The Stellar Consensus Protocol
A federated model for Internet-level consensus

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Monday, June 6, 2016
Banking system robustness

A bank’s core job is tracking customer assets and liabilities
  - Ensure robustness of ledger through replication

What about the robustness of inter-bank transfers?
  - Need trusted correspondent bank; adds delay and cost
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Banking system robustness

Migrants moving cash from Tanzania to Kenya pay average fees of 22%, but mobiles could make transfers cheaper and easier

It’s expensive to be poor

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We need an inter-financial network

Today’s financial networks like pre-Internet email
- Route a message through multiple UUCP nodes, BITNET, etc.
- Addresses not globally meaningful: host1!host2!host3!user

Can we make sending money as easy as Internet mail?

This would be possible if we had a global ledger
- Who would manage such a ledger?
- No globally trusted party or parties

We do have an existence proof of a global decentralized system: inter-domain routing

Idea: use pairwise trust to achieve secure global consensus
- Use Internet-level consensus to realize a global ledger
Consensus: The key to replication

Main challenge of replicating data is keeping copies in sync.

Common technique: *replicated state machine*

1. All replicas agree on initial state of system (easy), and
2. All replicas agree on sequence of deterministic operations

#2 requires *consensus* among replicas on each operation

- E.g., agree $\text{op}_7 = \text{credit dm }$ $150$ before considering payment settled
Outline

Byzantine agreement (background), recast in terms of voting on irrefutable & neutralizable statements

Federated Byzantine Agreement (FBA)

Optimal failure resilience

The Stellar consensus protocol (SCP)
The consensus problem

Goal: For multiple agents to agree on an output value

Each agent starts with an input value
- Typically a candidate for the $n$th op. on a replicated state machine

Agents communicate following some consensus protocol
- Use protocol to agree on one of the agent’s input values

Once decided, agents output the chosen value
- Output is write-once (an agent cannot change its value)
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Properties of a consensus protocol

A consensus protocol provides safety iff…
- All outputs produced have the same value (agreement), and
- The output value equals one of the agents’ inputs (validity)

A consensus protocol provides liveness iff…
- Eventually non-faulty agents output a value (termination)

A consensus protocol provides fault tolerance iff…
- It can recover from the failure of an agent at any point
- Fail-stop protocols handle agent crashes
- Byzantine-fault-tolerant protocols handle arbitrary agent behavior

Theorem (FLP impossibility result)
No deterministic consensus protocol can guarantee all three of safety, liveness, and fault tolerance in an asynchronous system.
Bivalent states

Recall agents chose value 9 in last example
But a network outage might be indistinguishable from $v_2$ failing
If protocol fault tolerant, $v_1$ and $v_3$ might decide to output 7
Once network back, $v_2$ must also output 7

Definition (Bivalent)
An execution of a consensus protocol is in a bivalent state when the network can affect which value agents choose.
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# Univalent and stuck states

## Definition (Univalent, Valent)

An execution of a consensus protocol is in a **univalent** state when only one output value is possible. If that value is $i$, call the state $i$-valent.

## Definition (Stuck)

An execution of a [broken] consensus protocol is in a **stuck** state when one or more non-faulty nodes can never output a value.

Recall output is write once and all outputs must agree
- Hence, no output is possible in bivalent state

If an execution starts in a bivalent state and terminates, it must at some point reach a univalent state
Consider a terminating execution of a bivalent system

Let $m$ be the last message received in a bivalent state
- Since $m$ caused transition to univalent state, call it *deciding message*

Suppose the network had delayed $m$
- Other messages could cause transitions to other bivalent states
- Then, receiving $m$ might no longer lead to a univalent state
- In this case, we say $m$ has been neutralized

**Overview of FLP proof.**

1. There are bivalent starting configurations.
2. Fault tolerance $\implies$ network can neutralize any deciding msg
3. Hence, the system can remain bivalent in perpetuity.

How can we cope? Design protocols that terminate *in practice*
- Key property: protocol must avoid stuck states
Suppose you have $N$ nodes with fail-stop behavior

Pick a quorum size $T > N/2$

If any $T$ nodes (a quorum) all vote for a value, output that value

- E.g., Quorum $A$ unanimously votes for 9, okay to output 9
- Any two quorums intersect, votes cannot change $\implies$ agreement

Problem: stuck states

- Node failure could mean not everyone learns of unanimous quorum
- Split vote could make unanimous quorum impossible
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What voting gives us

You might get system-wide agreement or you might get stuck.
Can’t vote directly on consensus question (\(\text{op}_7 \overset{?}{=} \text{credit dm $150}\))

What can we vote on without jeopardizing liveness?

