The Stellar Consensus Protocol (SCP)
draft-mazieres-dinrg-scp-04

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Motivation: Internet-level consensus

Atomically transact across incompatible/distrustful systems
- E.g., Transfer domain name in exchange for payment
- Can we leverage “the Internet” and its decentralized governance to create a secure, reliable two-phase commit coordinator?

Irrevocably delegate identifiers
- E.g., certify email user public key w/o ability to equivocate
- Can “the Internet” enforce delegation rules?

Verify public disclosure & timestamp of information
- Build IoT device that only upgrades to public firmware
- Can “the Internet” maintain a software transparency log?

All of these can be addressed w. public append-only log
What is the Internet?

We think of IANA, ICANN, recursive delegation

- But if Google, Netflix, Amazon, Comcast, etc. moved to a parallel IP network, most people in US wouldn’t care about IANA or ICANN
- People in China care about different sites—can’t even reach Google

Hypothesis: all notions of the Internet transitively converge

- Inherent Brinkmanship to network build out of pairwise peering
- But huge disincentive to leaving keeps network transitively connected
Consensus based on Internet hypothesis

Idea: Everyone picks a quorum slice that speaks for the Internet
- E.g., I pick Stanford, IETF
- You pick Baidu, Wechat, Alibaba
- Alibaba and Stanford both include Google in their quorum slices
- Transitively, we both depend on Google
- Want guaranteed agreement so long as Google honest

For fault tolerance, pick multiple quorum slices
- E.g., depend on 4/5 FAANG companies
- More realistically 3/4 of servers from each of 5 FAANGs

Define quorums as transitive closure of slices
- Let $V$ be all nodes, $Q(v)$ be all of node $v$’s quorum slices

**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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$Q(v_1) = \{\{v_1, v_2, v_3\}\}$

$Q(v_2) = Q(v_3) = Q(v_4) = \{\{v_2, v_3, v_4\}\}$

**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

$v_1, \ldots, v_4$ is the smallest quorum containing $v_1$
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\[
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Quorum slice representation

```c
struct SCPSlices {
    uint32 threshold; // the k in k-of-n
    PublicKey validators<>
    SCPSlices1 innerSets<>
};

struct SCPSlices1 {
    uint32 threshold; // the k in k-of-n
    PublicKey validators<>
    SCPSlices2 innerSets<>
};

struct SCPSlices2 {
    uint32 threshold; // the k in k-of-n
    PublicKey validators<>
};
```

Can’t represent arbitrary quorum slices compactly

Instead, use k-of-n configuration that can recurse twice

- E.g., allows policies like 51% of each organization for 3/4 of organizations
Vote messages

```c
struct SCPStatement {
    PublicKey nodeID;  // v (node signing message)
    uint64 slotIndex;
    Hash quorumSetHash;
    union switch (SCPStatementType type) {
        case SCP_ST_PREPARE:
            SCPPrepare prepare;
        case SCP_ST_COMMIT:
            SCPCommit commit;
        case SCP_ST_EXTERNALIZE:
            SCPExternalize externalize;
        case SCP_ST_NOMINATE:
            SCPNominate nominate;
    } pledges;
};

struct SCPEnvelope {
    SCPStatement statement;
    Signature signature;
};
```

Transmit quorum slices as SHA-256 hash of SCPQuorumSet
- Use side protocol to request preimage if not cached
Nodes vote for or against a conceptual statement $a$

Can’t *accept* contradictory statements if quorum intersection despite faulty nodes (intertwined) and in honest quorum (intact)

Can’t *confirm* contradictory statements if intertwined

Could get stuck in *voted* or *accepted* stage

- But if one intact node *confirms* statement, all will
Federated voting outcomes

If you can vote for or against statement \( a \), vote may get stuck
- E.g., split vote precludes quorum (since no way to change vote)
- Or was quorum but nodes failed before everyone learned of it

If you can’t vote against \( a \), then vote can always terminate
- As long as there’s a non-failed quorum, it can always vote for \( a \)
- Call \( a \) irrefutable if honest nodes can’t vote against it
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- Call $a$ irrefutable if honest nodes can’t vote against it
SCP nomination message

typedef opaque Value<>;

struct SCPNominate {
    Value voted<>; // vote to nominate these values
    Value accepted<>; // assert that these are accepted
};

union SCPStatement switch (SCPStatementType type) {
    case SCP_ST_NOMINATE:
        SCPNominate nominate;
    /* ... */
};

Nodes broadcast nominated values in voted
- Initially vote values in all received votes (ignoring optimization here)

