

STELLAR CONSENSUS PROTOCOL

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ABSTRACT. This is my personal notes on the Stellar consensus protocol. This roughly follows the structure of the white paper on <https://www.stellar.org/>.

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1. BASIC PROPERTIES OF QUORUMS

Definition 1.1. Let V be a set and $Q : V \rightarrow 2^V \setminus \{\emptyset\}$ be a function such that $\forall v \in V, \forall q \in Q(v), v \in q$. Then we call the pair $\langle V, Q \rangle$ a federated Byzantine agreement system, or FBAS for short.

Definition 1.2. Let $\langle V, Q \rangle$ be an FBAS. $U \subset V$ is called a quorum if and only if $\forall v \in U, \exists q \in Q(v), q \subset U$.

Theorem 1.3. In an FBAS $\langle V, Q \rangle$, the union of two quorums is a quorum.

Proof. Let U_1, U_2 be two quorums. Let $v \in U_1 \cup U_2$. Then $v \in U_i$ for $i = 1$ or $i = 2$. Then $q \subset U_i$ for some $q \in Q(v)$. Therefore, $q \subset U_1 \cup U_2$, so $U_1 \cup U_2$ is indeed a quorum. \square

Theorem 1.4. In an FBAS $\langle V, Q \rangle$, V is a quorum.

Proof. For any $v \in V$, for any $q \in Q(v)$, $q \subset V$. Therefore, V is indeed a quorum. \square

Example 1.5. One might wonder if the intersection of quorums is always a quorum. However, this is not true in general.

Let $V = \{v_1, \dots, v_4\}$ and

- $Q(v_1) = \{\{v_1, v_2, v_3\}, \{v_1, v_2, v_4\}, \{v_1, v_3, v_4\}\},$
- \vdots
- $Q(v_4) = \{\{v_1, v_2, v_4\}, \{v_1, v_3, v_4\}, \{v_2, v_3, v_4\}\}.$

In other words, $Q(v_i) = \{U \mid U \in 2^V, v_i \in U\}$.

Then $U_1 = \{v_1, v_2, v_3\}$ is a quorum, and $U_2 = \{v_2, v_3, v_4\}$ is a quorum. However, $U_1 \cap U_2 = \{v_2, v_3\}$ is not a quorum because the size of any quorum slice is 3.

Definition 1.6. Let $\langle V, Q \rangle$ be an FBAS. We say $\langle V, Q \rangle$ enjoys quorum intersection if and only if for any pair of quorums U_1, U_2 , $U_1 \cap U_2 \neq \emptyset$.

Definition 1.7. Let $\langle V, Q \rangle$ be an FBAS and $B \subset V$. Then the FBAS $\langle V, Q \rangle^B$ is defined to be $\langle V \setminus B, Q^B \rangle$ where $\forall v \in V, Q^B(v) = \{q \setminus B \mid q \in Q(v)\}$.

Theorem 1.8. *Definition 1.7 is well-defined. In other words, if $\langle V, Q \rangle$ is an FBAS and $B \subset V$, then $\langle V, Q \rangle^B$ is an FBAS.*

Proof. Let $v \in V \setminus B, q' \in Q^B(v)$ be given. Then $q' = q \setminus B$ for some $q \in Q(v)$. By the definition of an FBAS, $v \in q$. Since $v \notin B$, $v \in q \setminus B = q'$. Therefore, $\langle V, Q \rangle^B$ is an FBAS. \square

Theorem 1.9. *Let U be a quorum in FBAS $\langle V, Q \rangle$, let $B \subset V$ be a set of nodes, and let $U' = U \setminus B$. If $U' \neq \emptyset$, then U' is a quorum in $\langle V, Q \rangle^B$.*

Proof. Since $U' \neq \emptyset$, it suffices to show that $\forall v \in U', \exists q \in Q^B(v), q \subset U'$. Let $v \in U'$. Then $v \in U$. Since U is a quorum in $\langle V, Q \rangle$, we can find $q \in Q(v)$ such that $q \subset U$. Then $q' = q \setminus B \in Q^B(v)$, and $q' = q \setminus B \subset U \setminus B = U'$. Therefore, U' is a quorum in $\langle V, Q \rangle^B$. \square

Definition 1.10. Let $\langle V, Q \rangle$ be an FBAS and $B \subset V$ be a set of nodes. We say $\langle V, Q \rangle$ enjoys quorum intersection despite B if and only if $\langle V, Q \rangle^B$ enjoys quorum intersection.

Definition 1.11. Let $\langle V, Q \rangle$ be an FBAS and $B \subset V$ be a set of nodes. We say $\langle V, Q \rangle$ enjoys quorum availability despite B if and only if $V \setminus B$ is a quorum in $\langle V, Q \rangle$ or $B = V$.