1. Statements that never get stuck, and
2. Statements whose hold on consensus question can be broken if stuck.
1. Statements that never get stuck
   - Observation: stuck states arise because nodes can’t change votes
   - If nobody votes against a statement, can’t get stuck

**Definition (irrefutable)**

An **irrefutable** statement is one that correct nodes never vote against.

2. Statements whose hold on consensus question can be broken
   - Recall fault tolerance requires neutralizing deciding messages

**Definition (neutralizable)**

A **neutralizable** statement is one that can be rendered irrelevant to the consensus question.

How to formulate useful yet neutralizable statements?
Ballot-based neutralization [Paxos]

Vote to *commit* or *abort* ballots (the two are contradictory)
- Each ballot is $\langle n, x \rangle$ where $n$ is a counter and $x$ a candidate output value
- If a quorum votes to commit $\langle n, x \rangle$ (for any $n$), safe to output $x$

Invariant: all committed and stuck ballots must have same $x$

To preserve: cannot vote to commit a ballot before *preparing* it
- Prepare $\langle n, x \rangle$ by aborting all $\langle n', x' \rangle$ with $n' \leq n$ and $x' \neq x$.
- Concisely encode whole set of abort votes with PREPARE message

If ballot $\langle n, x \rangle$ stuck, neutralize by restarting with $\langle n + 1, x \rangle$
- Can prepare $\langle n + 1, x \rangle$ even if $\langle n, x \rangle$ is stuck
# Paxos example

<table>
<thead>
<tr>
<th>counter</th>
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1. Agree that \langle 1, g \rangle is prepared and vote to commit it
2. Lose vote on \langle 1, g \rangle; agree \langle 2, f \rangle prepared and vote to commit it
3. \langle 2, f \rangle is stuck, so agree \langle 3, f \rangle prepared and vote to commit it
4. See T votes to commit \langle 3, f \rangle (commit-valent) and externalize f
   - At this point nobody cares about \langle 2, f \rangle—neutralized
5. Node failure makes \langle 3, f \rangle stuck, prepare and commit \langle 4, f \rangle
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**candidate values**

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What if nodes may experience Byzantine failure?

- Byzantine nodes can illegally change their votes
- In fail-stop case, safety required any two quorums to share a node
- Now, any two quorums to share a non-faulty node

**Safety requires:** \# failures \( \leq f_S = 2T - N - 1 \)

**Liveness requires:** \# failures \( \leq f_L = N - T \)
- At least one entirely non-faulty quorum exists

**Longstanding practical protocols exist** [Castro’99]
- Typically \( N = 3f + 1 \) and \( T = 2f + 1 \) to tolerate \( f_S = f_L = f \) failures
Byzantine agreement

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When has a vote succeeded?

If $f_S + 1 = 2T - N$ nodes malicious, system loses safety

Suppose $f_S + 1$ nodes all claim to have seen $T$ votes for $a$
- Can assume system is $a$-valent with no loss of safety

Now say $f_L + f_S + 1 = T$ nodes all make same assertion
- If $> f_L$ fail, system loses liveness (0 correct nodes in whole system)
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Federated Byzantine Agreement (FBA)

FBA is a generalization of the Byzantine agreement problem
- Byzantine agreement without magically blessing $N$ nodes

Idea: determine quorums in decentralized way
- Each node $v$ picks one or more quorum slices, where $v$ in all its slices
- $v$ requires any quorum to contain at least one of its slices
- Slice inclusion analogous to Internet peering/transit between ISPs

Definition (Federated Byzantine Agreement System)
An FBAS is of a set of nodes $V$ and a quorum function $Q$, where $Q(v)$ is the set slices chosen by node $v$.

