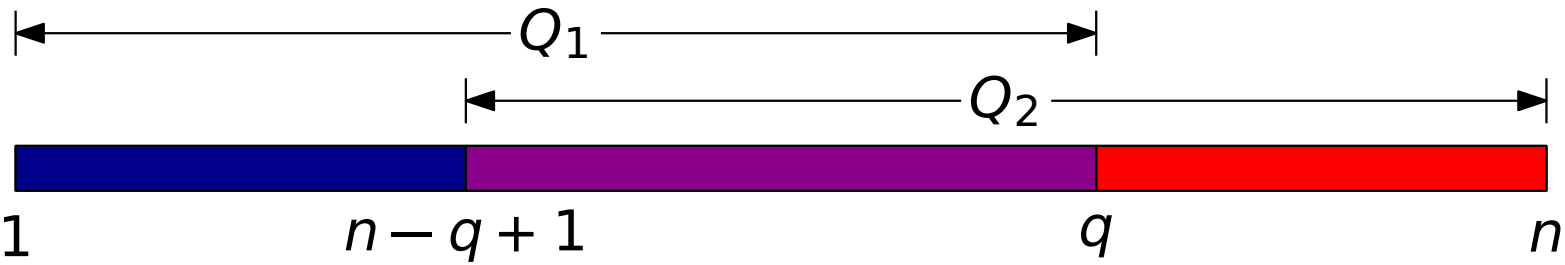
M-consistency

$$\forall Q_1, Q_2 \in \mathcal{Q}, \forall B_1, B_2 \in \mathcal{B} : (Q_1 \cap Q_2) \setminus B_1 \not\subseteq B_2$$

- This ensures that a client always obtains an up-to-date-value
- But, how does it know **which is the up-to-date value**?

Assuming all servers are peers

- Let f be the bound on faulty servers
- Then we need at least $f + 1$ up-to-date non-faulty servers
  - To outnumber the faulty servers, even if they collude
- Thus every pair of quorums must intersect in at least $2f + 1$ servers



n: number of servers
q: quorum size
f: upper bound on byzantine servers

$$q-(n-q+1)+1 \geq 2f+1$$
$$2q-n \geq 2f+1$$

Size-based Byzantine Masking Quorums (2/2)

M-availability

$\forall B \in \mathcal{B} : \exists Q \in \mathcal{Q} : B \cap Q = \emptyset$

- This is required for liveness

Assuming all servers are peers

- Let f be the upper-bound on byzantine servers
- Let q be the size of a quorum
- Let n be the number of servers
- Then $n - f \geq q$

Combining with the inequality derived from M-consistency:

$2q - n \geq 2f + 1$

We get:

$2(n - f) - n \geq 2f + 1$

Thus:

$n \geq 4f + 1$

Let $n = 4f + 1$

Then:

$q = 3f + 1$

Non-byzantine Read-Write Quorums Based on Size

$w \geq f + 1$ (1) this ensures that writes survive failures

$w + r > n$ (2) this ensures that reads see most recent write

$n - f \geq r$ (3) this ensures read availability

$n - f \geq w$ (4) this ensures write availability

- $2n - 2f \geq r + w$ from (3) and (4)
- $2n - 2f > n$ from (2)
- $n > 2f$
- Let:
  $n = 2f + 1$
  Then: $w = f + 1$, from (1) and (4)
  Then: $r = f + 1$, from (2) and (3)
- Apparently, increasing n only worsens performance (as it requires larger quorums)
  - But, by increasing n we can increase fault tolerance, as f can increase

Byzantine Quorums Based on Size: Read operation

Read (generic) of variable x by client c

1. c queries all servers of some quorum Q to obtain a set of value/timestamp pairs $A = \{(v_u, t_u) : u \in Q\}$
2. c applies a **deterministic function** $Result()$ to A to obtain the result $Result(A)$ of the read operation

Read for size-based quorums of variable x by client c

1. c queries servers until it gets a reply from a set Q of $3f + 1$ **different servers**. Let $A = \{(v_u, t_u) : u \in Q\}$ be the **set** of value/timestamp pairs received from at least $f + 1$ servers
2. the result of the read operation is the value returned by $Result(A)$
   Where $Result(X) = \{v : (v, t) \in X \wedge t \geq t', \forall (v', t') \in X\}$
   I.e. $Result(X)$ returns the value of the value/timestamp pair with the highest timestamp in the set X or $\perp$, if no such value
   - It is possible a read to fail because of concurrent writes

