Federated Byzantine Quorum Systems

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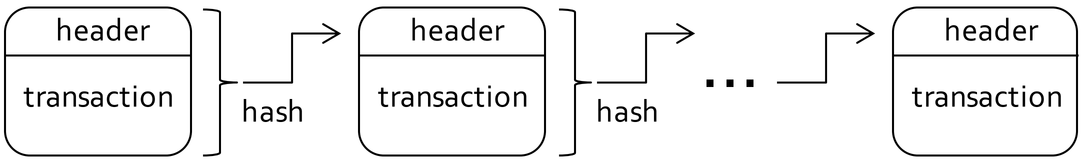
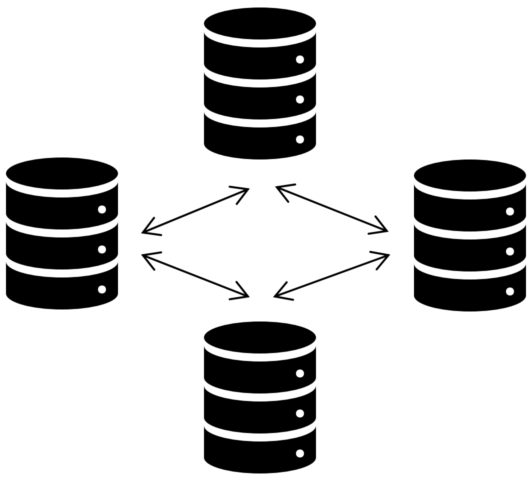
Blockchains

- Append-only, distributed ledger.
- Uses a Byzantine fault-tolerant (BFT) consensus algorithm to ensure that distributed nodes agree on the next block to append.





Permissioned and permissionless blockchains

- Permissioned blockchains assume a fixed set of participants:
  - classic consensus algorithms, decisions rely on a quorum, I.e., $3f$+1.
- Permissionless blockchains have open membership:
  - often rely on proof-of-work, high energy consumption.

Flexible trust

- Combines quorum systems with decentralisation:
  - The set of participants is fixed, the choice of trust is not.

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- Classic quorum systems:
  - Dissemination quorum systems (DQS) [Malkhi and Reiter, 1998].
  - Allow to choose a tailor-made quorum system.
- Stellar's federated systems [Mazières, 2016]:
  - Federated Byzantine quorum systems (FBQS) [Mazières, 2016].
  - Each participant decides who to trust, and participants may not know the whole system.

Broadcast and quorum systems

classic quorum systems

Stellar's federated systems

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Dissemination quorum systems
[Malkhi and Reiter, 1998]

Bracha broadcast
[Bracha, 1987]

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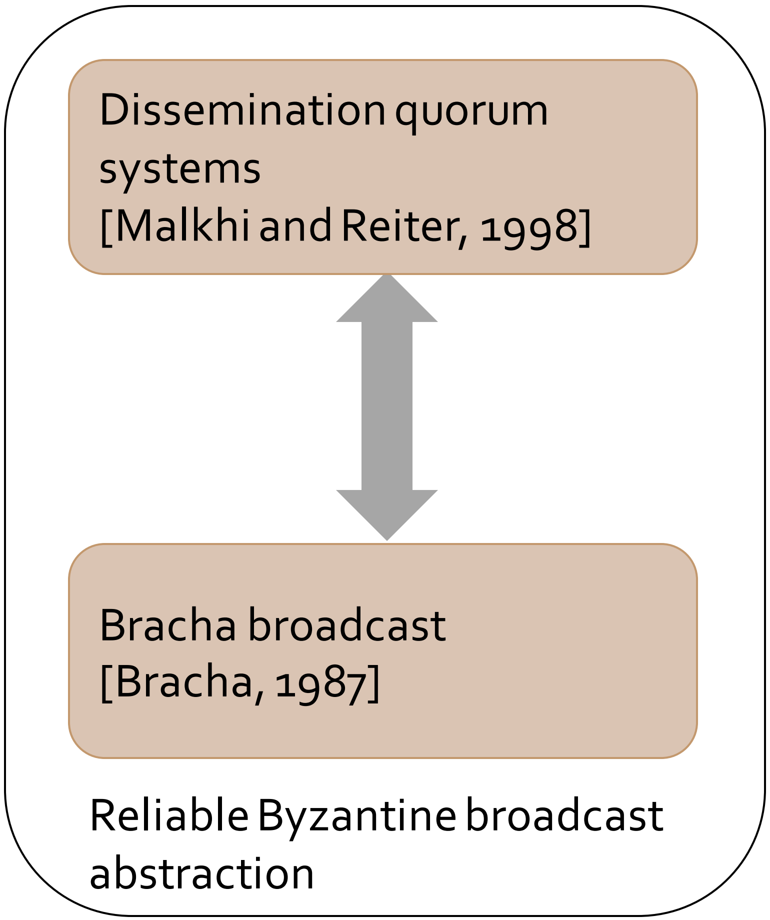

Stellar's federated systems

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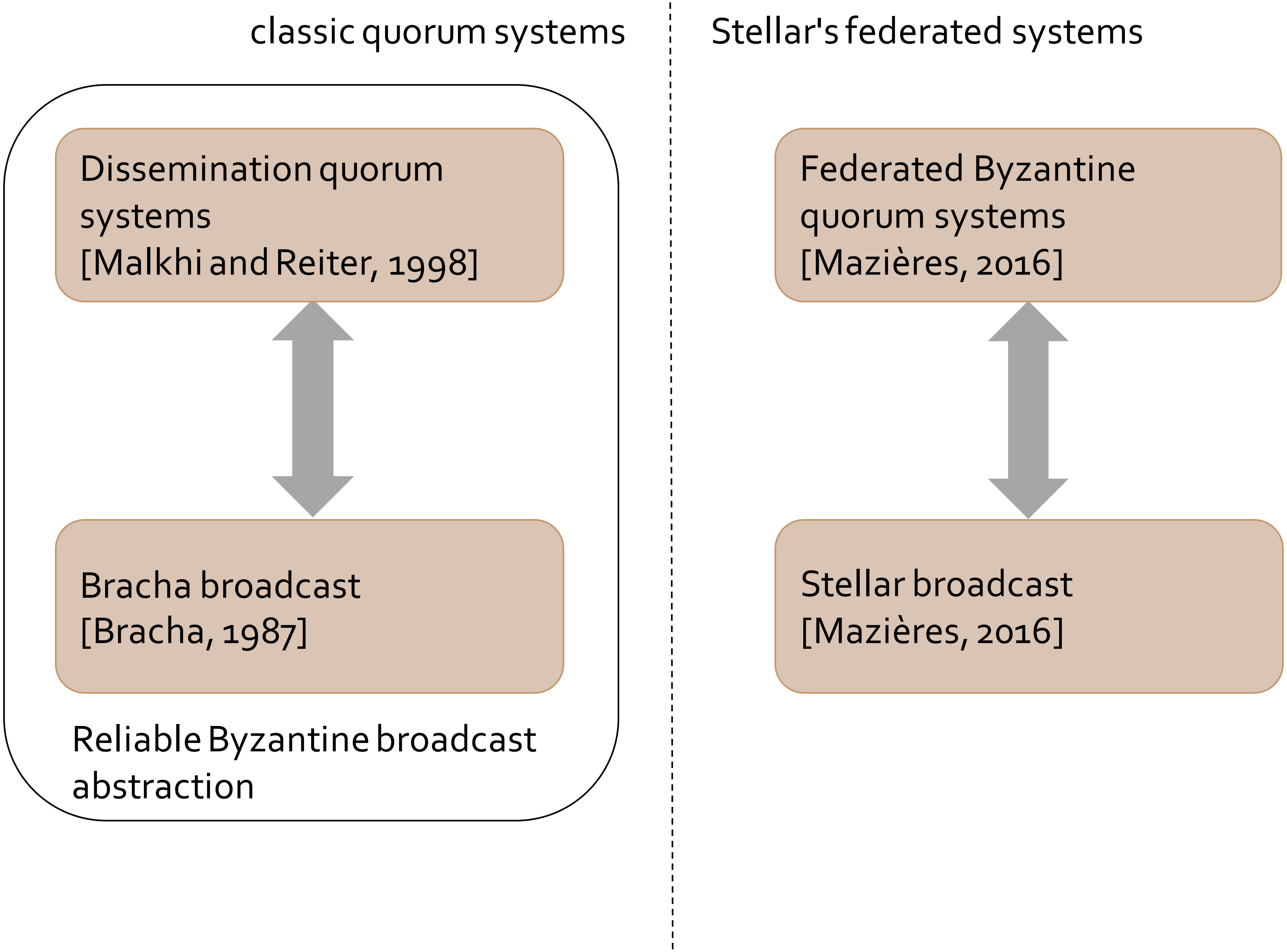
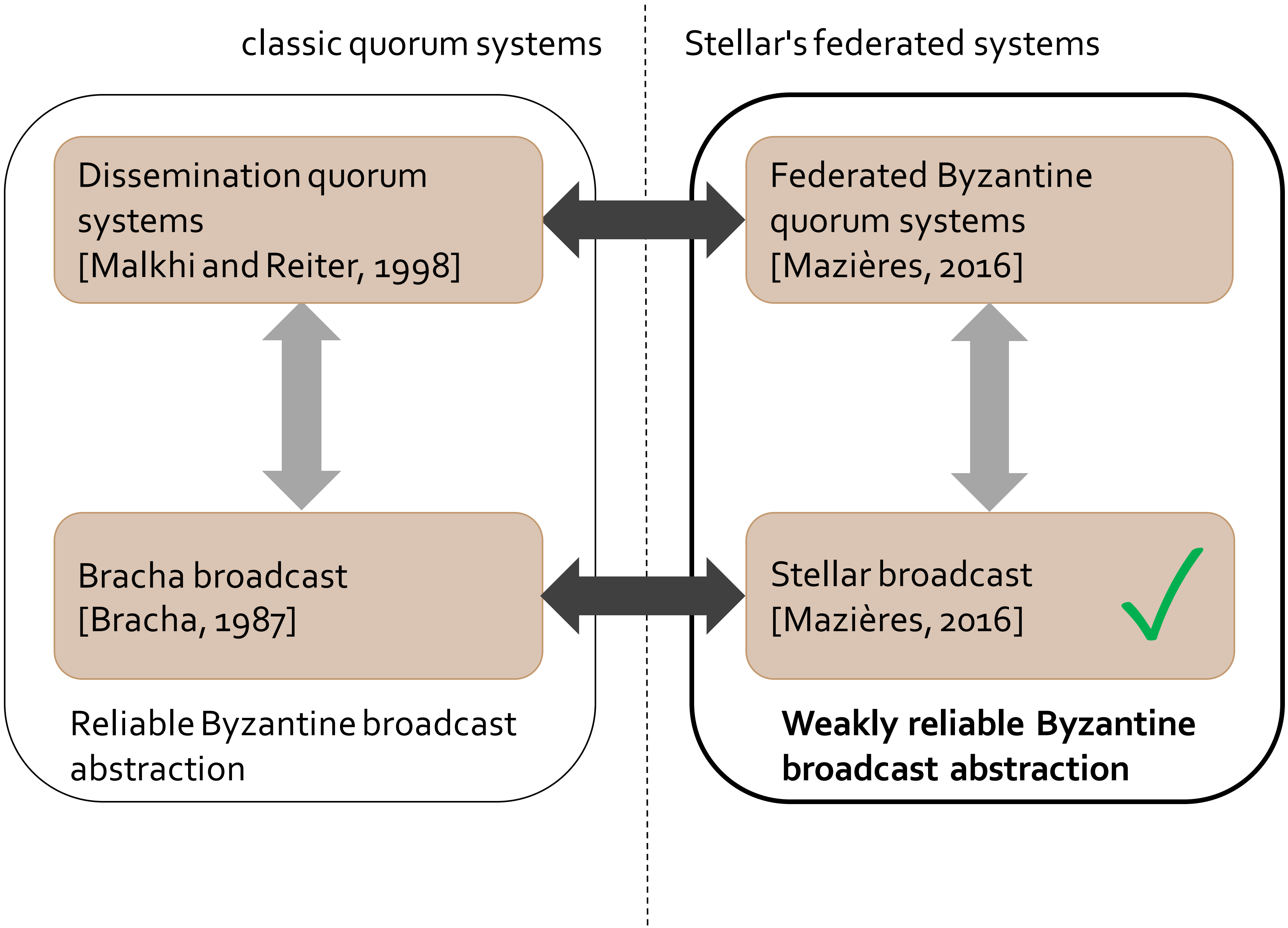


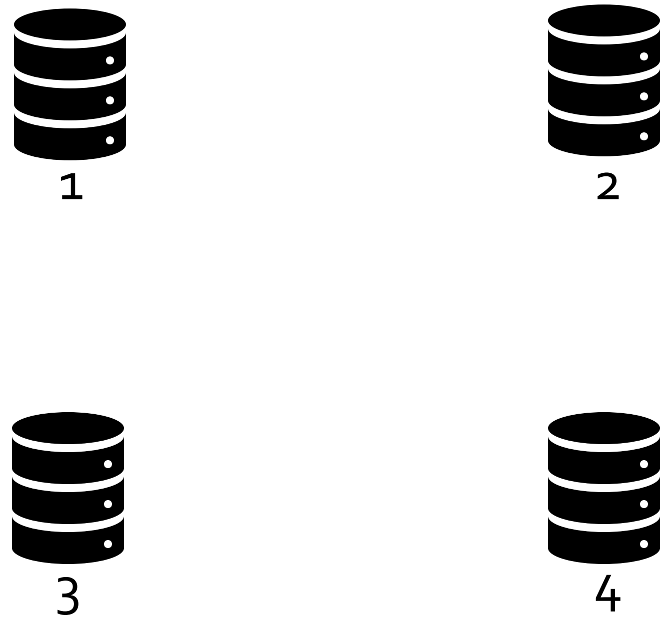
Our contribution



Dissemination Quroum System (DQS)

DQS

$\mathbb{V} = \{1,2,3,4\}$



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- **(Consistency)** The intersection of any two quorums U and U' in $\mathbb{Q}$ cannot lie within any element B of $\mathbb{B}$.
- **(Availability)** For any element B of $\mathbb{B}$ there exists some quorum U in $\mathbb{Q}$ that has empty intersection with B.

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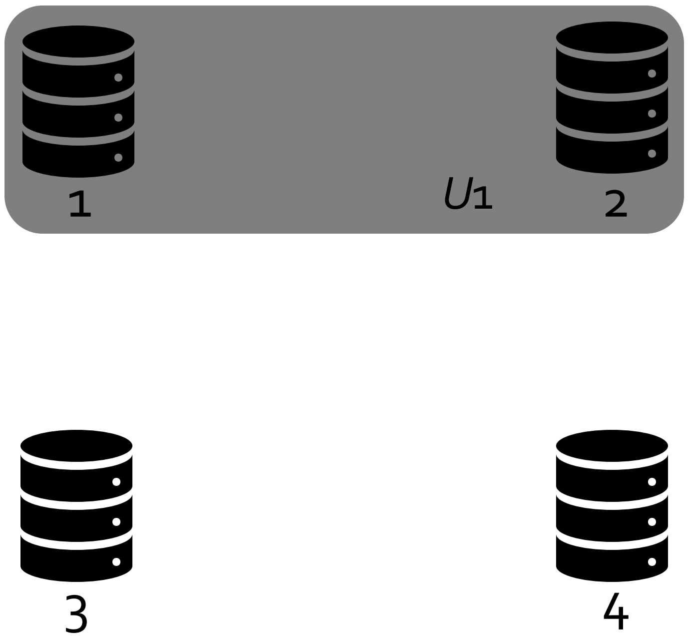

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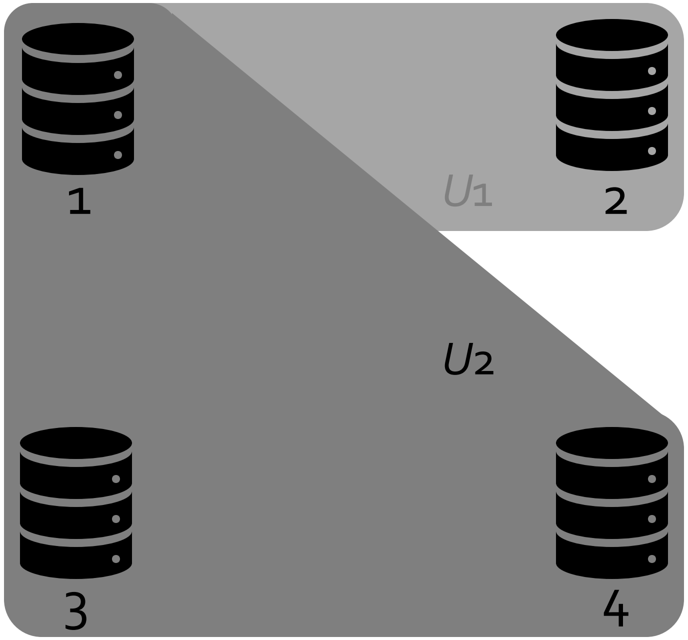

