The Stellar Consensus Protocol (SCP)

draft-mazieres-dinrg-scp-00

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An open Byzantine agreement protocol

Majority-based voting doesn't work against Sybil attacks

Instead, determine quorums in decentralized way based on trust

- Let $\mathbf{V}$ be all nodes in the world
- Each $v \in \mathbf{V}$ would accept any of $\mathbf{Q}(v) = \{q_1, \ldots, q_n\}$ as a quorum
- But q_i is *not* a quorum—it is a quorum slice
- A quorum must (transitively) satisfy *all* of its members

Definition (Quorum)

A quorum $U \subseteq \mathbf{V}$ is a set of nodes that contains at least one slice of each of its members: $\forall v \in U, \exists q \in \mathbf{Q}(v)$ such that $q \subseteq U$

Assumes trust overlaps transitively. Analogies:

- Transitive reachability on the Internet
- Rough agreement on who constitutes a tier-1 ISP
- Overlapping notions of valid certificate authorities

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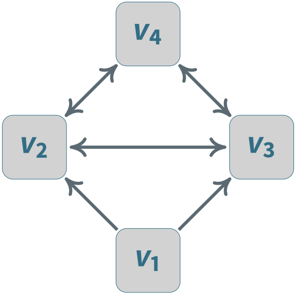

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Visualize quorum slice dependencies with arrows

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

$v_1, \ldots, v_4$ **is the smallest quorum containing** v_1

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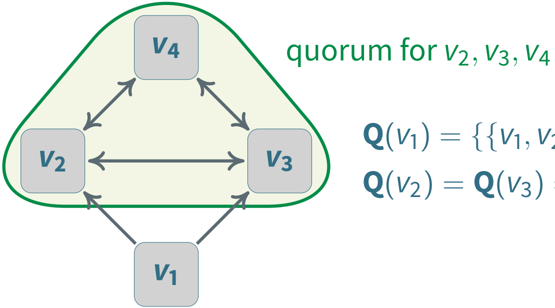

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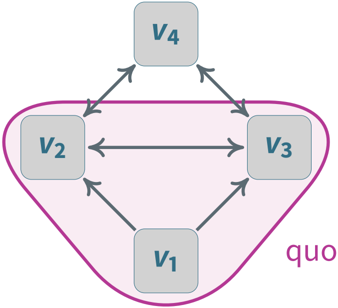

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quorum slice for v_1, but not a quorum

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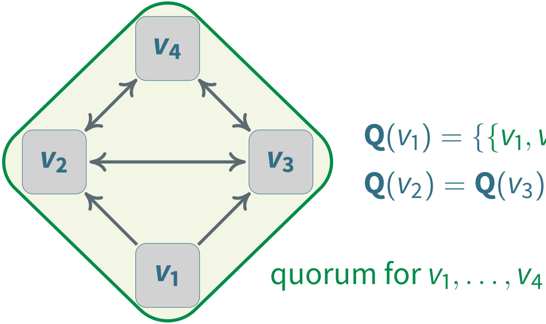

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Quorum slice representation

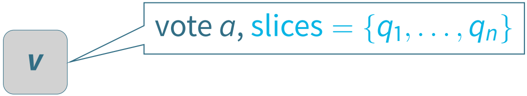
```
union PublicKey switch (PublicKeyType type) {
case PUBLIC_KEY_TYPE_ED25519:
   uint256 ed25519;
};

// supports things like: A,B,C,(D,E,F),(G,H,(I,J,K,L))
// only allows 2 levels of nesting
struct SCPQuorumSet {
   uint32 threshold;        // the k in k-of-n
   PublicKey validators<>;
   SCPQuorumSet innerSets<>;
};
```

Can't represent arbitrary quorum slices compactly

Instead, use two-levels of k-of-n configuration

Federated voting



Nodes exchanges vote messages to agree on statements

- Well-behaved nodes cannot vote for contradictory statements
- Every vote specifies quorum slices
- Allows dynamic quorum discovery while assembling votes

Two important thresholds for statement a at node v:

- quorum threshold – a quorum containing v unanimously votes for a
- blocking threshold – $\forall q \in \mathbf{Q}(v), \exists v' \in q$ such that v' voted for a (no contradictory $\overline{a} \neq a$ can reach quorum threshold w/o illegal votes)

v ratifies a iff a reaches quorum threshold at v

- Can't ratify contradictory statements if you have quorum intersection despite [i.e., after deleting] ill-behaved nodes (qidin)