Definition (Quorum)
A quorum $U \subseteq V$ is a set of nodes that contains at least one slice of each of its members: $\forall v \in U, \exists q \in Q(v)$ such that $q \subseteq U$
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**Visualize quorum slice dependencies with arrows**

$v_2, v_3, v_4$ is a quorum—contains a slice of each member
$v_1, v_2, v_3$ is a slice for $v_1$, but not a quorum
  - Doesn’t contain a slice for $v_2, v_3$, who demand $v_4$’s agreement

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Tiered quorum slice example

Top tier: slice is three out of \( \{v_1, v_2, v_3, v_4\} \) (including self)

Middle tier: slice is self + any two top tier nodes

Leaf tier: slice is self + any two middle tier nodes

Like the internet, no central authority appoints top tier
- But market can decide on \textit{de facto} tier one organizations
- Don’t even require exact agreement on who is a top tier node
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- Colludes to reverse transaction and double-spend same money to $v_8$
- Stellar & EFF won’t revert, so ACLU cannot accept and $v_8$ won’t either
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Tiered quorum slice example

Example: Citibank pays $1,000,000,000 to \( v_7 \)
- Colludes to reverse transaction and double-spend same money to \( v_8 \)
- Stellar & EFF won’t revert, so ACLU cannot accept and \( v_8 \) won’t either

I don’t believe anything unless EFF or Stellar does
Outline

Byzantine agreement (background), recast in terms of voting on irrefutable & neutralizable statements

Federated Byzantine Agreement (FBA)

Optimal failure resilience

The Stellar consensus protocol (SCP)
FBAS failure is per-node

Each node is either well-behaved or ill-behaved

All ill-behaved nodes have failed

Enough ill-behaved nodes can cause well-behaved nodes to fail
  - Bad: well-behaved nodes that cannot make progress (safe but not live)
  - Worse: well-behaved nodes in divergent states (not safe)

Well-behaved nodes are correct if they have not failed
What is necessary to guarantee safety?

Suppose there are two entirely disjoint quorums
- Each can make progress with no communication from the other
- No way to guarantee the two externalize consistent statements

Like traditional consensus, safety requires quorum intersection

Definition (Quorum intersection)
An FBAS enjoys quorum intersection when every two quorums share at least one node.
What about Byzantine failures?

Suppose two quorums intersect only at Byzantine nodes
- Byzantine nodes behave arbitrarily
- Can feed inconsistent data to different honest nodes
- No way to guarantee safety

Necessary property for safety with Byzantine failures:
Quorum intersection **despite ill-behaved nodes**
- Means deleting ill-behaved nodes doesn’t undermine intersection
- In this example, reduces to diagram on previous slide
What about Byzantine failures?

\[
\begin{align*}
Q(v_1) &= \{v_1, v_2, v_3, v_7\} \\
Q(v_2) &= \{v_1, v_2, v_3, v_7\} \\
Q(v_3) &= \{v_1, v_2, v_3, v_7\}
\end{align*}
\]

Suppose two quorums intersect only at Byzantine nodes
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- Means deleting ill-behaved nodes doesn’t undermine intersection
- In this example, reduces to diagram on previous slide
What is necessary to guarantee liveness?

Suppose each of \( v_1 \)'s slices contains a Byzantine node
- Byzantine includes crashed—might not agree to anything
- Impossible to guarantee liveness for \( v_1 \)

Definition (\( \nu \)-blocking)
A \( \nu \)-blocking set contains at least one node from each of \( \nu \)'s slices.

Failed nodes cannot be \( \nu \)-blocking for any correct node \( \nu \)
- Equivalent to saying correct nodes form a quorum

Necessary property for liveness: Correct nodes form a quorum
What is necessary to guarantee liveness?

\[ Q(v_1) = v_1 \text{ plus two of } \{v_2, v_3, v_4\} \]
\[ Q(v_2) = v_2 \text{ plus two of } \{v_1, v_3, v_4\} \]

Suppose each of \( v_1 \)'s slices contains a Byzantine node

- Byzantine includes crashed—might not agree to anything
- Impossible to guarantee liveness for \( v_1 \)

**Definition (\( v \)-blocking)**

A **\( v \)-blocking** set contains at least one node from each of \( v \)'s slices.

Failed nodes cannot be **\( v \)-blocking** for any correct node \( v \)

- Equivalent to saying correct nodes form a quorum

**Necessary property for liveness:** Correct nodes form a quorum
Summary of failure resilience

Suppose $U$ is a set of well-behaved nodes in an FBAS
- Let $\bar{U}$ be the nodes not in $U$—might be ill-behaved

An FBAS can guarantee safety for $U$ only if:
1. $U$ enjoys quorum intersection despite $\bar{U}$.

Can guarantee correctness (safety+liveness) for $U$ only if:
1. $U$ enjoys quorum intersection despite $\bar{U}$, and
2. $U$ is a quorum (equivalently, $\bar{U}$ is not $v$-blocking for any $v \in U$).