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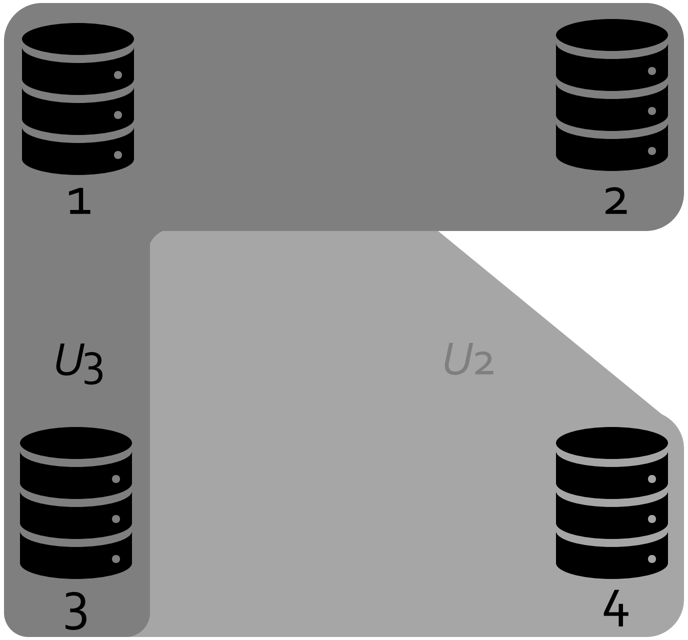

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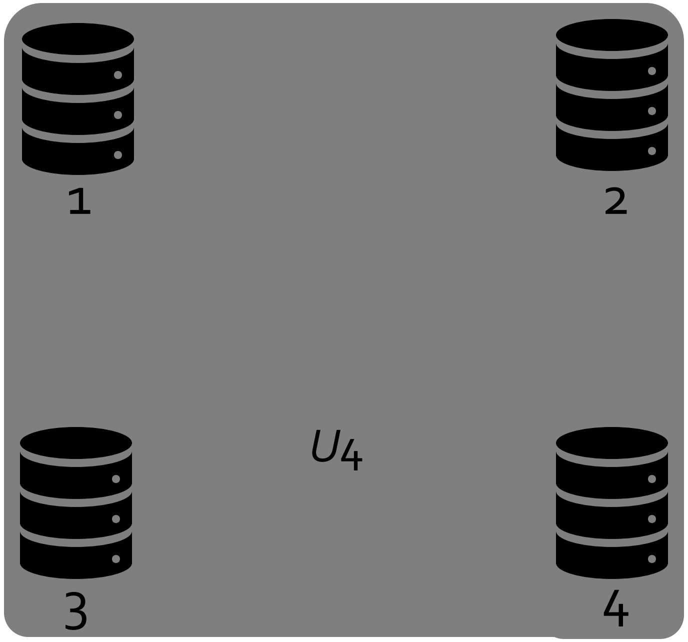

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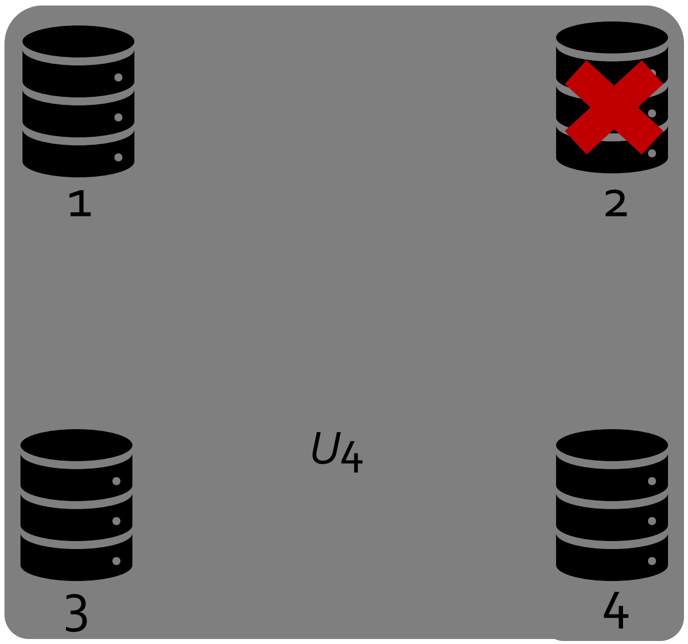

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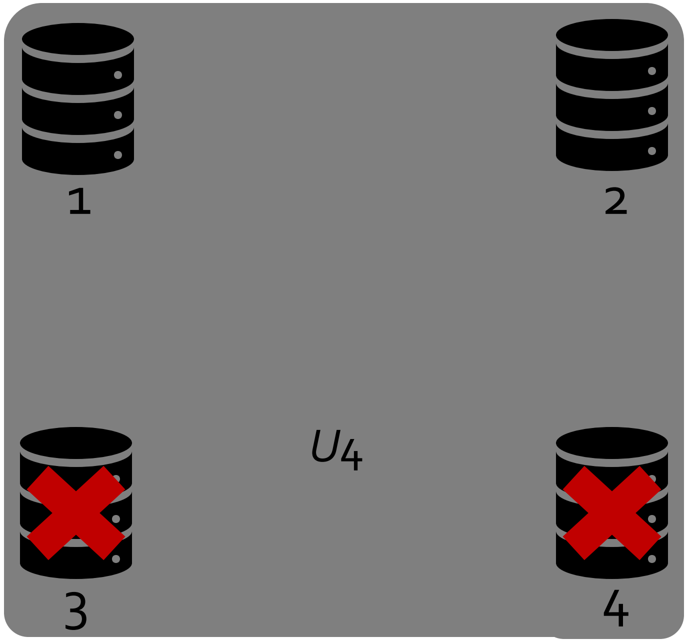

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Quorums equal or bigger than $2f+1 = 3$

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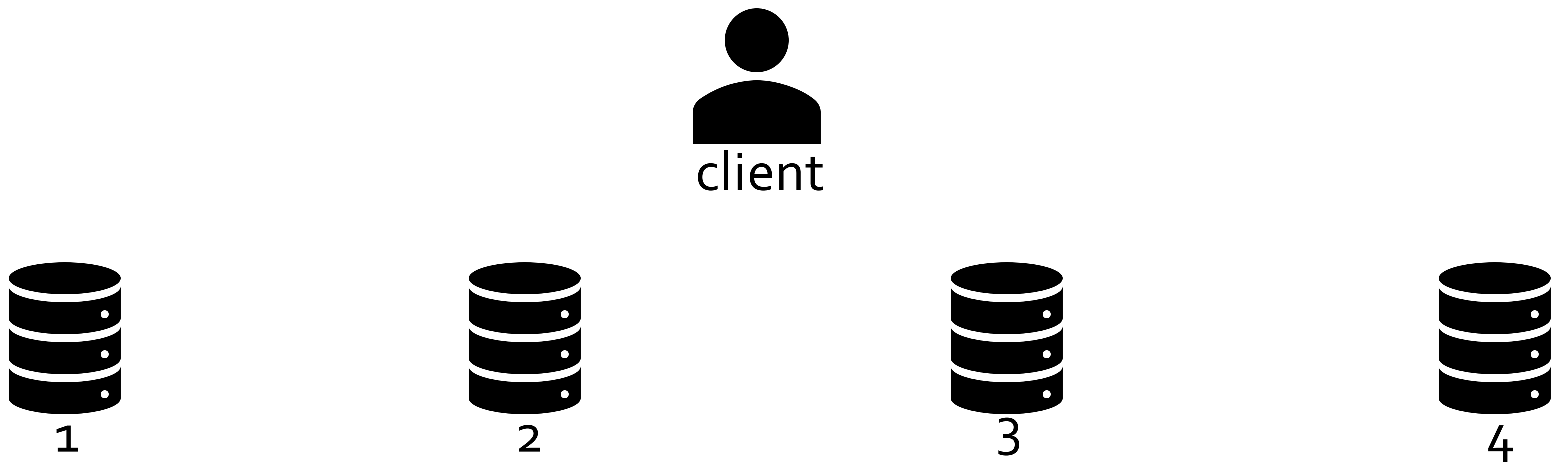
- **(Consistency)** Every two quorums intersect in at least f+1 servers.
- **(Availability)** If f servers fail, the remaining ones constitutes a quorum.

Bracha Broadcast

Example: $3f+1$



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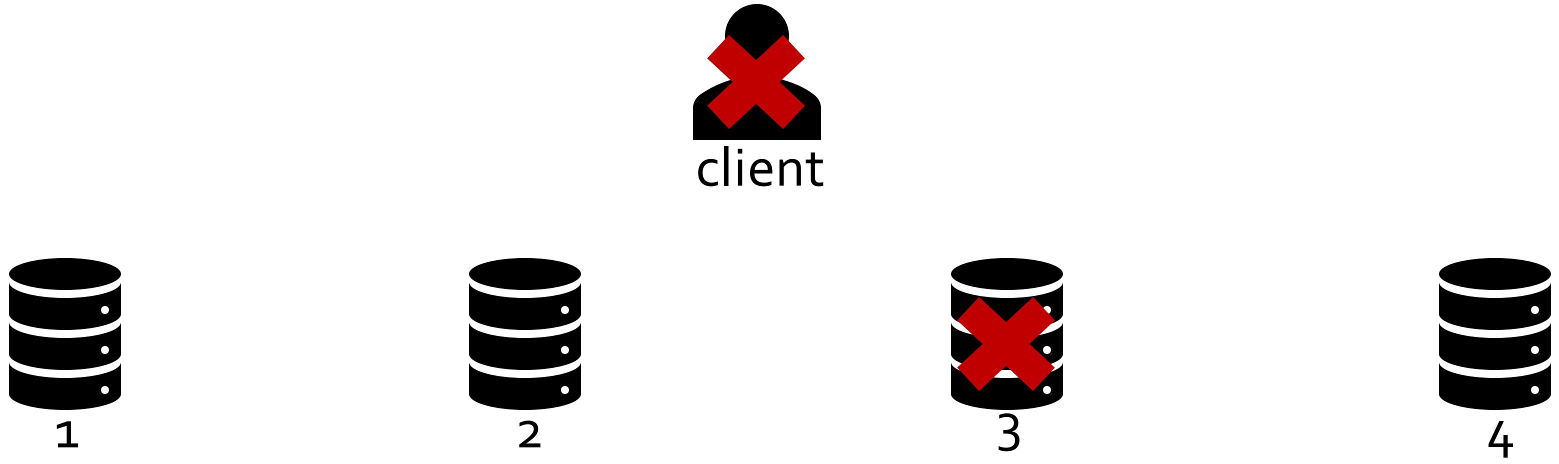

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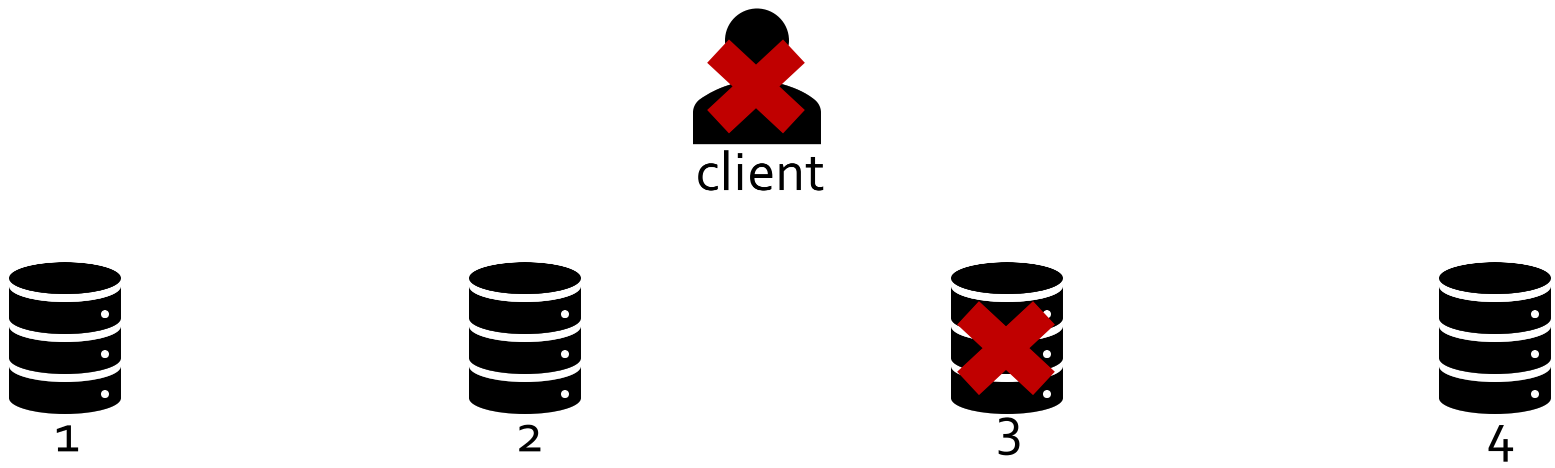

receive [BCAST *a*]	receive [BCAST *a*]		receive [BCAST *b*]

To broadcast a value *a*, the client sends `[BCAST` *a*`]` to every server.

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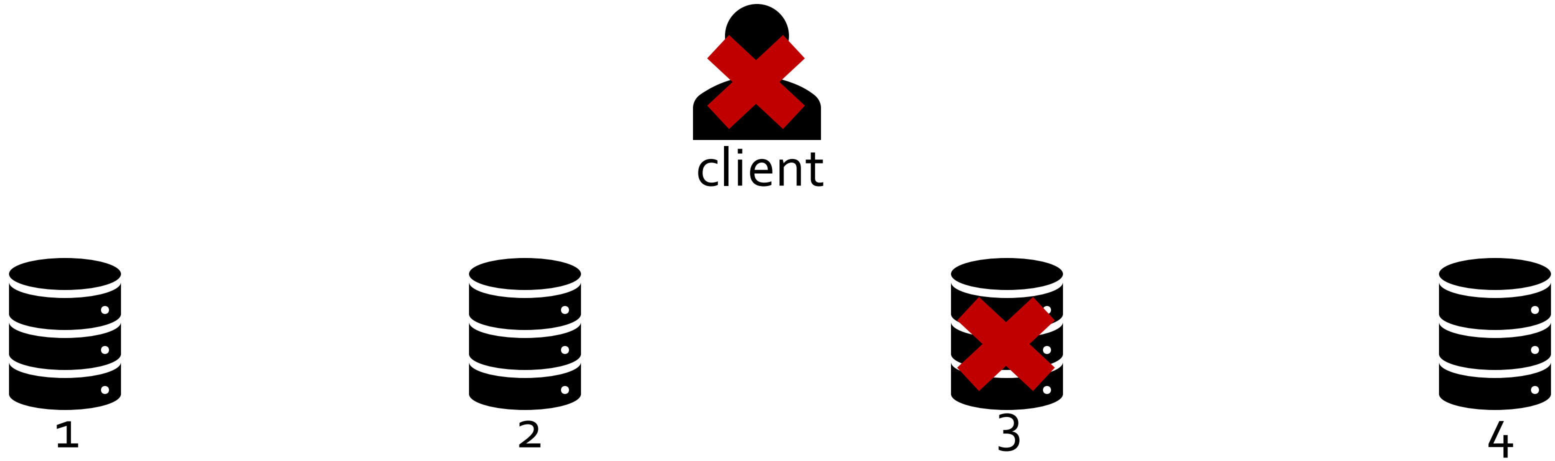
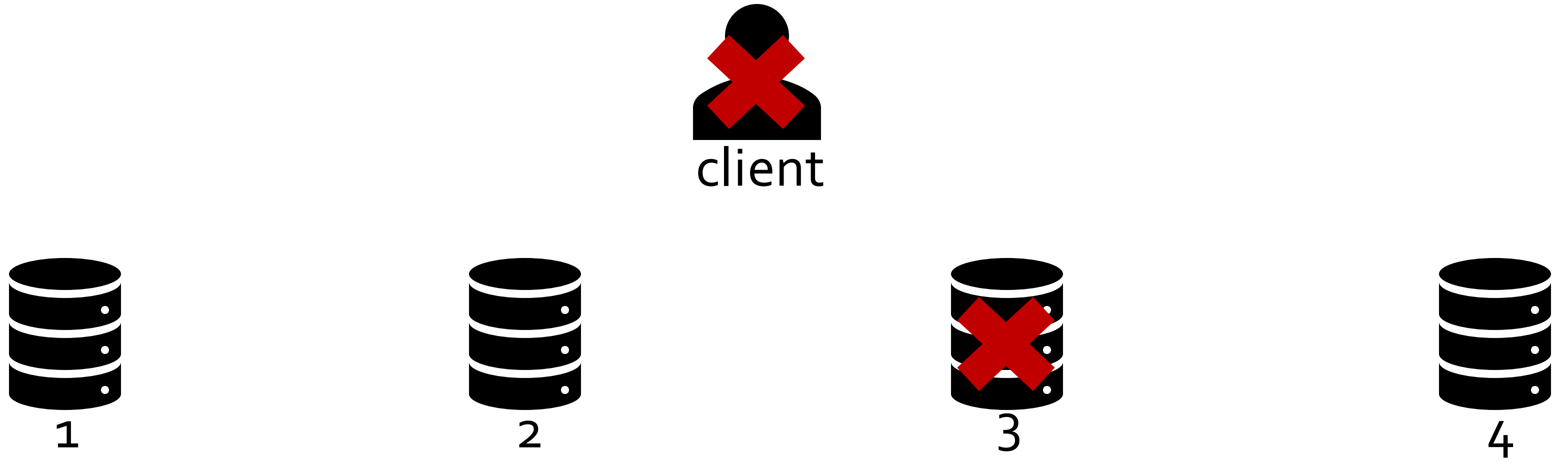


receive [BCAST a]	receive [BCAST a]		receive [BCAST b]
send [ECHO a] to all	send [ECHO a] to all		send [ECHO b] to all

After receiving [BCAST a], a server sends [ECHO a] to every server.