Definition 1.12. Let $\langle V, Q \rangle$ be an FBAS. Let $v \in V$. A subset $B \subset V$ is called v -blocking if and only if $\forall q \in Q(v), q \cap B \neq \emptyset$.

Theorem 1.13. *Let $\langle V, Q \rangle$ be an FBAS. Let $v \in V$. Then*

- *The union of two v -blocking sets is v -blocking.*
- *Any superset of a v -blocking set is v -blocking.*

Proof. If B, B' are v -blocking, then $q \cap (B \cup B') = (q \cap B) \cup (q \cap B') \neq \emptyset$ for any $q \in Q(v)$ because the union of two nonempty sets is nonempty. If $B \subset B'$ and B is v -blocking, $q \cap B' \supset q \cap B \neq \emptyset$ for any $q \in Q(v)$. \square

Theorem 1.14. *Let $\langle V, Q \rangle$ be an FBAS. Let $B \subset V$. $\langle V, Q \rangle$ enjoys quorum availability despite B if and only if B is not v -blocking for any $v \in V \setminus B$.*

Proof.

$$\begin{aligned}
\forall v \in V \setminus B, \neg(B \text{ is } v\text{-blocking}) &\iff \forall v \in V \setminus B, \neg(\forall q \in Q(v), q \cap B \neq \emptyset) \\
&\iff \forall v \in V \setminus B, \exists q \in Q(v), q \cap B = \emptyset \\
&\iff \forall v \in V \setminus B, \exists q \in Q(v), q \subset V \setminus B \\
&\iff V = B \text{ or } V \setminus B \text{ is a quorum in } \langle V, Q \rangle \\
&\iff \langle V, Q \rangle \text{ enjoys quorum availability despite } B
\end{aligned}$$

\square

Theorem 1.15. *Let $\langle V, Q \rangle$ be an FBAS with quorum intersection. Let I, B denote the sets of intact and befouled nodes, respectively. Let U be a quorum such that $U \cap I \neq \emptyset$. For any set $U \subset S \subset I$,*

2. DISPENSABLE SETS

Definition 2.1. Let $\langle V, Q \rangle$ be an FBAS and $B \subset V$ be a set of nodes. B is called a dispensable set, or DSet, if and only if $\langle V, Q \rangle$ enjoys quorum intersection and availability despite B .

Definition 2.2. Let $\langle V, Q \rangle$ be an FBAS and $v \in V$. v is said to be intact if and only if there exists a DSet B containing all ill-behaved nodes and $v \notin B$. v is said to be befouled if and only if v is not intact.

Theorem 2.3. If B_1 and B_2 are DSets in an FBAS $\langle V, Q \rangle$ enjoying quorum intersection, then $B = B_1 \cap B_2$ is a DSet, too.

Proof. If $B_1 = V$ or $B_2 = V$, then we are done. Suppose otherwise.

For any $v \in V$,

$$\begin{aligned}
 v \in V \setminus B &\iff v \in V \wedge v \notin B \\
 &\iff v \in V \wedge (v \notin B_1 \vee v \notin B_2) \\
 &\iff (v \in V \wedge v \notin B_1) \vee (v \in V \wedge v \notin B_2) \\
 &\iff (v \in (V \setminus B_1)) \vee (v \in (V \setminus B_2)) \\
 &\iff v \in ((V \setminus B_1) \cup (V \setminus B_2)).
 \end{aligned}$$

Thus, $V \setminus B = (V \setminus B_1) \cup (V \setminus B_2)$. By the definition of a DSet, $V \setminus B_1$ and $V \setminus B_2$ are both quorums in $\langle V, Q \rangle$. By Theorem 1.3, $V \setminus B$ is a quorum in $\langle V, Q \rangle$.

We must now show quorum intersection despite B . Let U_a, U_b be quorums in $\langle V, Q \rangle^B$.

- $U_a \setminus B_1$ is a quorum in $(\langle V, Q \rangle^B)^{B_1} = \langle V, Q \rangle^{B_1}$ by Theorem 1.7.
- Similarly, $U_b \setminus B_1$ is a quorum in $\langle V, Q \rangle^{B_1}$, and $U_a \setminus B_2$ and $U_b \setminus B_2$ are both quorums in $\langle V, Q \rangle^{B_2}$.

$$\begin{aligned}
 (U_a \setminus B_1) \cup (U_a \setminus B_2) &= U_a \setminus (B_1 \cap B_2) \\
 &= U_a \setminus B \\
 &= U_a
 \end{aligned}$$

because U_a is a quorum in $\langle V, Q \rangle^B$. In other words, $(U_a \setminus B_1) \cup (U_a \setminus B_2) \neq \emptyset$. Similarly, $(U_b \setminus B_1) \cup (U_b \setminus B_2) \neq \emptyset$.