Vote messages

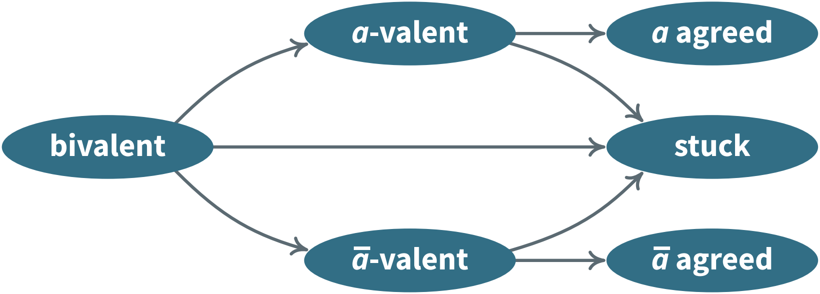
```
typedef opaque Hash[32];  // SHA-256
struct SCPStatement {
   PublicKey nodeID;      // v (node signing message)
   uint64 slotIndex;
   Hash quorumSetHash;
   SCPStatement pledges;
};

typedef opaque Signature<64>;
struct SCPEnvelope {
   SCPStatement statement;
   Signature signature;
};
```

Transmit quorum slices as SHA-256 hash of SCPQuorumSet

- Use side protocol to request preimage if not cached

Federated voting outcomes



Before any node votes, system is bivalent

- Any value may be ratified

If a node ratifies a, system is a-valent

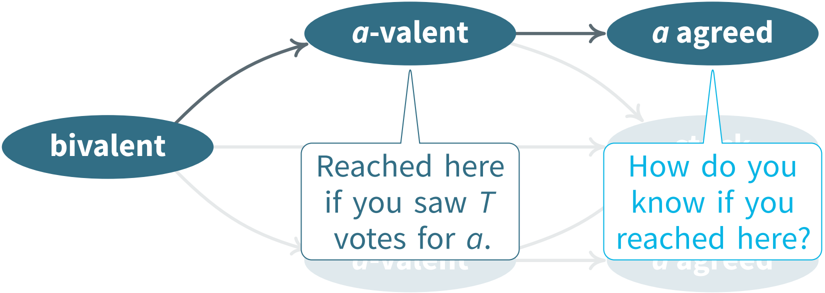
- With qidin, no contradictory $\bar{a}$ can be ratified

If every node learns system a-valent, then system agrees on a

System can also get stuck at any point along the way

- Non-faulty node can't ratify a because voting for $\bar{a}$
- Or ratified a and don't know it because of crash & message loss

When have we reached agreement?



Centralized protocols (e.g., PBFT) accept statement if quorum intersection says ratified

- Centralized systems care about whole-system failure, not per-node
- Now can't 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 everyone else will learn system agreed on *a*?

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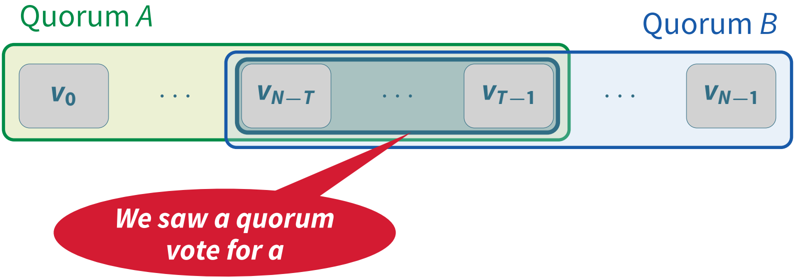

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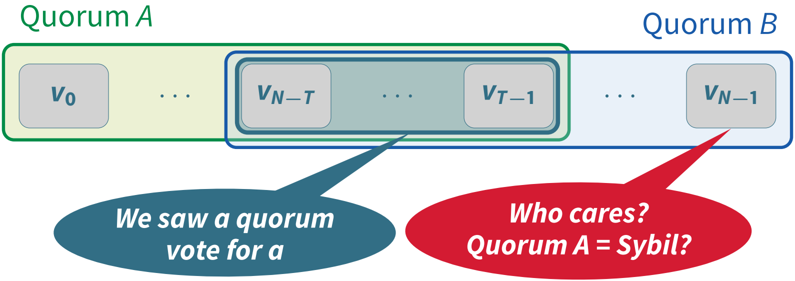

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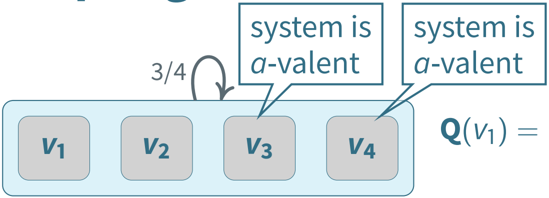
Accepting statements



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What if "system is a-valent" reaches blocking threshold at v_1?

- Either true or v_1 not member of any well-behaved quorum (no liveness)

Node v accepts a statement a consistent with history iff either:

1. "I vote a or I accept a" reaches quorum threshold, or
2. "I accept a" reaches blocking threshold

#2 lets nodes accept statements they voted against, but

- Nodes can accept contradictory statements in cases with no fully honest quorum but where you still have qidin
- No guarantee all nodes in non-faulty quorum will accept a

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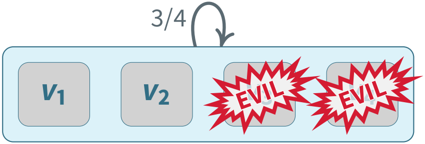

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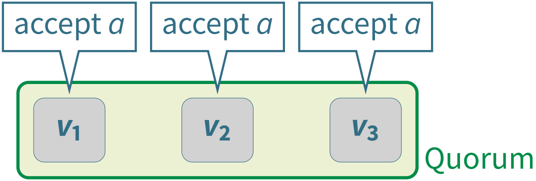
Confirming statements



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

Node v confirms a by ratifying "I accepted a."