Example: $3f$+1



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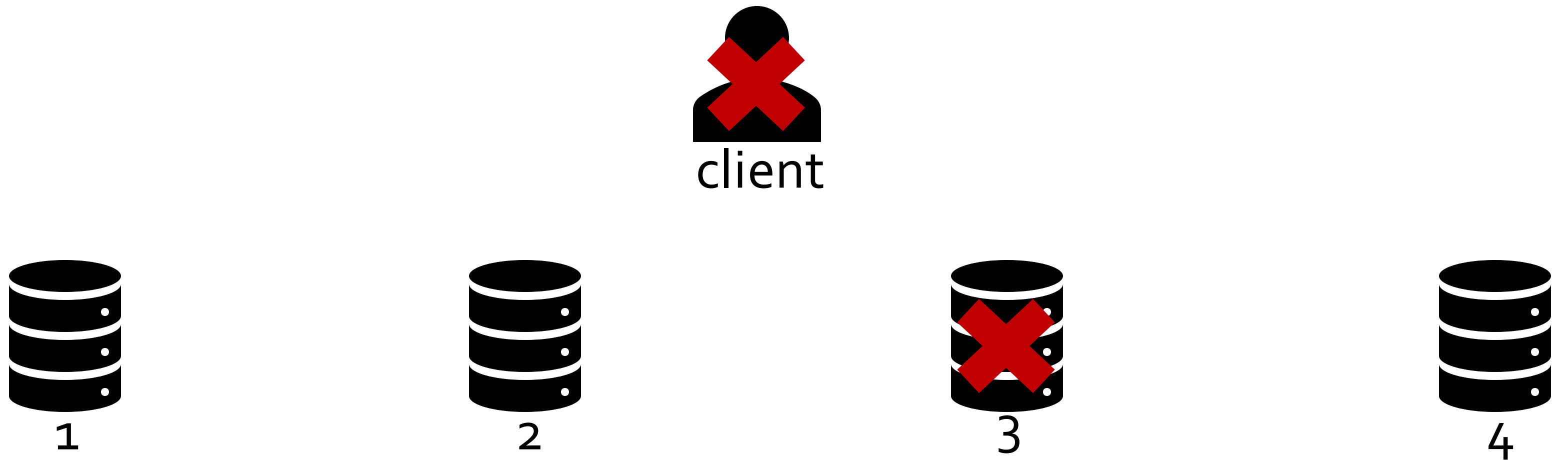
Example: 3*f*+1



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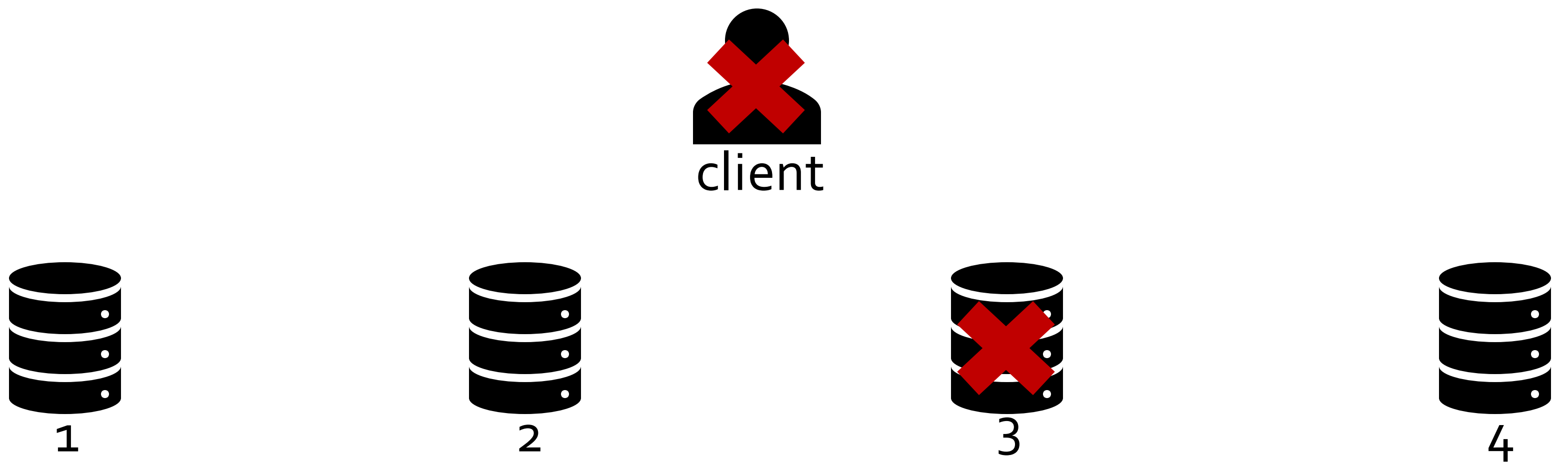
send [READY *a*] to all	send [READY *a*] to all		

After receiving [ECHO *a*] from a quorum, a server sends [READY *a*] to every server.

Example: $3f$+1



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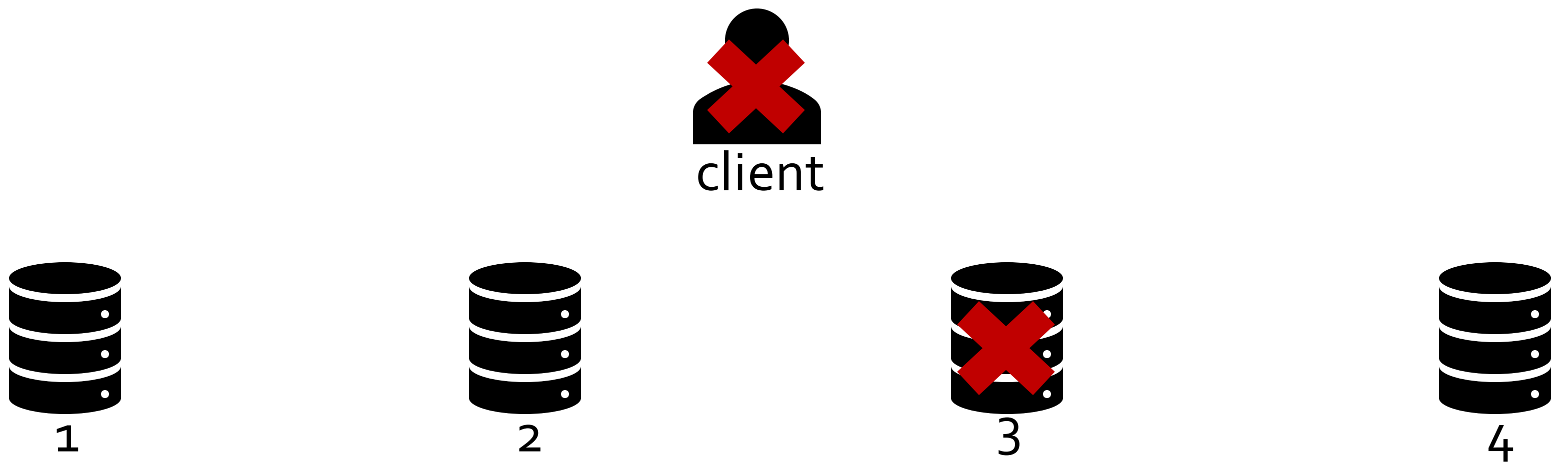
After receiving [READY a] from a set B such that $\forall B' \in \mathbb{B}, B \not\subseteq B'$, a server sends [READY a] to every server.

Example: $3f$+1



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send [READY *a*] to all	send [READY *a*] to all		
			send [READY *a*] to all
`deliver`(*a*)	`deliver`(*a*)		`deliver`(*a*)

After receiving `[READY` *a*`]` from a quorum, a server delivers value *a*.

Reliable Byzantine broadcast

Bracha broadcast satisfies the specification of reliable Byzantine broadcast when all faulty servers belong to some element of $\mathbb{B}$:

- ***Safety:*** If some correct server delivers a value a and another correct server delivers a value b, then $a = b$.
- ***Liveness:*** If a correct server delivers a value, then every correct server eventually delivers a value.

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The protocol needs to compute $\mathbb{B}$, which requires global information!

Federated Byzantine Quroum Systems (FBQS)

FBQS

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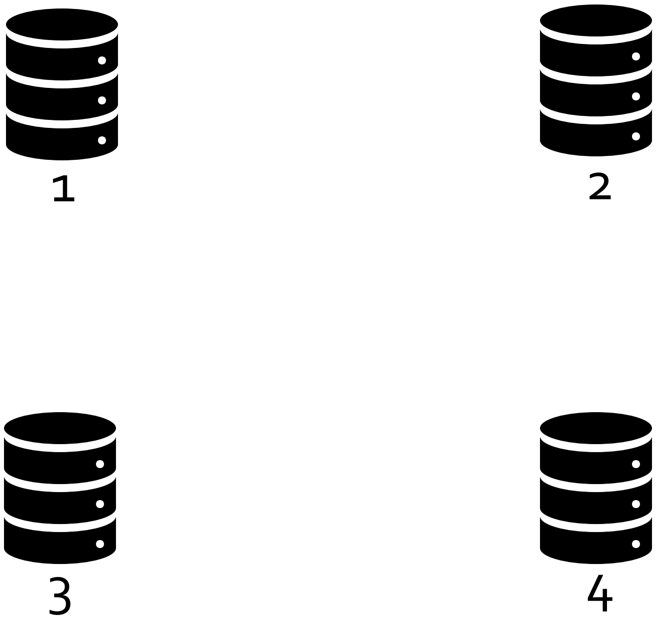

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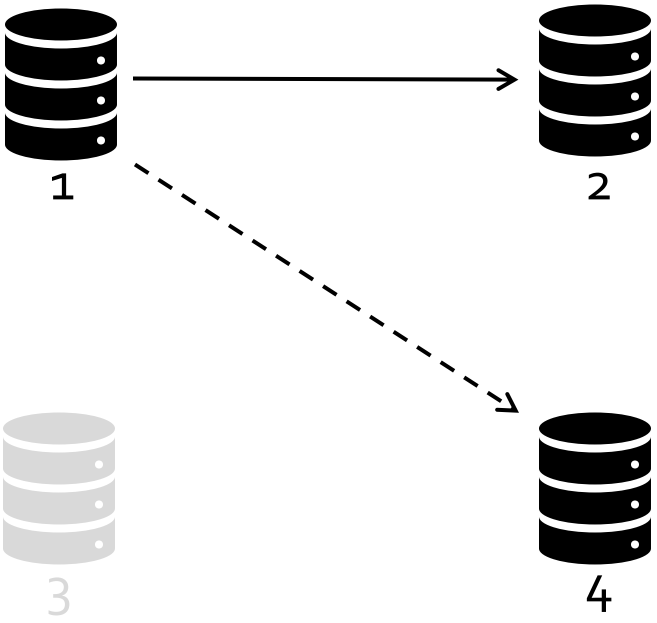

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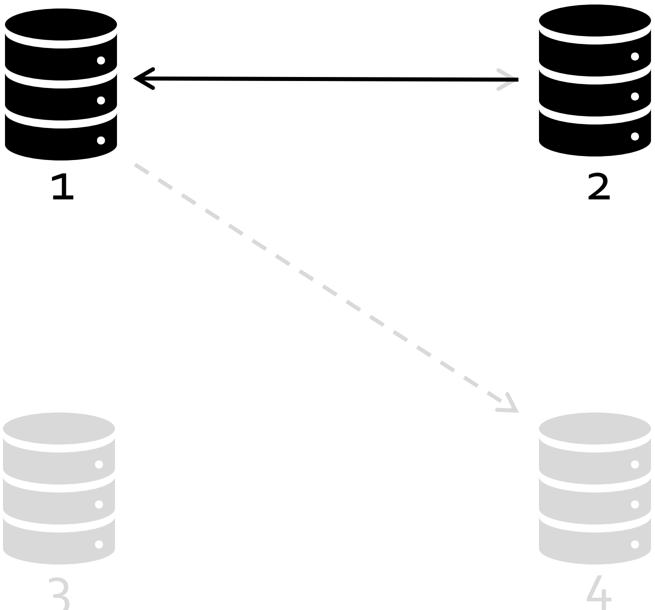

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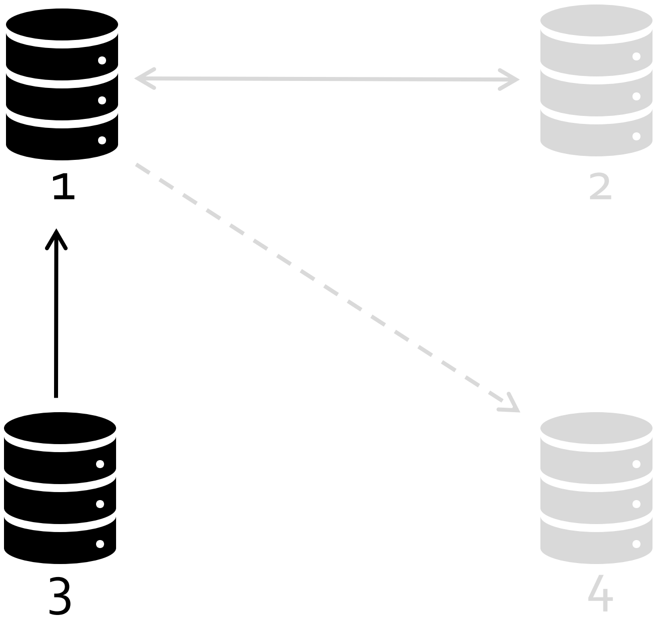

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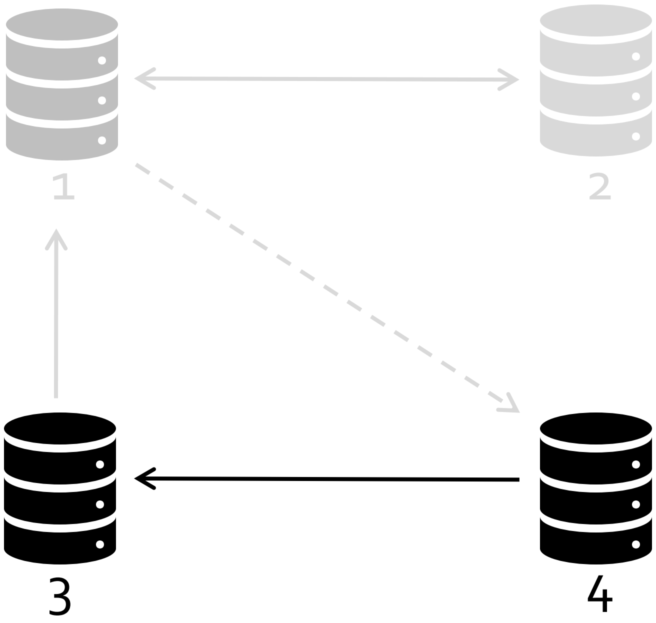