Without loss of generality, assume that $U_a \setminus B_1 \neq \emptyset$.

- $V \setminus B_1$ is a quorum in $\langle V, Q \rangle$ because B_1 is a DSet. Similarly, $V \setminus B_2$ is a quorum in $\langle V, Q \rangle$. Because $\langle V, Q \rangle$ enjoys quorum intersection, $(V \setminus B_1) \cap (V \setminus B_2) \neq \emptyset$. In other words, $(V \setminus B_2) \setminus B_1$ is a quorum. By Theorem 1.7, $(V \setminus B_2) \setminus B_1$ is a quorum in $\langle V, Q \rangle^{B_1}$.
- $U_a \setminus B_1$ is a quorum in $(\langle V, Q \rangle^B)^{B_1} = \langle V, Q \rangle^{B_1}$ for the same reason.

Because B_1 is a DSet in $\langle V, Q \rangle$, $\langle V, Q \rangle^{B_1}$ enjoys quorum intersection. Therefore, $(U_a \setminus B_1) \cap ((V \setminus B_2) \setminus B_1) \neq \emptyset$.

$$\begin{aligned} (U_a \setminus B_1) \cap ((V \setminus B_2) \setminus B_1) &= (U_a \cap (V \setminus B_2)) \setminus B_1 \\ &\subset U_a \cap (V \setminus B_2) \\ &= (U_a \cap V) \setminus B_2 \\ &= U_a \setminus B_2. \end{aligned}$$

Thus, $U_a \setminus B_2 \neq \emptyset$. Using the same argument, we can show that $U_b \setminus B_1 \neq \emptyset$ and $U_b \setminus B_2 \neq \emptyset$. Since $U_a \setminus B_1$ and $U_b \setminus B_1$ are quorums in $\langle V, Q \rangle^{B_1}$ and B_1 is a DSet, $(U_a \setminus B_1) \cap (U_b \setminus B_1) \neq \emptyset$ by the definition of a DSet. This implies $(U_a \cap U_b) \setminus B_1 \neq \emptyset$. Therefore, $U_a \cap U_b \neq \emptyset$. \square

Theorem 2.4. *In an FBAS with quorum intersection, the set of befouled nodes is a DSet.*

Proof. Let $\langle V, Q \rangle$ be an FBAS with quorum intersection. Let B be the intersection of all DSets that contain all ill-behaved nodes. By Theorem 2.3, B is a DSet.

- Case 1: $v \in B$. Then there exists no DSet B_v such that B_v contains all ill-behaved nodes and $v \notin B_v$. Therefore, v is not an intact node. In other words, v is a befouled node.
- Case 2: $v \notin B$. Then there exists a DSet B_v that contains all ill-behaved nodes and $v \notin B_v$. In other words, v is intact and thus v is not a befouled node.

Therefore, B is precisely the set of befouled nodes and it is a DSet. \square

Theorem 2.5. *Let $\langle V, Q \rangle$ be an FBAS and let $B \subset V$ be the set of befouled nodes. If B is a DSet, B is not v -blocking for any intact v .*

Proof. By Definition 2.2, a node $v \in V$ is intact if and only if $v \notin B$. By Theorem 1.14, $\langle V, Q \rangle$ enjoys quorum availability despite B if and only if B is not v -blocking for any $v \in V \setminus B$. Since B is a DSet, $\langle V, Q \rangle$ enjoys quorum availability despite B . Thus B is not v -blocking for any intact v . \square

3. VOTING, ACCEPTING, AND RATIFYING

Definition 3.1. A node v votes for a statement a if and only if v asserts

- a is valid,
- a is consistent with all statements v has accepted,
- v has never voted against a ,
- v promises never to vote against a in the future.

Definition 3.2. Let $\langle V, Q \rangle$ be an FBAS, and let $v \in V$. v accepts a statement a if and only if

- It has never accepted a statement contradicting a .
- It determines that either
 - There exists a quorum such that $v \in U$ and each member of U either voted for a or told v that it has accepted a , or
 - There exists a v -blocking set B such that every member of B told v that it has accepted a .

Note that it is possible for a node to accept a statement it did not vote for. Furthermore, it is possible for a node to accept a statement after voting for a contradictory statement.

Definition 3.3. A quorum U_a ratifies a statement a if and only if every member of U_a votes for a . A node v ratifies a if and only if v is a member of a quorum U_a that ratifies a .

Theorem 3.4. Let $\langle V, Q \rangle$ be an FBAS. If a node $v \in V$ ratifies a statement a , then it must accept a .