**Definition (intact)**

A node is **intact** if it is in a set $U$ satisfying 1 and 2 above.

**Theorem:** Quorum intersection implies one maximal intact set $U$
- Without quorum intersection, must subjectively assign blame and (conceptually) delete bad nodes to make notion of intact useful.
Outline

Byzantine agreement (background), recast in terms of voting on irrefutable & neutralizable statements

Federated Byzantine Agreement (FBA)

Optimal failure resilience

The Stellar consensus protocol (SCP)
The Stellar Consensus Protocol [SCP]

First general FBA protocol

Guarantees safety for well-behaved nodes that enjoy quorum intersection despite ill-behaved nodes

- Means too many ill-behaved nodes can still cause divergence… but only if no other FBA protocol could guarantee safety, either

Guarantees intact nodes will not get stuck

Core idea: *federated voting*

- Nodes exchange vote messages to agree on statements
- Every message also specifies the voter’s quorum slices
- Allows dynamic quorum discovery while assembling votes
Federated voting

As before, each node $v$ can vote for a statement $a$
  - $a$ must be consistent with past votes & accepted statements

**Definition (ratify)**

A quorum $U$ ratifies a statement $a$ iff every member of $U$ votes for $a$.
A node $v$ ratifies $a$ iff $v$ is a member of a quorum $U$ that ratifies $a$.

Theorem: if well-behaved nodes enjoy quorum intersection despite ill-behaved nodes, won’t ratify contradictory statements

Problem: intact node $v$ may be unable to ratify $a$ after others do
  - $v$ or nodes in $v$’s slices might have voted against $a$, or
  - Some nodes that voted for $a$ may subsequently have failed
Federated voting has same possible outcomes as regular voting

Apply the same reasoning as in centralized voting?
- Premise was whole system couldn’t fail; now failure is per node
- Cannot assume correctness of quorums you don’t belong to

First-hand ratification now the only way to know system $a$-valent
- How to agree on statement $a$ even after voting against it?
- How to know system has agreed on $a$?
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- How to know system has agreed on $a$?
Accepting

Idea: say a $\nu$-blocking set claims system is $\alpha$-valent
- Either whole set lying (so $\nu$ is not intact), or system in fact $\alpha$-valent

**Definition (accept)**

Node $\nu$ accepts a statement $\alpha$ consistent with history iff either:
1. A quorum containing $\nu$ each either voted for or accepted $\alpha$, or
2. Each member of a $\nu$-blocking set claims to accept $\alpha$.

#2 allows a node to accept a statement after voting against it

Theorem: intact nodes cannot accept contradictory statements

But two problems remain:
1. Still no guarantee all intact nodes can accept a statement
2. Suboptimal safety for non-intact nodes enjoying quorum intersection ($\nu$-blocking analogous to $f_L + 1$ in centralized system, not $f_S + 1$)
Confirmation

Idea: Hold a second vote on the fact that the first vote succeeded

**Definition (confirm)**

A quorum *confirms* a statement $a$ by ratifying the statement “We accepted $a$.” A node *confirms* $a$ iff it is in such a quorum.

Solves problem 2 (suboptimal safety)

- Straight-up ratification provides optimal safety

Solves problem 1 (intact nodes unable to accept)

- Intact nodes may vote against accepted statements
- Won’t vote against the *fact* that those statements were accepted
- Hence, the fact of acceptance is irrefutable

Theorem: Once a single intact node confirms a statement, all intact nodes will eventually confirm it
Summary of federated voting process

A node $\nu$ that locally confirms $a$ knows system has agreed on $a$

- Nodes enjoying quorum intersection with $\nu$ despite ill-behaved nodes will not contradict $a$
- If $\nu$ is intact, all other intact nodes will eventually confirm $a$
From voting to consensus

Like Paxos, vote to *commit* or *abort* ballots
- Each ballot is $\langle n, x \rangle$ where $x$ is candidate consensus value
- Committing $\langle n, x \rangle$ choses $x$ as the value

Same invariant: all committed & stuck ballots must have same $x$

Must *prepare* ballot $\langle n, x \rangle$ before voting to commit it:
- For convenience, totally order ballots with $n$ most significant
- Prepare means agree to abort all $\langle n', x' \rangle < \langle n, x \rangle$ such that $x' \neq x$