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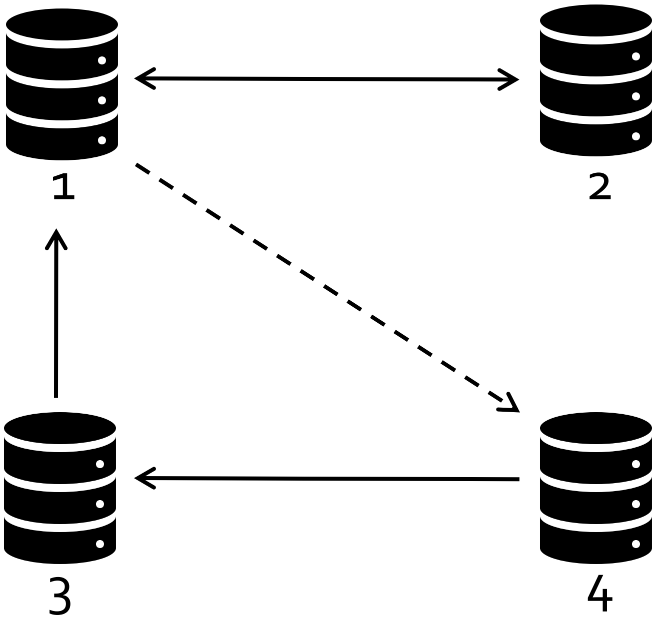

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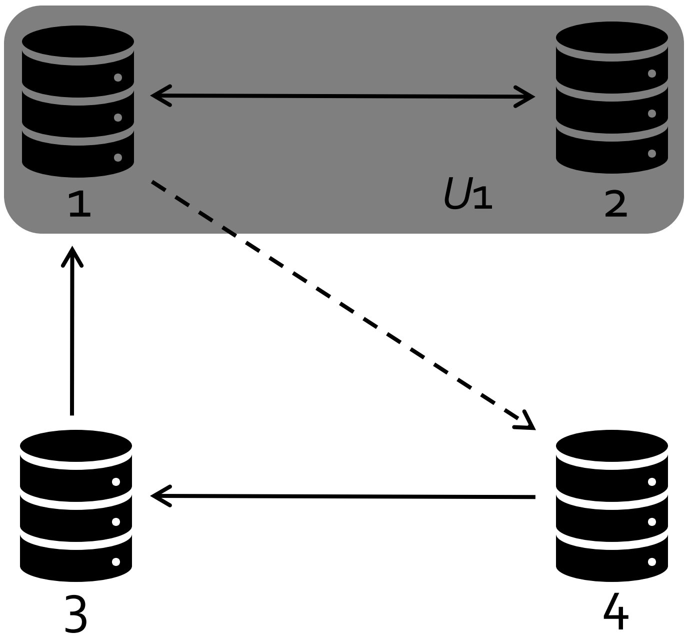

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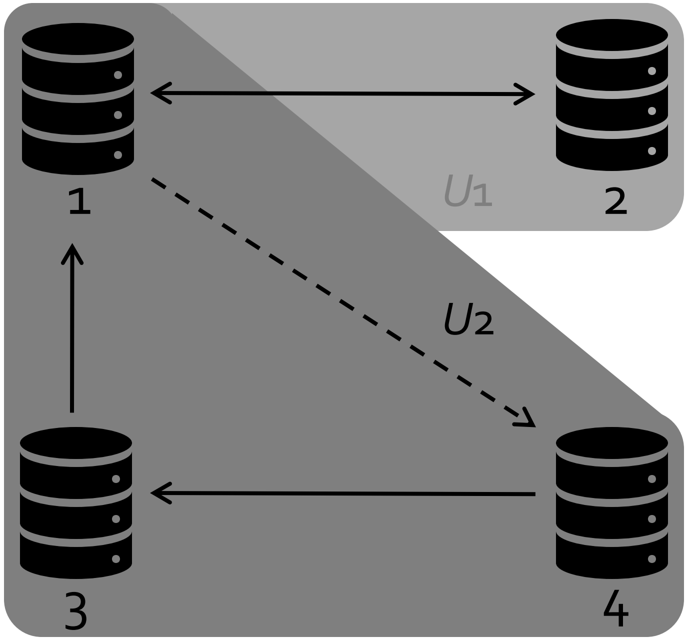

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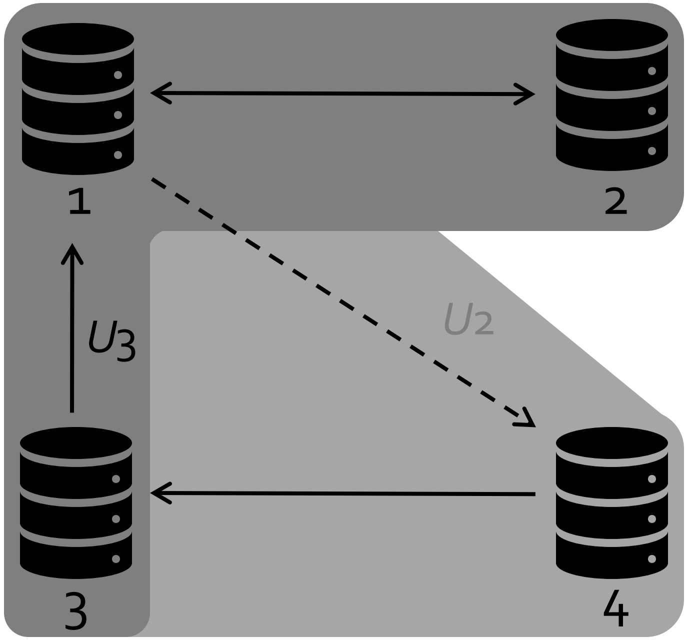

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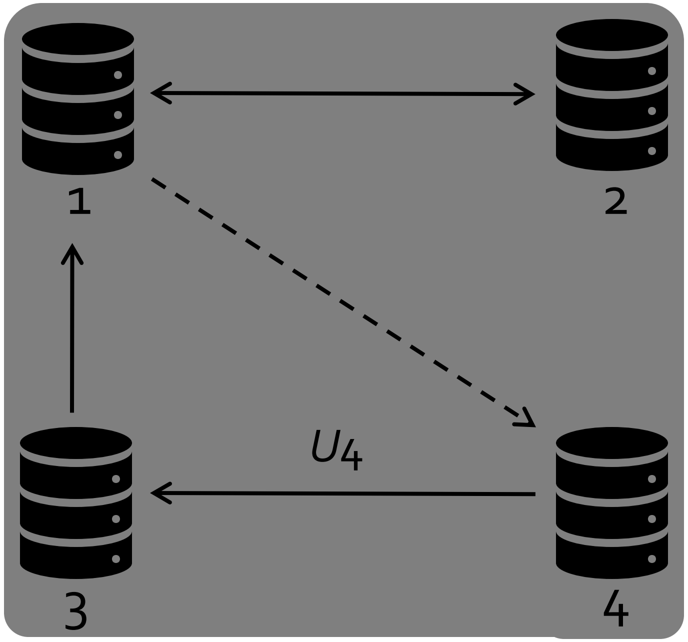

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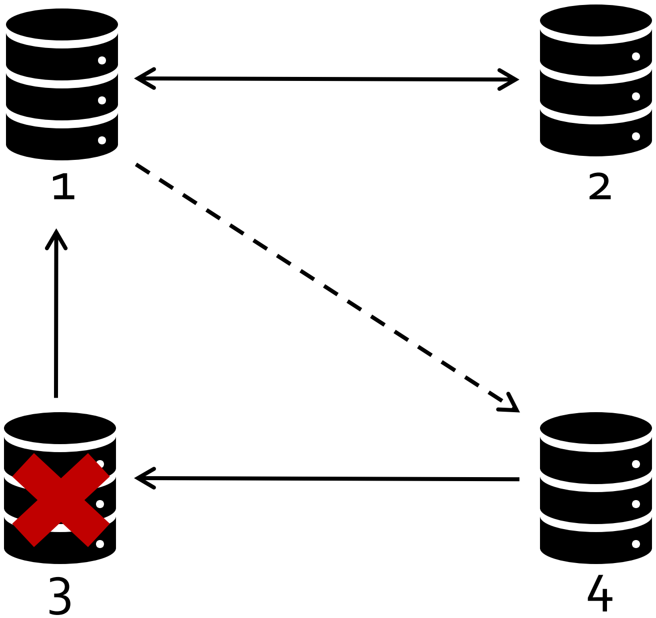

Given a set of faulty servers, $\mathbb{V}_{int}$ is the biggest quorum $\mathbb{V}_{int} \in \mathbb{Q}$ such that:

- $\forall v \in \mathbb{V}_{int}$, v is correct,
- $\mathbb{Q}|_{\mathbb{V}_{int}}$ has quorum intersection.

FBQS (Intact and befouled servers)

$\mathbb{V}\text{int} = \{1,2\}$

$\mathbb{S} : \mathbb{V} \longrightarrow 2^{2^{\mathbb{V}}}$

$\mathbb{S}(1) = \{\{1,2\},\{1,\cancel{4}\}\}$

$\mathbb{S}(2) = \{\{1,2\}\}$

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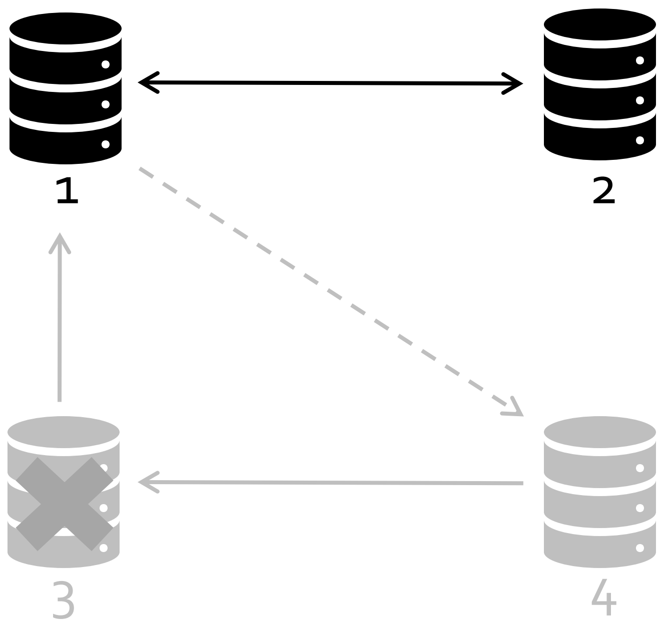

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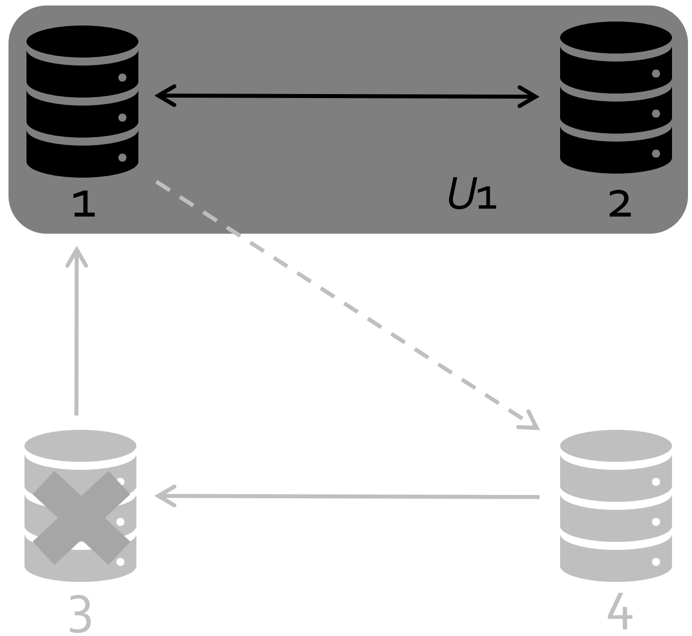

$U_1 = \{1,2\} \in \mathbb{Q}|_{\{1,2\}}$

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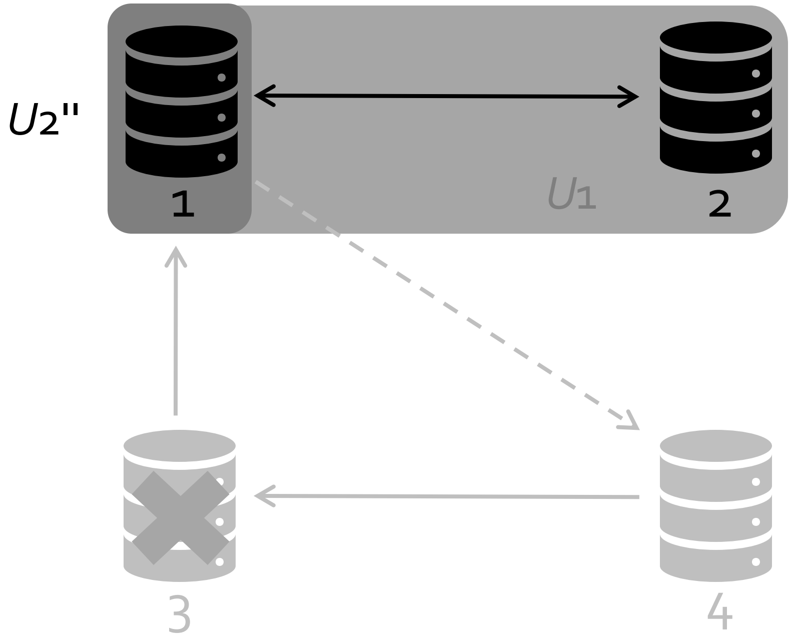

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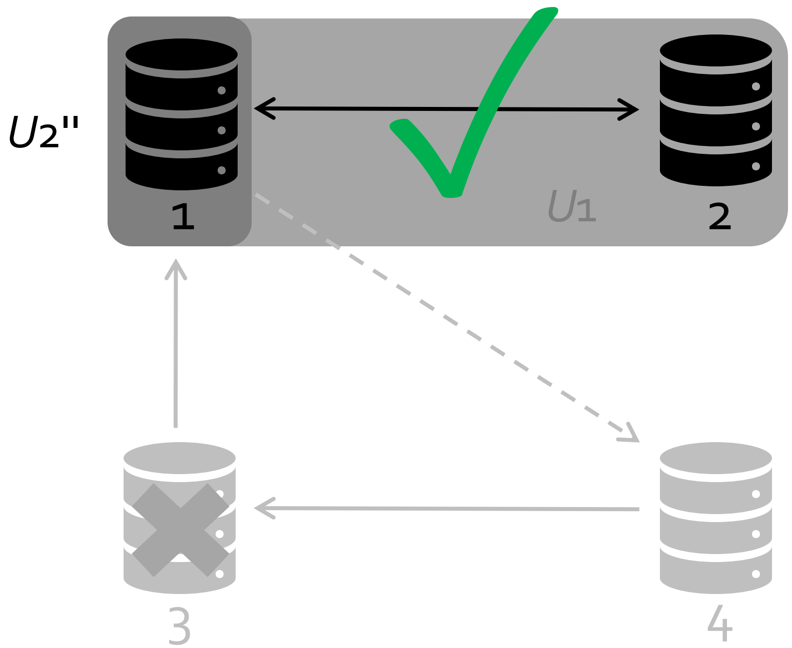

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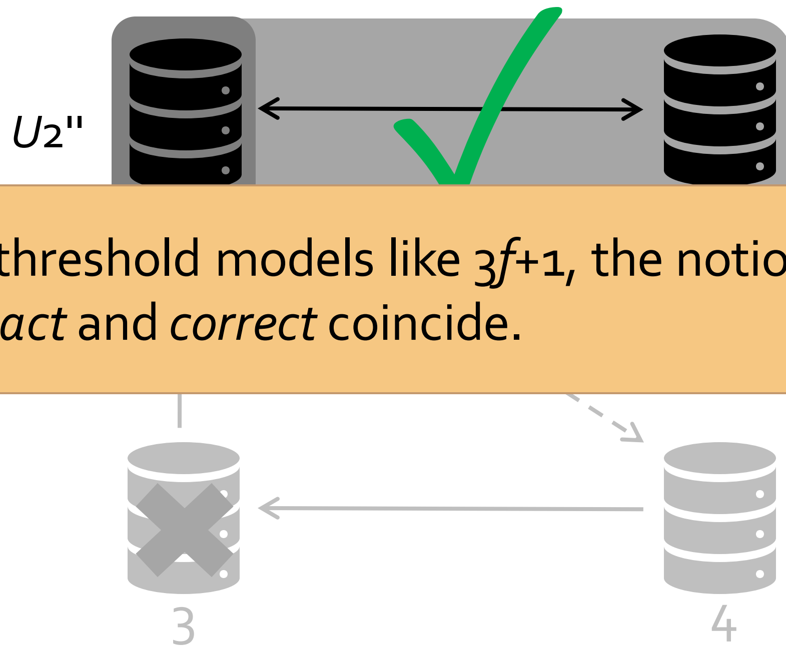

$U_1 = \{1,2\} \in \mathbb{Q}|_{\{1,2\}}$

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In threshold models like $3f$+1, the notions of *intact* and *correct* coincide.