Safety

Safety any read that is not concurrent with writes returns the last value written in some serialization of the preceding writes

Order of operations

write of value v with timestamp t

begin when the client initiates the operation

end when all servers in some quorum have processed the update $\langle v, t \rangle$

read

begin when the client initiates the operation

end when the *Result*() function returns, thus determining the read result

op_1 precedes op_2 if op_1 ends before op_2

op_1 and op_2 are concurrent if neither op_1 precedes op_2, nor op_2 precedes op_1

Safety - No concurrent writes

Scenario the begin event of a write operation occurs always after the end event of the write operation that precedes it

Consider the latest write, (v, t) i.e. the one completed before the read

All correct servers of some quorum have updated their local state with (v, t) by definition of the end event of a write operation and by the writing protocol

The read client gets a reply from at least $2f + 1$ servers of that quorum by the read protocol the client gets a reply from a server quorum and any two quorums intersect in at least $2f + 1$ servers

At least $f + 1$ of these servers are correct since f is the maximum number of faulty servers

$(v, t) \in A$ because the read client receives the (v, t) of the last write from at least $f + 1$ servers

$Result(A)$ returns the value v written in the last write because the timestamp of (v, t) is higher than that of the previous writes, by the writing protocol

Safety - With concurrent writes

Scenario the begin of a write operation **may** occur always before the end event of a write operation whose begin event happened earlier

But the read operation **is not concurrent** with any write

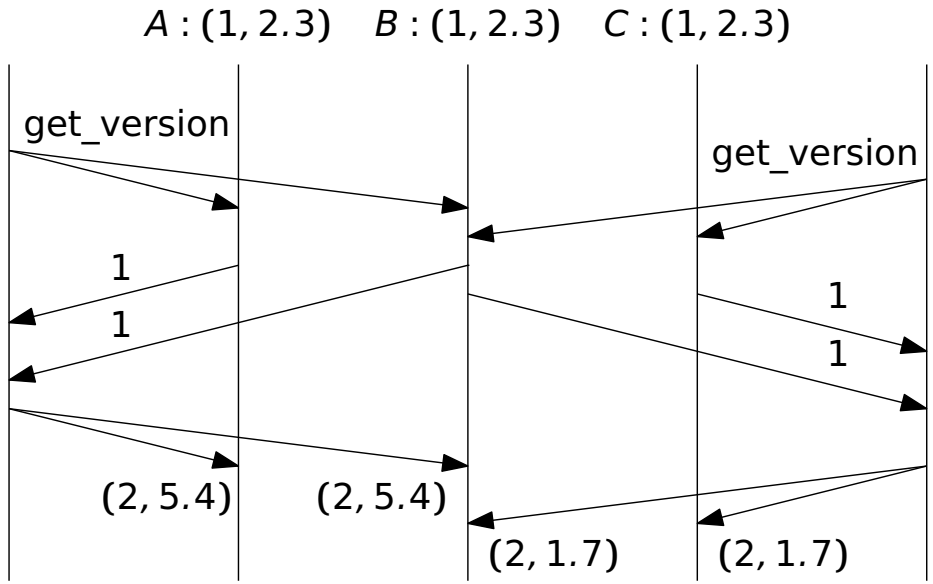
Thus, it suffices to argue that the concurrent execution of the write protocol ensures that once all write operations end, the correct servers of a quorum have applied the update (v, t_{max}) with the highest timestamp to their local copy last

- Timestamps are totally ordered and every write operation has a different timestamp, by the rule used to choose timestamps in the writing protocol
- (v, t_{max}) is received by a quorum of servers, by the write protocol
- (v, t_{max}) is always applied by the correct servers in this quorum because t_{max} is the highest timestamp of the concurrent writes and by the writing protocol
- Once (v, t_{max}) is applied, no other concurrent update is applied by the same reasons as above.

Naïve Implementation with Concurrent Writes

Naïve Implementation with Concurrent Writes

- $N = 3, N_R = 2, N_W = 2$
- Two clients attempt to write the replicas at more or less the same time
- The two write quorums are not equal, even though they overlap
- Again, replicas end up in an inconsistent state.



Why don't we have the same problem now?

Does this also prevent inconsistency in the case of failures?