If ballot $\langle n, x \rangle$ stuck, neutralize it by trying again with $\langle n + 1, x \rangle$

Also in paper: decentralized nomination protocol
- Tells you how to select $x$ for system to terminate in practice
- Key idea: no way to vote against nominating value, so irrefutable
## Summary of properties

<table>
<thead>
<tr>
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<th>low latency</th>
<th>flexible trust</th>
<th>asympt. security</th>
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<td>maybe</td>
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</tbody>
</table>

**Note consensus ≠ cryptocurrency! SCP does not:**

- ✗ Offer a rate-limited way to distribute (“mint”) new digital coins
- ✗ Provide intrinsic incentives for good behavior
- ✗ Tell you whom to trust (some good configurations, some bad)

**SCP has applications beyond financial networks**
Problem: One bad certificate authority (CA) undermines TLS
- E.g., Turktrust issued fake Google certificates [ArsTechnica’13]
- Even more important for end-to-end email encryption

Can be addressed by auditing [certificate transparency], [CONIKS]

SCP can increase confidence in the auditing process
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SCP can increase confidence in the auditing process
As of February, 200 MFIs can transact with Stellar and Oradian [Techpoint][Forbes][IBTimes][TechCrunch].
We’re hiring!

https://www.stellar.org/
View-based neutralization [Oki]

Instead of voting on $\text{op}_1, \ldots$ directly, vote on $\langle \text{view 1}, \text{op}_1 \rangle, \ldots$
- Each $\langle \text{view}, \text{op} \rangle$ selected by a single leader for view, so irrefutable
- E.g., chose leader by round-robin using $\text{view} \# \mod N$

What if votes on $\text{op}_4$ and $\text{op}_5$ are stuck (e.g., leader fails)?
- Neutralize by agreeing view 1 had only 3 meaningful operations
- Vote to form view 2 that immediately follows $\langle \text{view 1}, \text{op}_3 \rangle$

Failed to form view 2 (e.g., because a node wants $\langle \text{view 1}, \text{op}_4 \rangle$)?
- Just go on to form view 3 after $\langle \text{view 1}, \text{op}_4 \rangle$
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Properties of Byzantine agreement

+ **Low latency** – by human standards
  - E.g., might require 5 communication rounds in common case

+ **Flexible trust** – The $N$ nodes can include anyone appropriate
  - E.g., small nonprofit can help keep big banks honest

+ **Asymptotic security** – based on standard cryptography
  - Can tune to resist attackers with arbitrary computational power

– **Centralized control** – who chooses the $N$ nodes?
  - Imagine if one party dictated all tier-one ISPs worldwide
  - Makes Byzantine agreement totally unsuitable for global ledger
  - Yet Bitcoin provides overwhelming evidence of the utility of decentralized consensus
Proof-of-work-based consensus

Digitally sign transaction history with *DMMS*
- Dynamic Membership Multi-party Signature
- Cost requires worldwide collaboration
- Each signature compounds security

Motivate attackers to participate in DMMS
- Reward participation with coin distribution or transaction fees

+ Completely decentralized and open membership
  - Bitcoin introduced it, achieved astounding impact
  - Clearly the missing ingredient from past consensus approaches

– Lacks benefits of Byzantine agreement
  - High latency, trust determined by computing power, modest computational security assumes rational attackers
Living with FLP

General plan: devise protocols that terminate *in practice*
- …unless the network exhibits truly pathological behavior

**FLP is for deterministic algorithms**—so randomize [Ben-Or]
- Bivalent? Keep flipping a coin in a series of rounds
- Terminates with probability 1, but expected time $\Omega \left( \frac{2^\#\text{nodes}}{p_{\text{num}}} \right)$
- Fancy crypto can help [Rabin], but often assumes trusted dealer

**FLP is for asynchronous systems**—so assume synchrony [DLS]
- E.g., long enough timeout means node has failed
- Ideally only liveness, not safety rests on this assumption

**Key property**: protocol must avoid stuck states
- Hence, can always hope for better luck or lengthen timeouts
Cyclic quorum slice example

\[ Q(v_i) = \{ \{ v_i, v(i \mod 6) + 1 \} \} \]

Traditional Byzantine agreement requires \( \forall (i, j), Q(v_i) = Q(v_j) \)
- Means no distinction between quorums and quorum slices

**Federated** Byzantine agreement accommodates different slices
- May even have disjoint slices if you have cycles
- Shouldn’t necessarily invalidate safety guarantees