Given a set of faulty servers, $\mathbb{V}_{\text{int}}$ is the biggest quorum $\mathbb{V}_{\text{int}} \in \mathbb{Q}$ such that:

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Mapping FBQS into DQS

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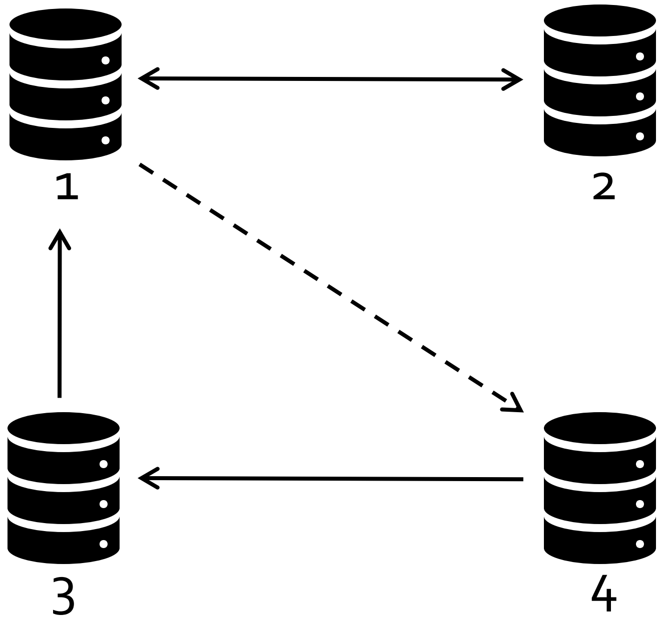

$U_1 = \{1,2\} \in \mathbb{Q}$
$U_2 = \{1,3,4\} \in \mathbb{Q}$
$U_3 = \{1,2,3\} \in \mathbb{Q}$
$U_4 = \{1,2,3,4\} \in \mathbb{Q}$

$B_1 = \{2\} \in \mathbb{B}$
$B_2 = \{3,4\} \in \mathbb{B}$

Mapping FBQS into DQS

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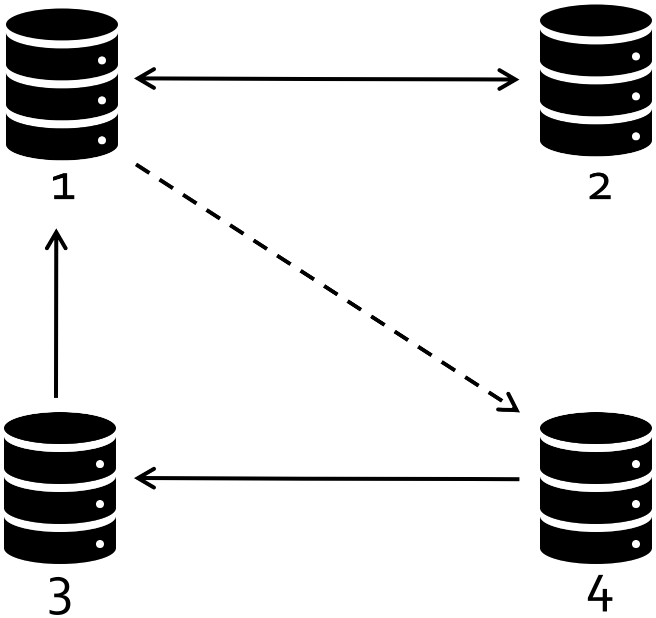

$U_1 = \{1,2\} \in \mathbb{Q}$
$U_2 = \{1,3,4\} \in \mathbb{Q}$
$U_3 = \{1,2,3\} \in \mathbb{Q}$
$U_4 = \{1,2,3,4\} \in \mathbb{Q}$

$B_1 = \{2\} \in \mathbb{B}$
$B_2 = \{3,4\} \in \mathbb{B}$

The elements in $\mathbb{B}$ are the maximal sets whose failure leave some intact server in the system.

Stellar Broadcast

v-blocking mecahnism

$\mathbb{V} = \{1,2,3,4\}$

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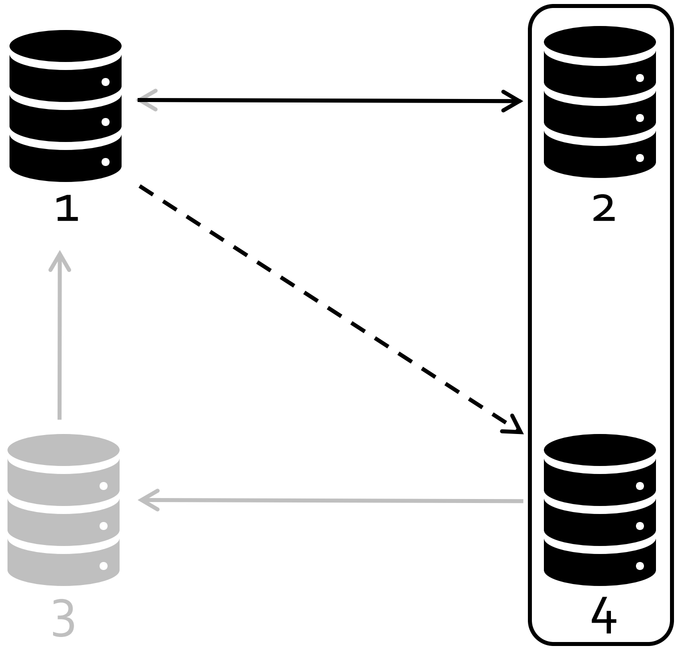

$B_1 \supseteq \{2,4\}$ is 1-blocking

v-blocking mecahnism

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$\mathbb{S} : \mathbb{V} \longrightarrow 2^{2^{\mathbb{V}}}$

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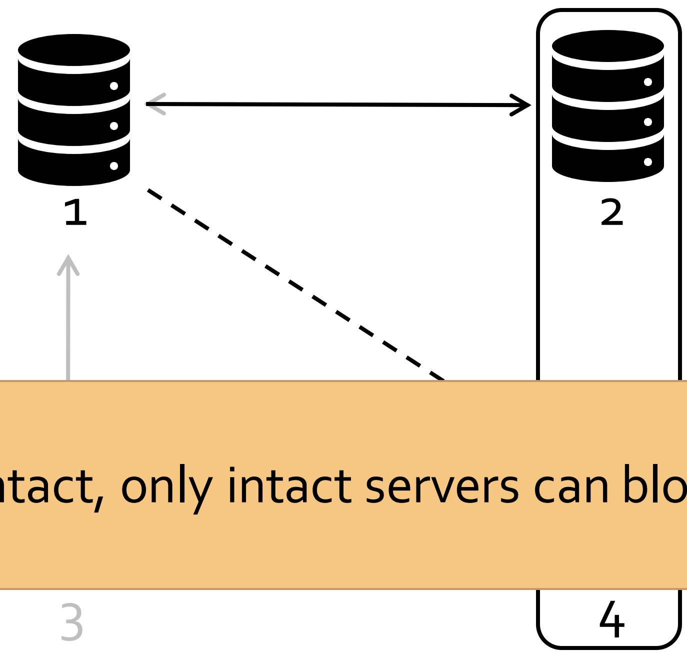

$B_1 \supseteq \{2,4\}$ is 1-blocking

If *v* is intact, only intact servers can block *v*.

v-blocking mecahnism

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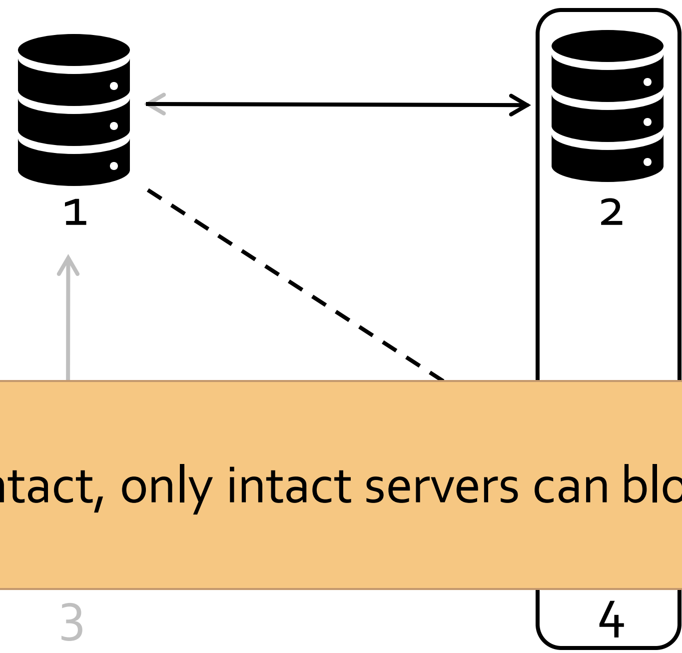
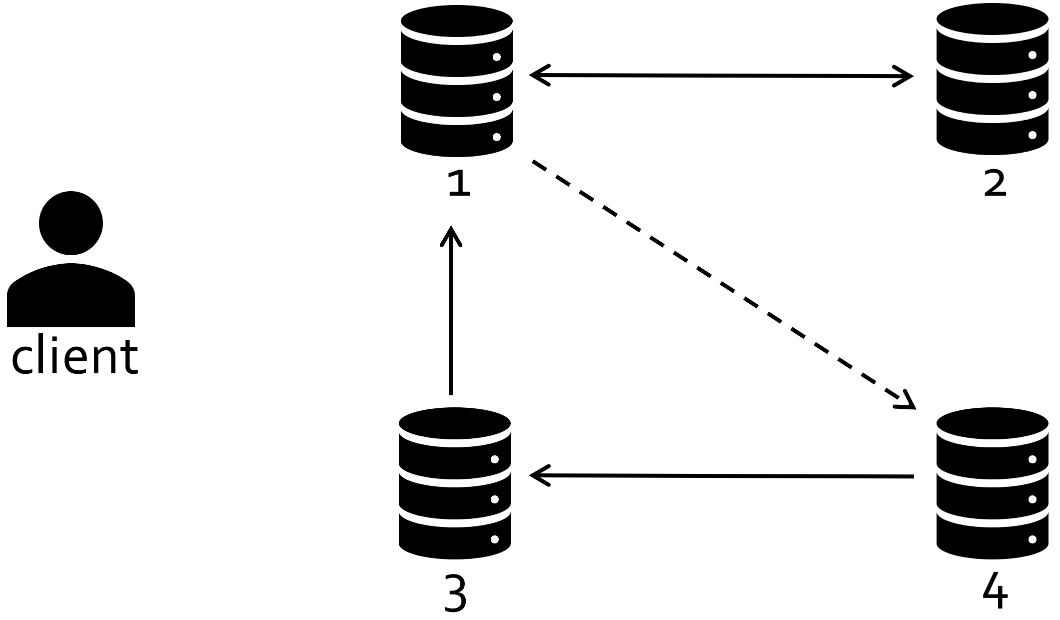


$B_1 \supseteq \{2,4\}$ is 1-blocking

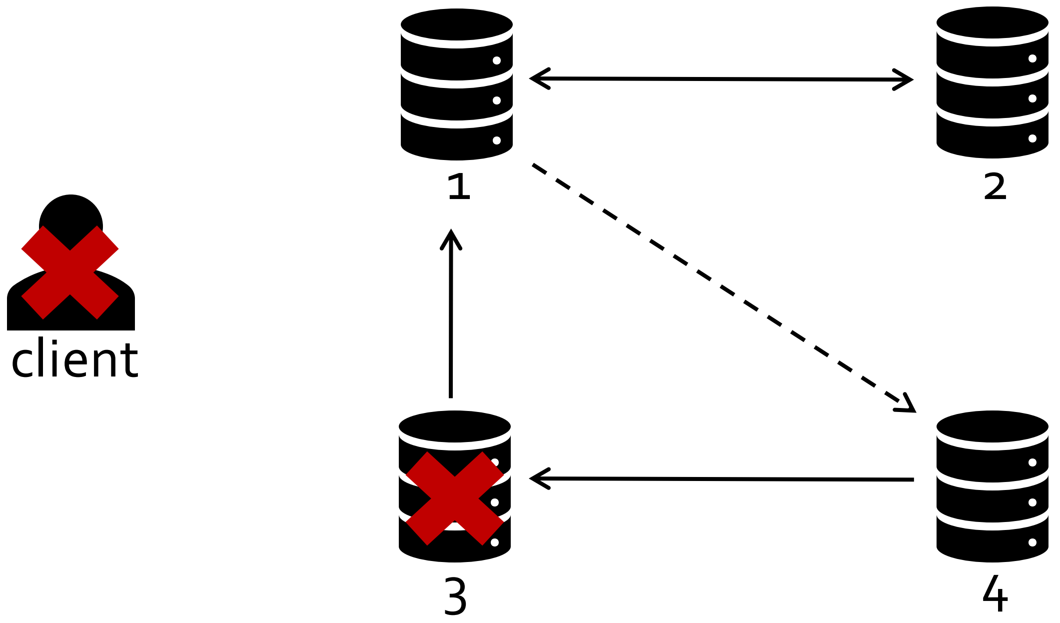
If *v* is intact, only intact servers can block *v*.

A *v*-blocking set can be computed by *v* locally!

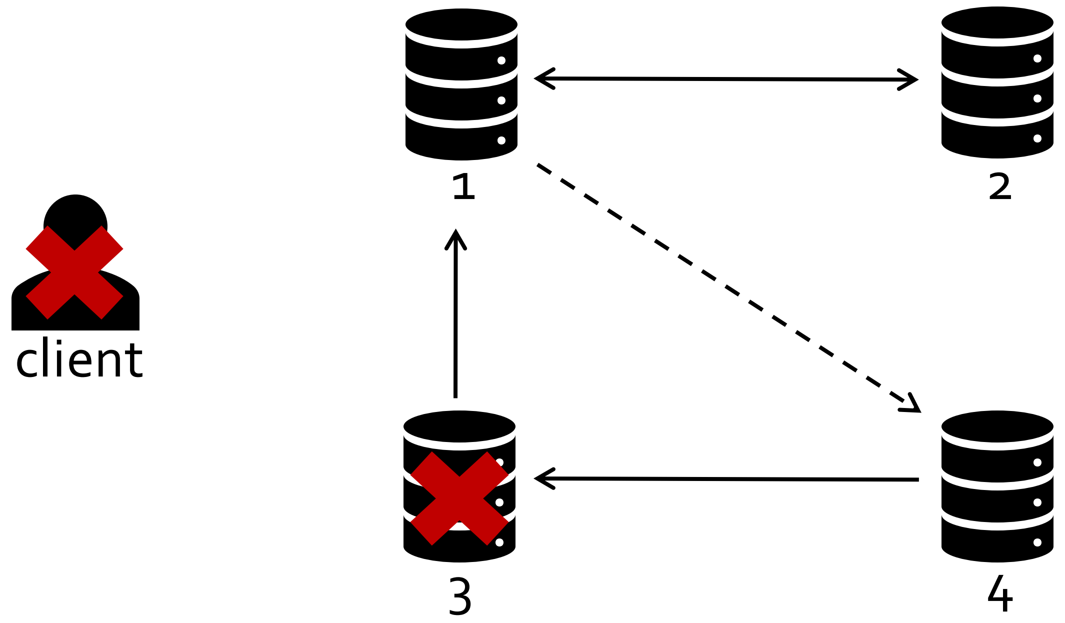
Example:



Example:



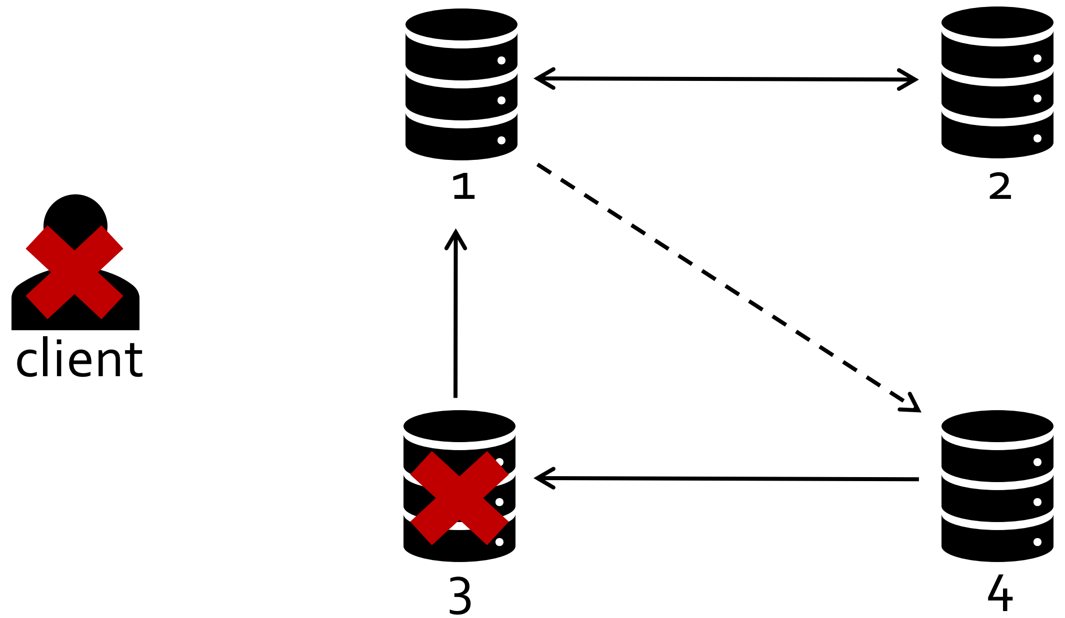
Example:



1	2	3	4
receive [BCAST a]	receive [BCAST a]		receive [BCAST b]

To broadcast a value a, the client sends [BCAST a] to every server.