Server Failures and Liveness

- By $M - Availability$, there is always a quorum, even if all f byzantine server fail
- By the write protocol:
  a client sends the update $\langle v, t \rangle$ to servers until it has received an acknowledgement from every server in some quorum Q'
  A server only updates its local copy and timestamp to the received values $\langle v, t \rangle$, only if t is greater than the timestamp of its current copy
    - In both cases, it returns an acknowledgement to the client
- I.e., the write protocol uses a **never give up** policy, which ensures delivery of sent messages, once the system becomes synchronous and communication problems fixed

Roadmap

Dissemination Quorum Systems

Application repositories of self-verifying information

- I.e. apps. in which clients can verify the validity of the information, i.e. where clients can detect the tampering of servers. E.g.

Repositories of public keys they are signed by CAs

Blockchains we will cover them in coming lectures

Dissemination Quorum System, $\mathcal{Q}$ for a fail-prone system $\mathcal{B}$ if:

D-consistency

$$\forall Q_1, Q_2 \in \mathcal{Q}, \forall B \in \mathcal{B} : (Q_1 \cap Q_2) \not\subseteq B$$

D-availability

$$\forall B \in \mathcal{B} : \exists Q \in \mathcal{Q} : B \cap Q = \emptyset$$

Safety

1. any read that is not concurrent with writes returns the last value written in some serialization of the preceding writes
2. **a read that is concurrent with one or more writes returns**
   - either the value written by the last preceding write
   - or any of the values being written in a concurrent write

Dissemination Quorum Systems: Read Operation

Read operation of variable x by client c

1. c queries servers until it gets a reply from some quorum Q. Let $A = \{(v_u, t_u) : u \in Q\}$ the set of value/timestamp pairs received
2. The client then:
   - 2.1 discards those pairs that fail the verification algorithm
   - 2.2 chooses the pair (v, t) with the highest timestamp of the remaining pairs
   - 2.3 the value v is the result of the read operation.

IMP. timestamps must be part of the verified information

- Otherwise, byzantine servers may mess with these and break the protocol

Note: although an attempt to tamper with a value is detected, a byzantine server can send a stale value/timestamp pair.

Size-based Byzantine Dissemination Quorums (1/2)

D-consistency

$\forall Q_1, Q_2 \in \mathcal{Q}, \forall B \in \mathcal{B} : (Q_1 \cap Q_2) \not\subseteq B$

- This ensures that there is at least a non-byzantine server in the intersection of every two quorums

Assuming all servers are peers

- Let f be the bound on faulty servers
- Thus every pair of quorums must intersect in at least $f + 1$ servers

n: number of servers
q: quorum size
f: upper bound on byzantine servers

$$q-(n-q+1)+1 \geq f+1$$
$$2q-n \geq f+1$$

Size-Based Byzantine Dissemination Quorums (2/2)

D-availability

$\forall B \in \mathcal{B} : \exists Q \in \mathcal{Q} : B \cap Q = \emptyset$

- This is required for liveness

Assuming all servers are peers

- Let f be the upper-bound on byzantine servers
- Let q be the size of a quorum
- Let n be the number of servers
- Then $n - f \geq q$

Combining with the inequality derived from D-consistency:

$2q - n \geq f + 1$

We get:

$2(n - f) - n \geq f + 1$

Thus:

$n \geq 3f + 1$

Let $n = 3f + 1$

Then:

$q = 2f + 1$

Roadmap

Critical Evaluation

- Compared with state machine replication, Byzantine Quorums appear to require fewer messages, by a large margin
- But the protocols we have seen assume that:
  - Either clients can be trusted
  - Or the information stored is self-verifiable
- To handle other cases, in Phalanx (the SRDS 1998 paper) Malkhi and Reiter use **consensus-objects**, which appear to require about the same number of messages as Byzantine SMR
- Furthermore, these protocols support only read/write operations.
  - Although, we can build more complex operations on top of read/write operations, the number of messages will increase
  - Also, although read/write operations are atomic, and performed in the same order, consistency problems may arise when we build more complex operations on top of read/write
    - In Phalanx (the SRDS 1998 paper) Malkhi and Reiter use **mutual exclusion** objects

Roadmap

Further Reading

- Dahlia Malkhi and Michael Reiter, *Byzantine quorum systems*, Distributed Computing 11, 4 (October 1998), 203–213. DOI:https://doi.org/10.1007/s004460050050
- D. Malkhi and M. K. Reiter, *Secure and scalable replication in Phalanx*, Proceedings Seventeenth IEEE Symposium on Reliable Distributed Systems, 1998, pp. 51-58, doi: 10.1109/RELDIS.1998.740474.