Proof. If a node v ratifies a , then it is a member of a quorum $U \subset V$ that ratifies a . Thus every member of U votes for a . This implies that v also votes for a . By Definition 3.1, v has never accepted a statement contradicting a . By Definition 3.2, v accepts a . \square

Theorem 3.5. If an FBAS enjoys quorum intersection and contains no ill-behaved node, then two contradictory statements cannot be both ratified.

Proof. Suppose the statement is false and let a, \bar{a} denote two contradictory statements ratified in such an FBAS. Let $U_a, U_{\bar{a}}$ denote quorums ratifying such statements, respectively. By the definition of quorum intersection, $U_a \cap U_{\bar{a}} \neq \emptyset$. Let $v \in U_a \cap U_{\bar{a}}$. This implies that v voted for both a and \bar{a} . However, this goes against the definition of voting. In other words, v must be ill-behaved, which is a contradiction to our assumption. \square

Theorem 3.6. Let $\langle V, Q \rangle$ be an FBAS. Let $B \subsetneq V$ be a subset containing all the ill-behaved nodes and suppose that $\langle V, Q \rangle^B$ enjoys quorum intersection. Let $v_1 \neq v_2 \in V \setminus B$. If v_1 ratifies a statement a , then v_2 cannot ratify any statement that contradicts a .

Proof. Suppose that the theorem is false and let U_1, U_2 be quorums of v_1, v_2 that ratify a, \bar{a} , respectively where a and \bar{a} are contradictory. Since $v_1 \in U_1 \setminus B$, $U_1 \setminus B \neq \emptyset$. By Theorem 1.9, $U'_1 = U_1 \setminus B$ is a quorum in $\langle V, Q \rangle^B$. Similarly, $U'_2 = U_2 \setminus B$ is a quorum in $\langle V, Q \rangle^B$. Since $\langle V, Q \rangle^B$ enjoys quorum intersection, $U'_1 \cap U'_2 \neq \emptyset$. Let $v \in U'_1 \cap U'_2$. Then $v \in U_1 \cap U_2$. In order for U_1, U_2 to ratify a, \bar{a} , respectively, v must vote for both a and \bar{a} . However, this is against the definition of voting. v must be an ill-behaved node, so $v \in B$, which is a contradiction because $v \in U_1 \setminus B$. \square

Theorem 3.7. Let $\langle V, Q \rangle$ be an FBAS with quorum intersection. Then two intact nodes in V cannot ratify contradictory statements.

Proof. Let $v \neq v'$ be two intact nodes in V . Let $B \subset V$ be the set of befouled nodes. Then $v \notin B$ and $v' \notin B$. Since $\langle V, Q \rangle$ is an FBAS with quorum intersection, B is a DSet by Theorem 2.4. By the definition of a DSet (Definition 2.1), $\langle V, Q \rangle^B$ enjoys quorum intersection. By Theorem 3.6, v, v' cannot ratify contradictory statements. \square

Lemma 3.8. Let $\langle V, Q \rangle$ be an FBAS enjoying quorum intersection and B be the set of befouled nodes. If a is accepted by an intact node in V , then a is ratified by some intact node in $\langle V, Q \rangle^B$.

Proof. Since V is finite, there has to be an intact node v such that no intact nodes in V accepted a before v .

Since $\langle V, Q \rangle$ enjoys quorum intersection, B is a DSet by Theorem 2.4. By Theorem 2.5, B is not v -blocking. Therefore, by Definition 3.2, there must exist a quorum U of v such that, before v accepted a , every member of U either voted for a or told v that it has accepted

a . Because of the way we picked v , every intact node in U must have voted for a before v accepted a . In other words, every node in $U \setminus B$ voted for a . By Theorem 1.9, v ratified a in $\langle V, Q \rangle^B$. Finally, v is indeed an intact node in $\langle V, Q \rangle^B$ because $\langle V, Q \rangle^B$ contains no ill-behaved nodes. \square

Theorem 3.9. *Two intact nodes in an FBAS $\langle V, Q \rangle$ enjoying quorum intersection cannot accept contradictory statements.*

Note that Theorem 3.9 is a stronger version of Theorem 3.7 by Theorem 3.4.

Proof. Suppose otherwise. Let a, \bar{a} be contradictory statements accepted by two intact nodes in $\langle V, Q \rangle$. By Lemma 3.8, a, \bar{a} are ratified by some intact nodes in $\langle V, Q \rangle^B$. By Definition 2.1, $\langle V, Q \rangle$ enjoys quorum intersection despite B . In other words, $\langle V, Q \rangle^B$ enjoys quorum intersection. By Theorem 3.7, a, \bar{a} cannot be ratified by v, v' in $\langle V, Q \rangle^B$, which is a contradiction. \square