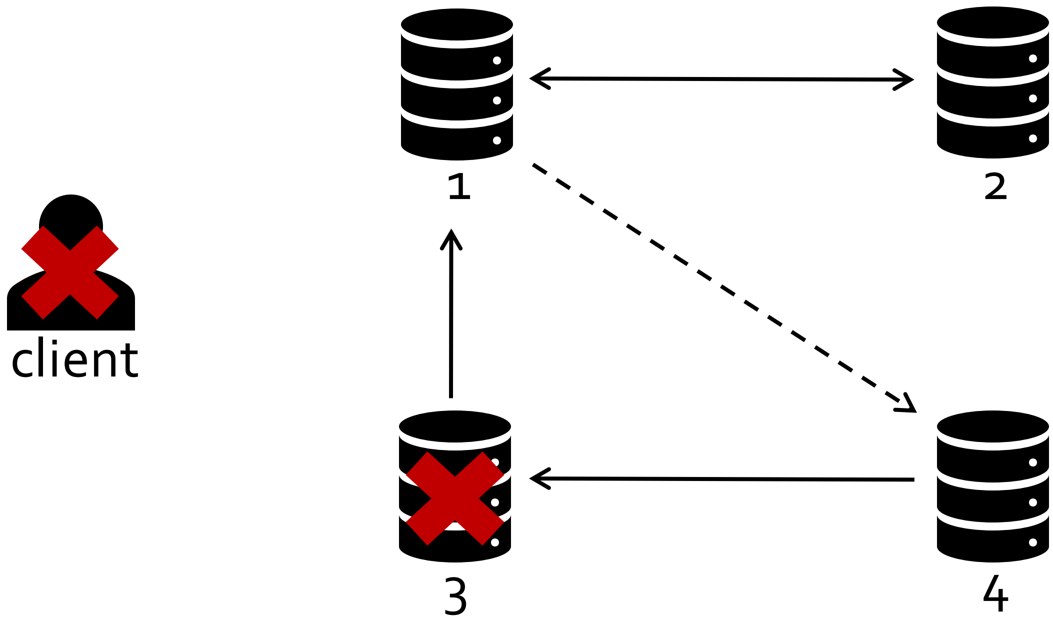
Example:



1	2	3	4
receive [BCAST a]	receive [BCAST a]		receive [BCAST b]
send [ECHO a] to all	send [ECHO a] to all		send [ECHO b] to all

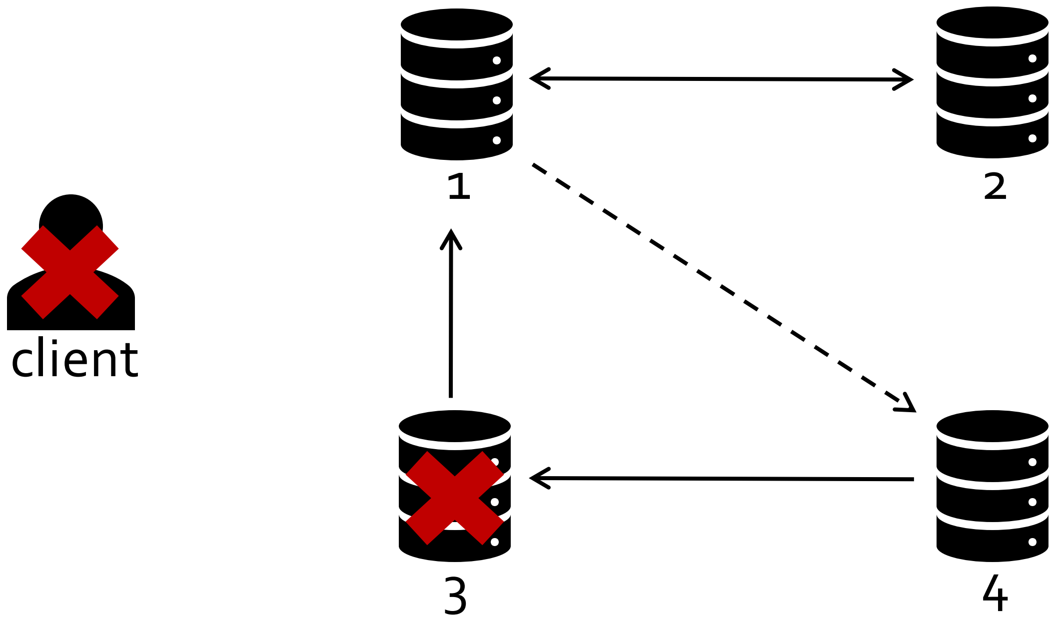
After receiving [BCAST a], a server sends [ECHO a] to every server.

Example:



1	2	3	4
receive [BCAST *a*]	receive [BCAST *a*]		receive [BCAST *b*]
send [ECHO *a*] to all	send [ECHO *a*] to all	send [READY *b*] to 4	send [ECHO *b*] to all

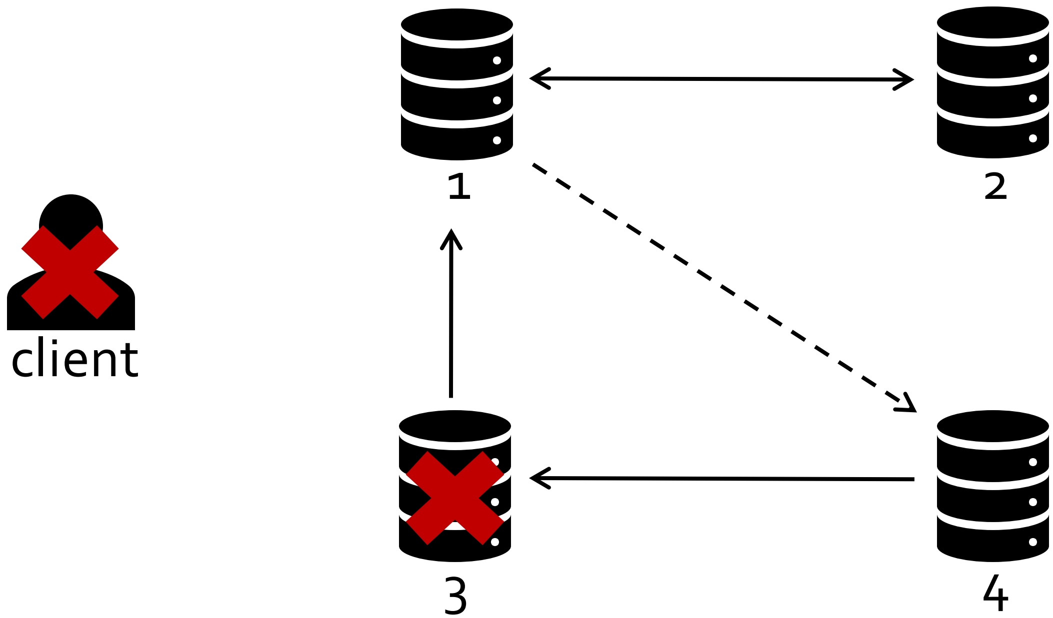
Example:



1	2	3	4
receive [BCAST a]	receive [BCAST a]		receive [BCAST b]
send [ECHO a] to all	send [ECHO a] to all	send [READY b] to 4	send [ECHO b] to all
send [READY a] to all	send [READY a] to all		

After receiving [ECHO a] from a quorum, a server sends [READY a] to every server.

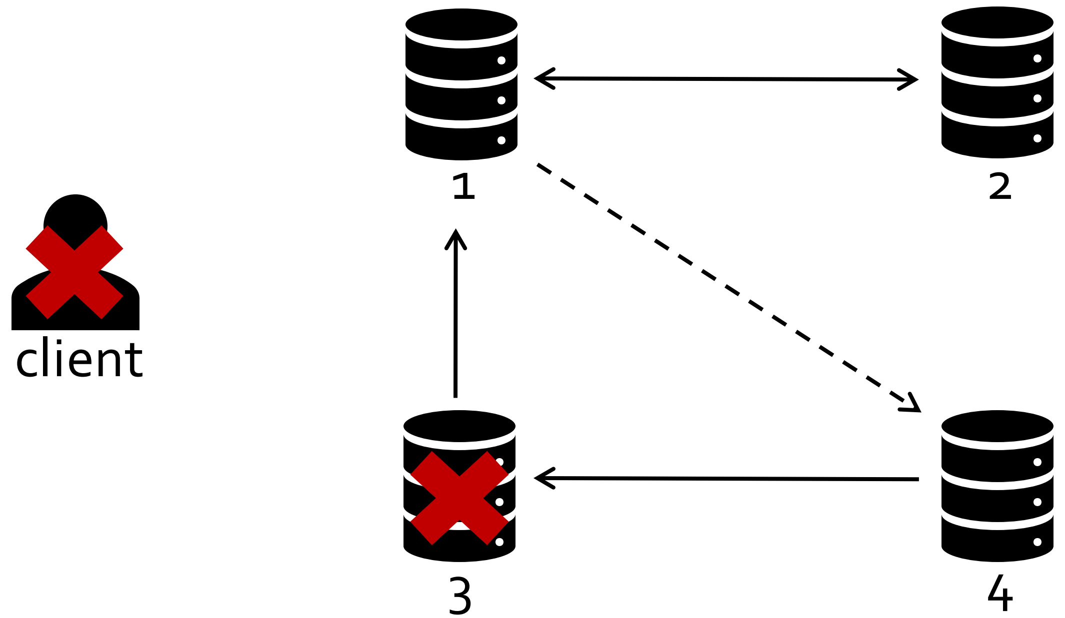
Example:



1	2	3	4
receive [BCAST *a*]	receive [BCAST *a*]		receive [BCAST *b*]
send [ECHO *a*] to all	send [ECHO *a*] to all	send [READY *b*] to 4	send [ECHO *b*] to all
send [READY *a*] to all	send [READY *a*] to all		send [READY *b*] to all

After receiving [READY *a*] from a *v*-blocking set, *v* sends [READY *a*] to every server.

Example:



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receive [BCAST *a*]	receive [BCAST *a*]		receive [BCAST *b*]
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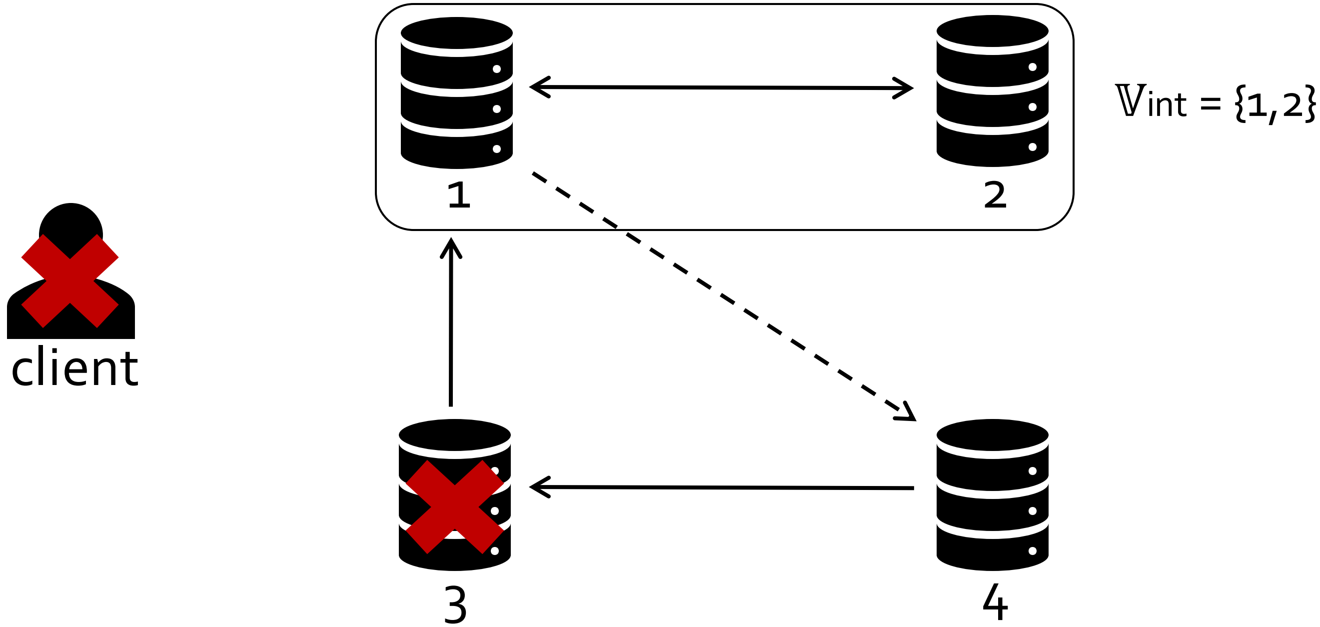
send [READY *a*] to all	send [READY *a*] to all		send [READY *b*] to all
deliver(*a*)	deliver(*a*)		

After receiving [READY *a*] from a quorum, a server delivers value *a*.

Example:



1	2	3	4
receive [BCAST *a*]	receive [BCAST *a*]		receive [BCAST *b*]
send [ECHO *a*] to all	send [ECHO *a*] to all	send [READY *b*] to 4	send [ECHO *b*] to all
send [READY *a*] to all	send [READY *a*] to all		send [READY *b*] to all
deliver(*a*)	deliver(*a*)		

After receiving [READY *a*] from a quorum, a server delivers value *a*.

Weakly reliable Byzantine broadcast

Stellar broadcast satisfies the specification of weakly reliable Byzantine broadcast when the faulty servers leave at least one intact server:

- ***Safety:*** If some correct server delivers a value *a* and another correct server delivers a value *b*, then *a* = *b*.
- ***Liveness:*** If a correct server delivers a value, then every intact server eventually delivers a value.