Upon accepting nomination of a, move from voted to accepted
Stop voting for new values once any is confirmed nominated
- But continue accepting and repeating votes already cast

New: stop sending SCPNominate when ballot confirmed prepared
- Means NOMINATION phase overlaps with PREPARE phase
Nodes nominate values and re-nominate any nominations seen

Stop adding to votes once any value confirmed nominated

Nomination irrefutable, so will converge on set of values

Deterministically combine nominations into *composite* value $\chi$

Nodes guaranteed to converge on same value $\chi$

- Complication: impossible to know when protocol has converged [FLP]
- c.f. asynchronous reliable broadcast
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Nomination flow

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SCP ballots

```c
struct SCPBallot {
    uint32 counter;  // n
    Value value;      // x
};
```

Composite nomination output must be run through balloting

- Guarantees safety even if started before nomination converges

A ballot \( b \) is a pair \( \langle b\text{.counter}, b\text{.value} \rangle \) where \( b\text{.counter} \) is a candidate output value

- Ballots totally ordered with \( \text{counter} \) more significant than \( \text{value} \)
- Nodes may vote to commit or abort a ballot, not both
- If a node confirms commit \( b \) for any \( b \), it outputs \( b\text{.value} \)

Let \( \text{prepared}(b) = \{ \text{abort } b' \mid b' < b \text{ and } b'\text{.value} \neq b\text{.value} \} \)

Invariant: cannot vote commit \( b \) unless federated voting has confirmed every statement in \( \text{prepared}(b) \)
SCP prepare message

```c
struct SCPPrepare {
    SCPBallot ballot;
    SCPBallot *prepared;
    SCPBallot *preparedPrime;
    uint32 hCounter;
    uint32 cCounter;
};
```

vote-or-accept prepare(ballot)

if prepared ≠ NULL: accept prepare(*prepared)
if preparedPrime ≠ NULL: accept prepare(*preparedPrime)
if hCounter ≠ 0: confirm prepare(⟨hCounter, ballot.value⟩)
if cCounter ≠ 0:
    {vote commit(⟨n, ballot.value⟩) | cCounter ≤ n ≤ hCounter}

Progress to COMMIT phase upon accepting commit of any ballot
Setting the prepare fields

**ballot.counter** starts at 1, increases w. timeouts and received messages (details in a few slides)

**ballot.value**  
- $b$.value from highest $b$ with confirmed prepared($b$) (if any), otherwise composite nomination value
- 

**prepared**  
- highest $b$ for which sender accepted prepared($b$)

**prepared**'  
- highest $b$ with accepted prepared($b$) and different $x$ from prepared

**hCounter**  
- $h$.counter from highest $h$ with confirmed prepared($h$) and $b$.value $\leftarrow h$.value (new), else 0

**cCounter**  
- 0 if hCounter $\leftarrow$ 0 or internal “commit ballot”  
  - $c$ $\leftarrow$ NULL. Else, $c$.counter. Note $c \leftarrow ballot$ when confirmed prepared and NULL when accepted aborted.
SCP commit message

```c
struct SCPCommit {
    SCPBallot ballot;
    uint32 preparedCounter;
    uint32 hCounter;
    uint32 cCounter;
};

{accept commit((n, ballot.value)) | hCounter ≤ n ≤ cCounter}
vote-or-accept prepare((∞, ballot.value))
accept prepare((preparedCounter, ballot.value))
confirm prepare((hCounter, ballot.value))
{vote commit((n, ballot.value)) | n ≥ cCounter}
```
SCP externalize message

```c
struct SCPExternalize {
    SCPBallot commit;
    uint32 hCounter;
};
```

```c
{accept commit(⟨n,commit.value⟩) | commit.counter ≤ n}
{confirm commit(⟨n,commit.value⟩) | commit.counter ≤ n ≤ hCounter}
accept prepare(⟨∞,commit.value⟩)
confirm prepare(⟨hCounter,commit.value⟩)
```

By the time you send this, already externalized `commit.value`
- Means you have confirmed committed a ballot with `commit.value`
- Goal is definitive record to help other nodes prove value/catch up
In the common case, will prepare and commit nominated value
Else, arm timer when ballot counter reaches quorum threshold
Bump counter and restart with new ballot whenever
- Timer fires
- A blocking threshold is at a higher ballot counter
Nomination may finish converging in background
Or if any value confirmed prepared, all nodes will eventually see
it confirmed prepared and start using that value
Balloting flow

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Bump counter and restart with new ballot whenever
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Questions?