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Trade-off: operating on local information weakens the liveness properties to intact servers

Subjective FBQS

Subjective FBQS

$\mathbb{V} = \{1,2,3,4\}$

$\mathbb{S} : \mathbb{V} \longrightarrow 2^{2^{\mathbb{V}}} \setminus \{\emptyset\}$

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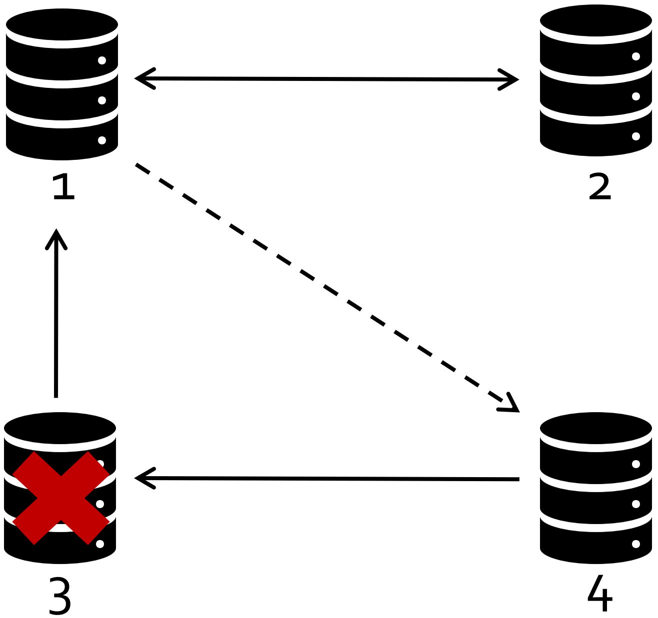

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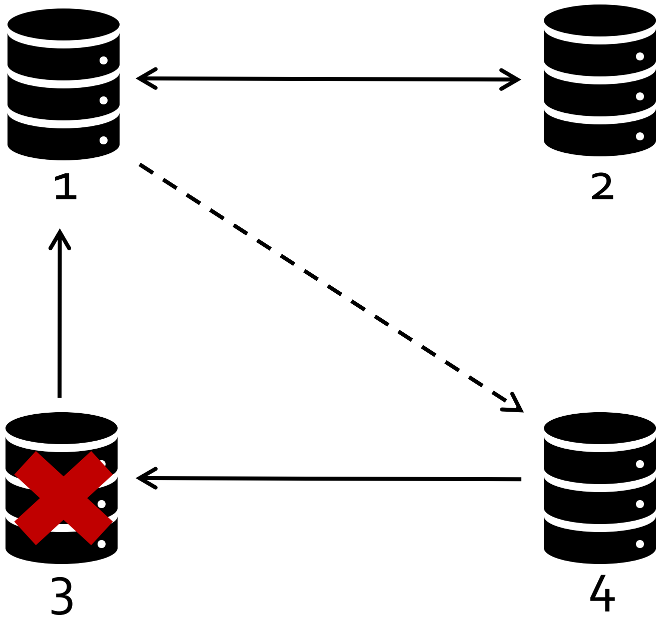

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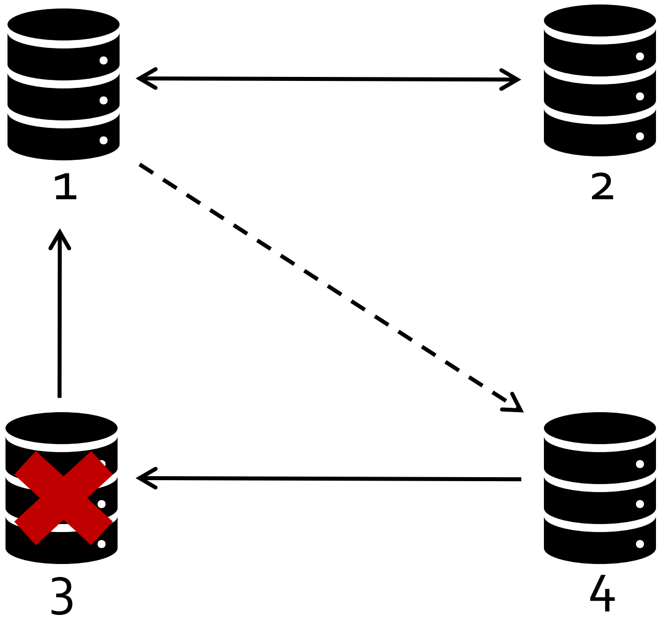
$\mathbb{S}_1 = \mathbb{S}_4$



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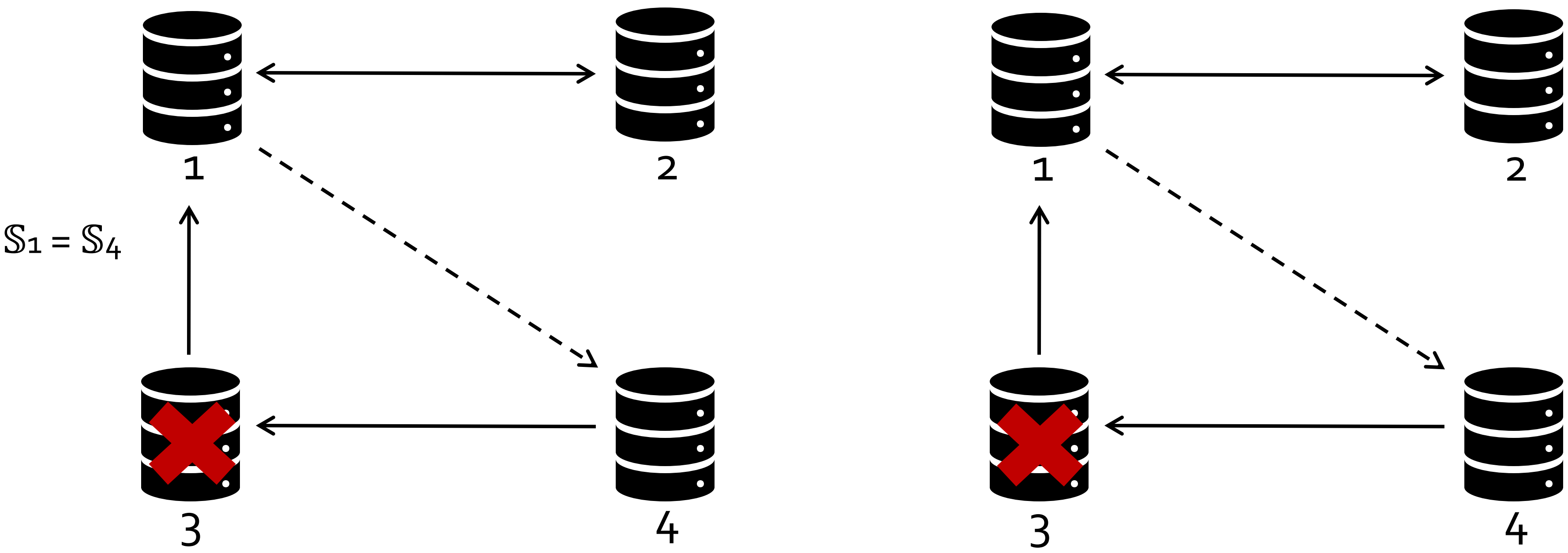

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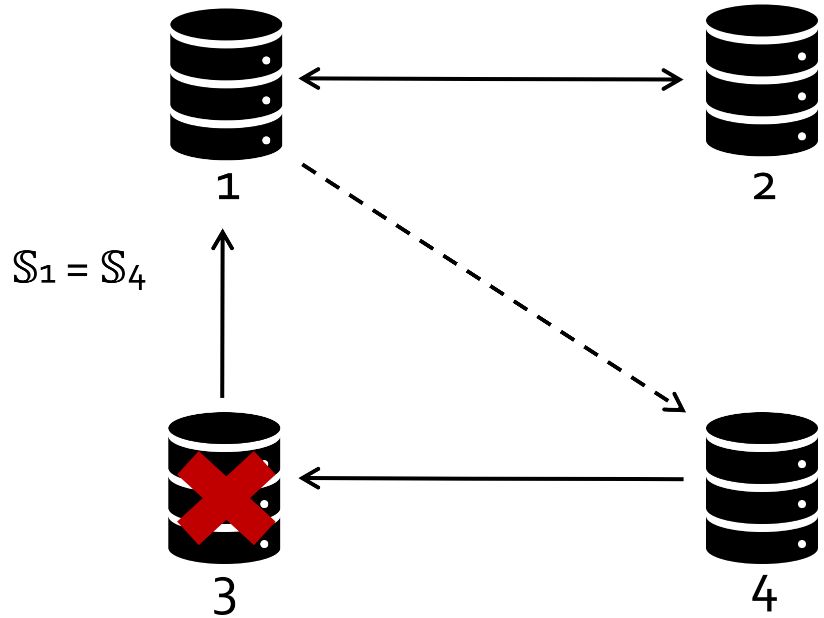

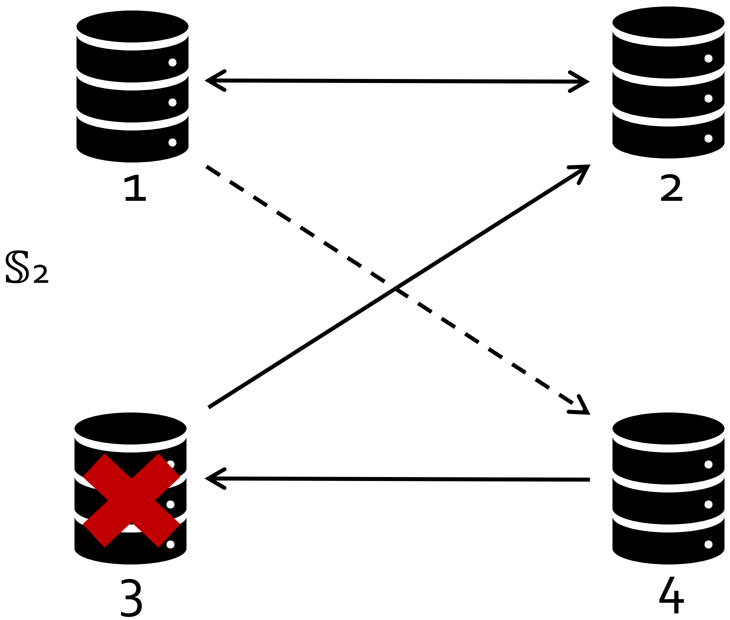

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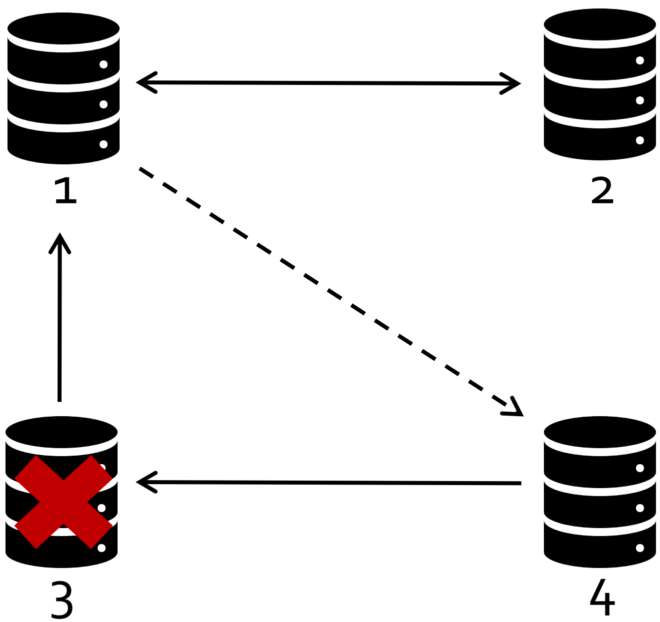
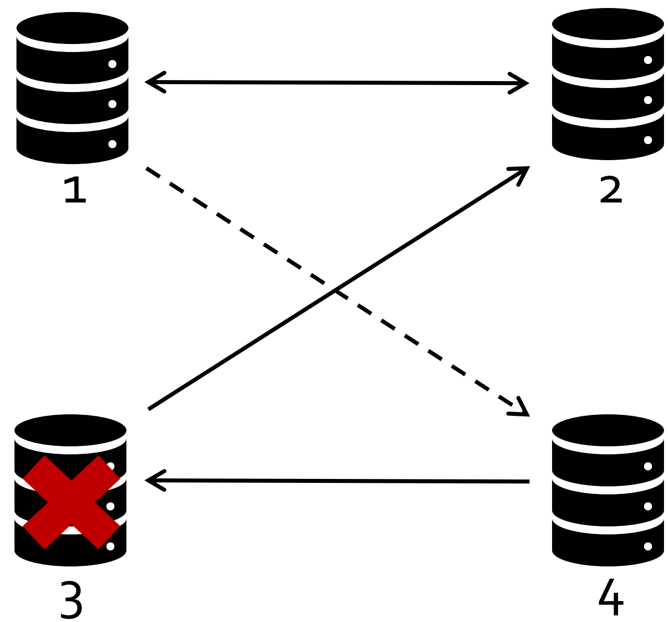


$\mathbb{S}_2$



$\mathbb{S}_1(1) = \mathbb{S}_4(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_1(2) = \mathbb{S}_4(2) = \{\{1,2\}\}$
$\mathbb{S}_1(3) = \mathbb{S}_4(3) = \{\{1,3\}\}$
$\mathbb{S}_1(4) = \mathbb{S}_4(4) = \{\{3,4\}\}$

$\mathbb{S}_2(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_2(2) = \{\{1,2\}\}$
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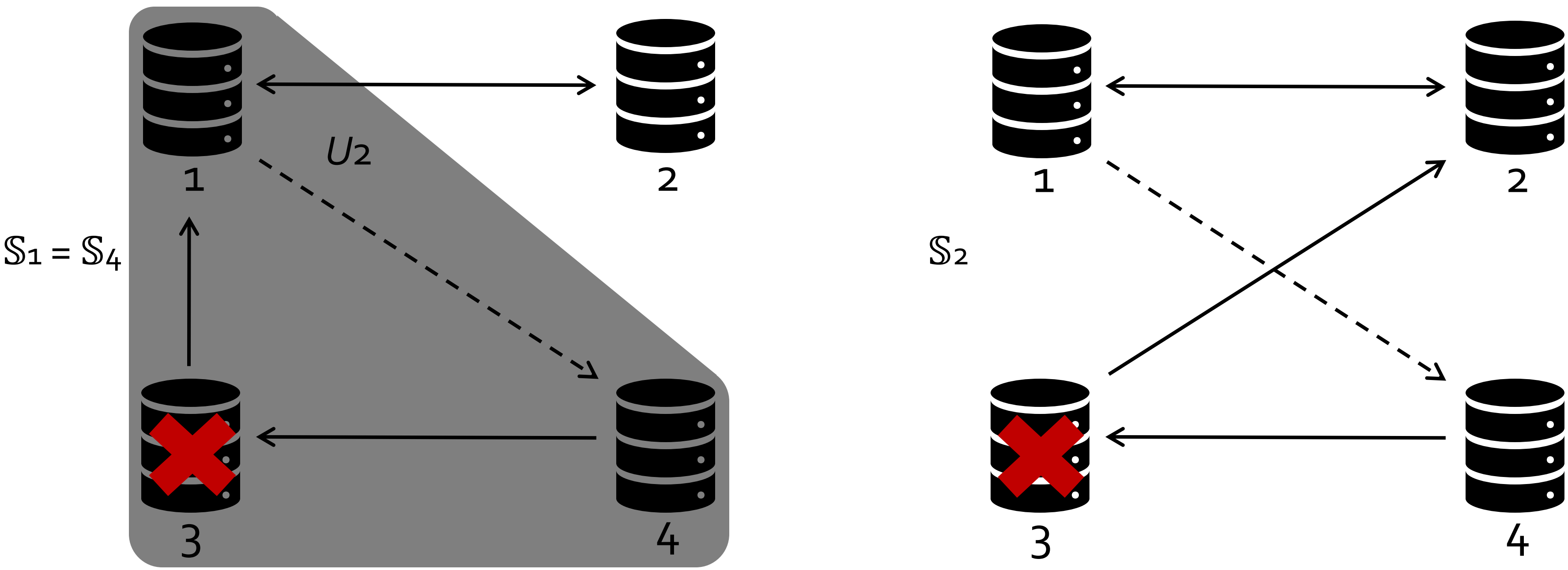
Subjective FBQS

$\mathbb{V} = \{1,2,3,4\}$



$\mathbb{S}_1(1) = \mathbb{S}_4(1) = \{\{1,2\},\{1,4\}\}$
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$\mathbb{S}_1(4) = \mathbb{S}_4(4) = \{\{3,4\}\}$

$\mathbb{S}_2(1) = \{\{1,2\},\{1,4\}\}$
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Subjective FBQS

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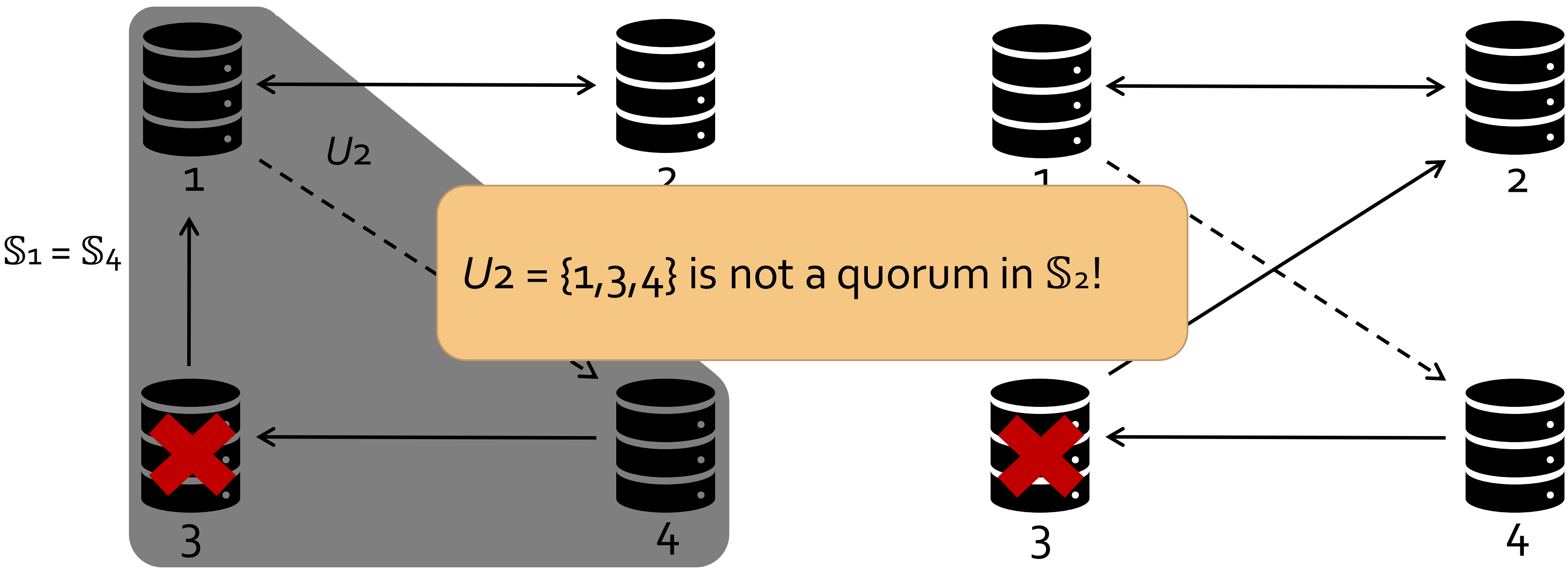

$U_2 = \{1,3,4\}$ is not a quorum in $\mathbb{S}_2$!

$\mathbb{S}_1(1) = \mathbb{S}_4(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_1(2) = \mathbb{S}_4(2) = \{\{1,2\}\}$
$\mathbb{S}_1(3) = \mathbb{S}_4(3) = \{\{1,3\}\}$
$\mathbb{S}_1(4) = \mathbb{S}_4(4) = \{\{3,4\}\}$

$\mathbb{S}_2(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_2(2) = \{\{1,2\}\}$
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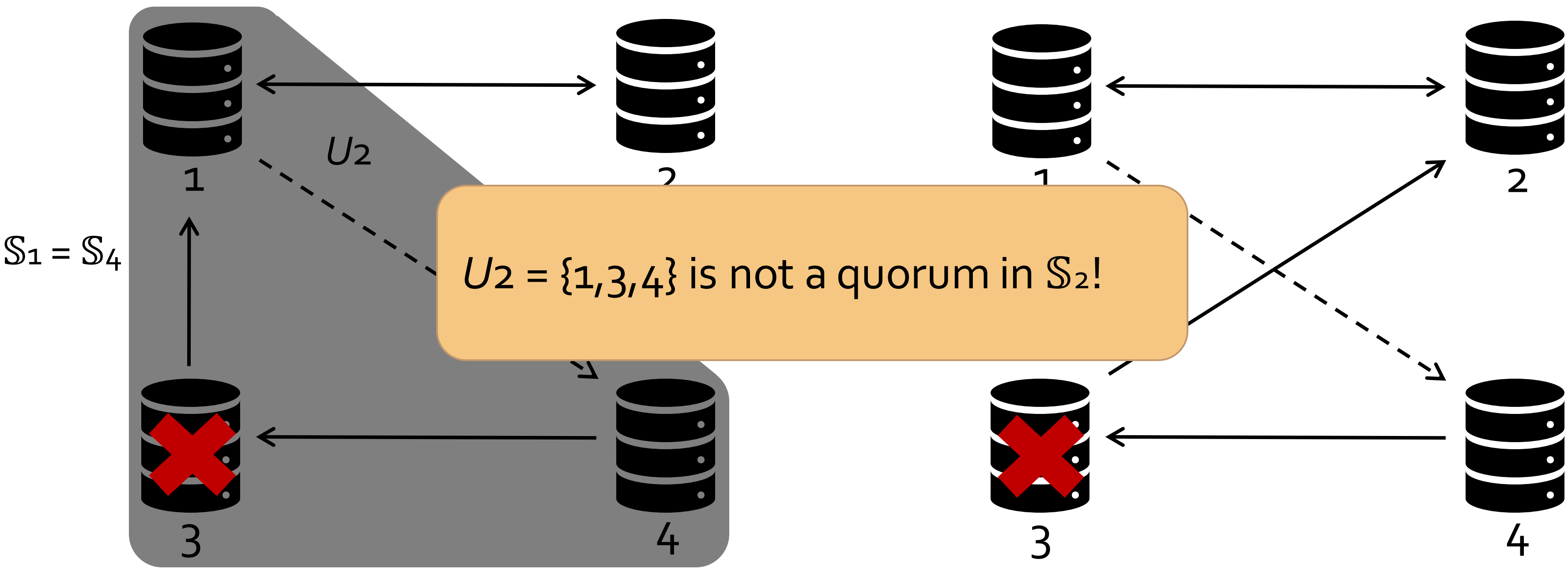
Subjective FBQS

$\mathbb{V} = \{1,2,3,4\}$



$\mathbb{S}_1(1) = \mathbb{S}_4(1) = \{\{1,2\},\{1,4\}\}$

$\mathbb{S}_1(2) = \mathbb{S}_4(2) = \{\{1,2\}\}$

~~$\mathbb{S}_1(3) = \mathbb{S}_4(3) = \{\{1,3\}\}$~~

$\mathbb{S}_1(4) = \mathbb{S}_4(4) = \{\{3,4\}\}$

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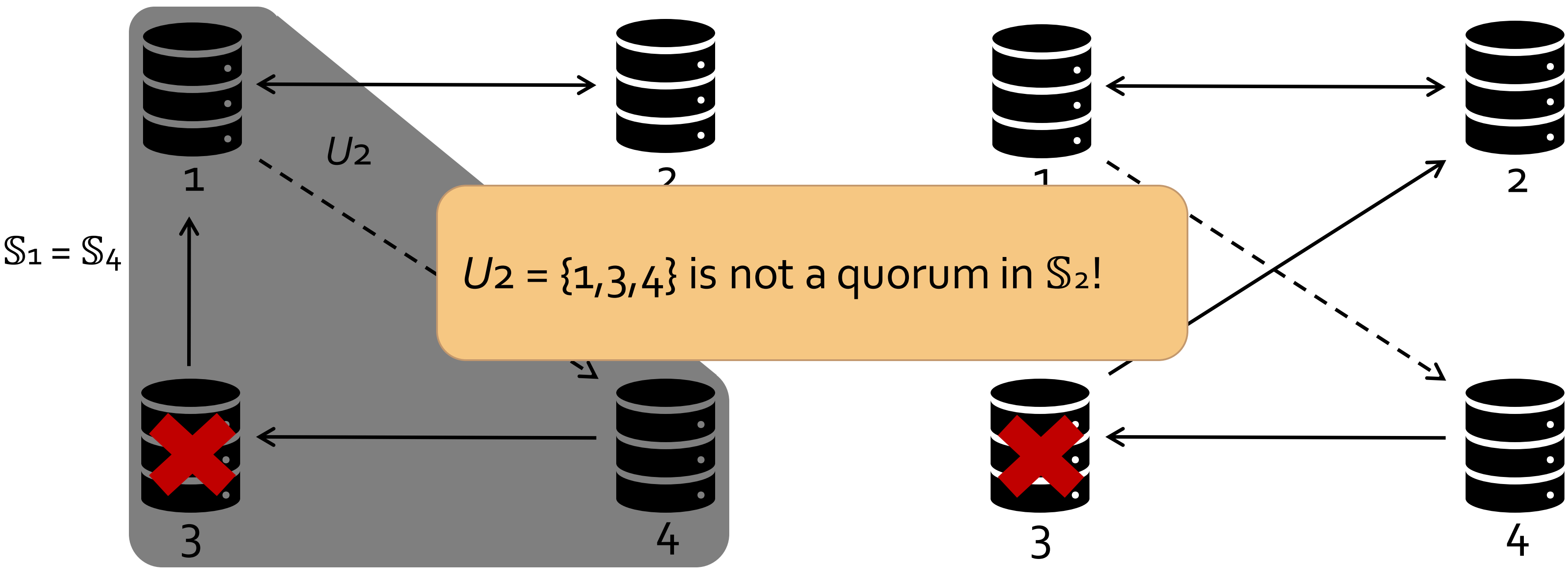
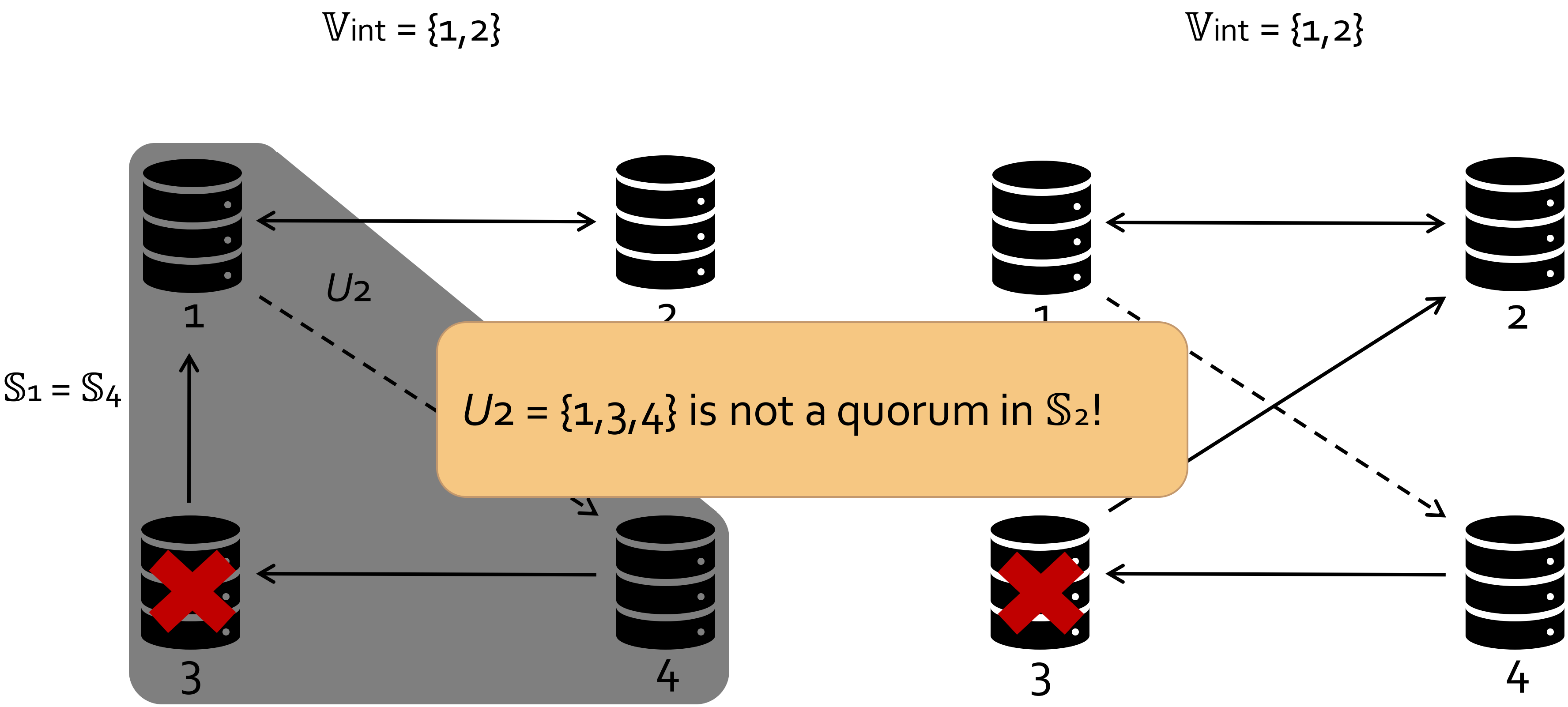


$\mathbb{S}_1(1) = \mathbb{S}_4(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_1(2) = \mathbb{S}_4(2) = \{\{1,2\}\}$
$\cancel{\mathbb{S}_1(3) = \mathbb{S}_4(3) = \{\{1,3\}\}}$
$\mathbb{S}_1(4) = \mathbb{S}_4(4) = \{\{3,4\}\}$

$=$

$\mathbb{S}_2(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_2(2) = \{\{1,2\}\}$
$\cancel{\mathbb{S}_2(3) = \{\{2,3\}\}}$
$\mathbb{S}_2(4) = \{\{3,4\}\}$

Subjective FBQS

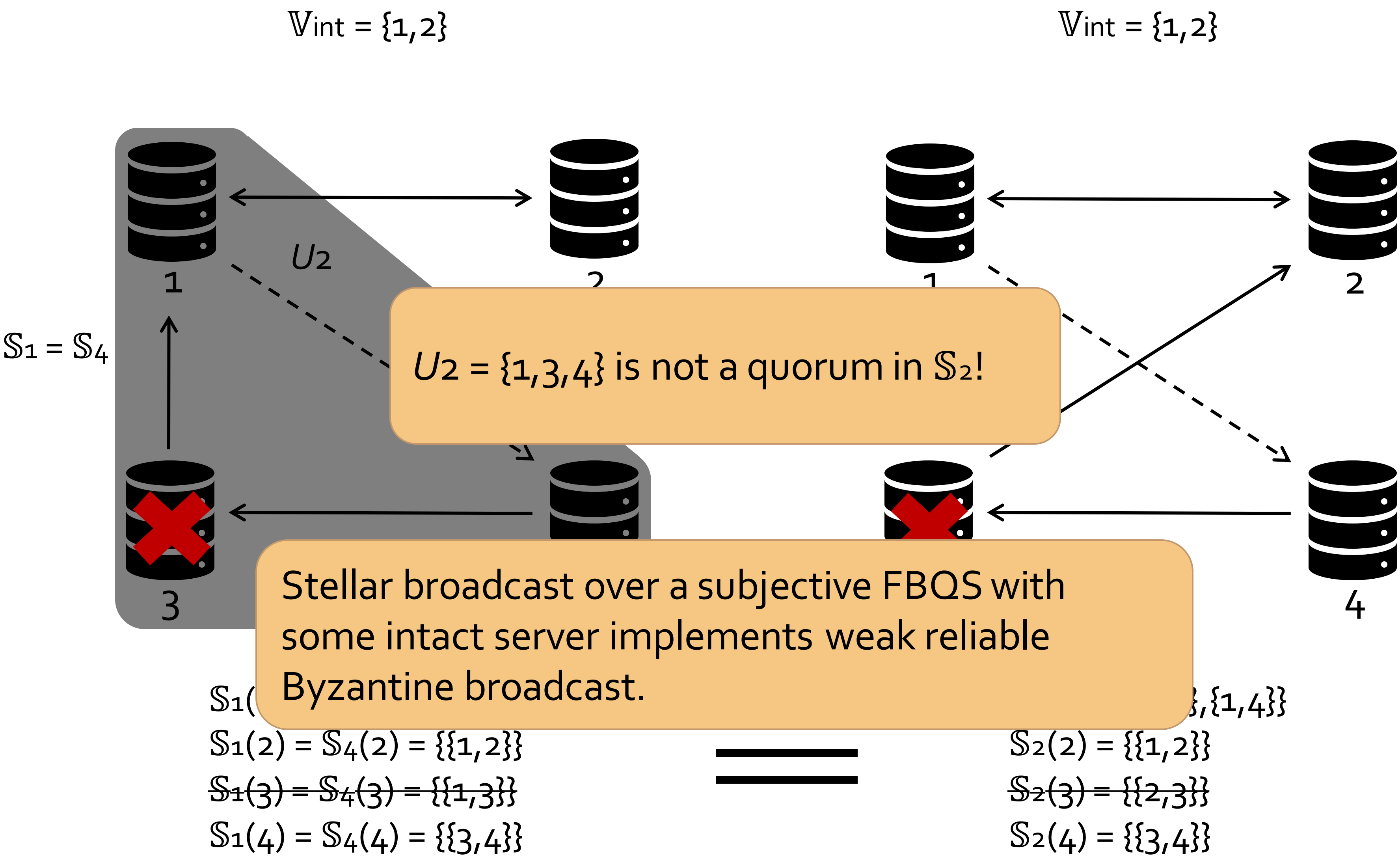


$\mathbb{S}_1(1) = \mathbb{S}_4(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_1(2) = \mathbb{S}_4(2) = \{\{1,2\}\}$
$\cancel{\mathbb{S}_1(3) = \mathbb{S}_4(3) = \{\{1,3\}\}}$
$\mathbb{S}_1(4) = \mathbb{S}_4(4) = \{\{3,4\}\}$

=

$\mathbb{S}_2(1) = \{\{1,2\},\{1,4\}\}$
$\mathbb{S}_2(2) = \{\{1,2\}\}$
$\cancel{\mathbb{S}_2(3) = \{\{2,3\}\}}$
$\mathbb{S}_2(4) = \{\{3,4\}\}$

Subjective FBQS



$U_2 = \{1,3,4\}$ is not a quorum in $\mathbb{S}_2$!

Stellar broadcast over a subjective FBQS with some intact server implements weak reliable Byzantine broadcast.

Work in progress

- Proof of correctness of the whole Stellar consensus protocol.
- Relation between Stellar consensus and existing BFT algorithms.

Conclusions

- An FBQS maps into a DQS, so off-the-shelf DQS algorithms can be run over FBQS:
  - Trade-off between servers relying on global/local information and liveness properties for correct/intact servers.
- If the set of intact servers coincides with the set of correct servers, then Stellar broadcast and Bracha broadcast are observtionally equivalent.
- We prove Stellar broadcast correct when servers lie about their slices.

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Thanks!