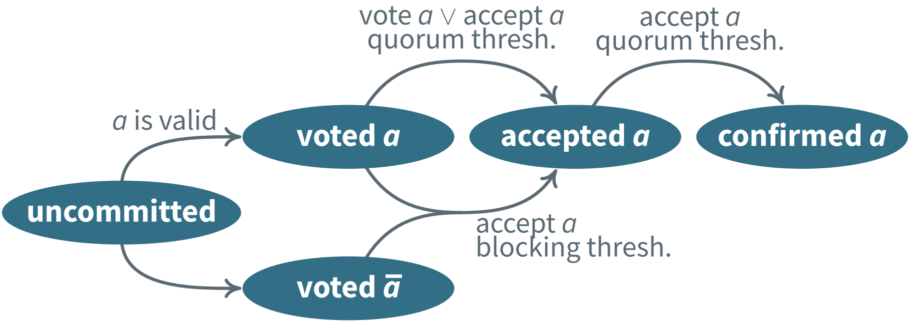
Solves safety through quorum threshold of ratification

Also solves nodes in honest quorum being unable to accept

- Nodes in well-behaved quorum may vote against accepted statements
- Won't vote against the *fact* that those statements were accepted

Theorem: If 1 node in well-behaved quorum confirms a, all will

Summary of federated voting process



A node v that locally confirms a knows system has agreed on a

- If **Q**() admits any safe protocol, well-behaved nodes can't contradict a
- If v in well-behaved quorum, whole quorum will eventually confirm a

SCP nomination message

```
typedef opaque Value<>;

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

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

Nodes broadcast nominated values in `votes`

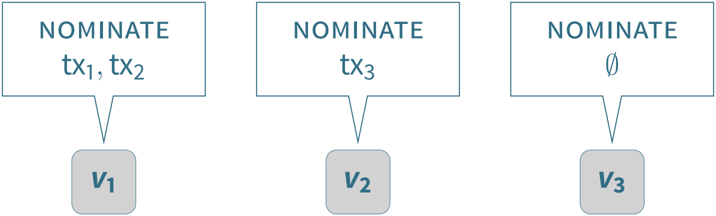
- Initially vote values in all received votes (ignoring optimization here)

Upon accepting nomination of a, move from `votes` to `accepted`

Stop voting for new values when any confirmed nominated

- But continue accepting and repeating votes already cast

Nomination flow



Nodes nominate values and re-nominate any nominations seen

Stop adding to `votes` once any value confirmed nominated

Converge on set of nominated values

Deterministically combine nominations into *composite* value x

All nodes guaranteed to converge on same value x!

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

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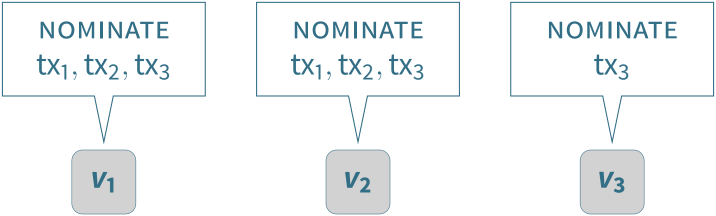

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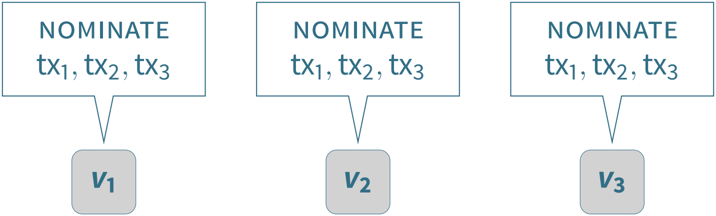

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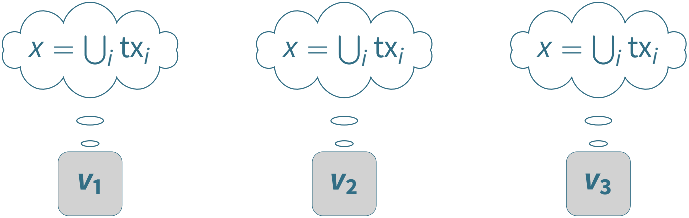

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SCP ballots

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

Composite nominated must be run through balloting

- Guarantees safety even if started before nomination converges

A ballot b is a pair $\langle b.n, b.x\rangle$ where $b.x$ is a candidate output value

- Ballots totally ordered with field n more significant than x
- Nodes may vote to commit or abort a ballot, not both
- If federated voting confirms commit b for any b, can output value $b.x$

Let prepared$(b) = \{$abort $b_{\mathbf{old}} \mid b_{\mathbf{old}} < b$ and $b_{\mathbf{old}}.x \neq b.x\}$

Invariant: cannot vote commit b unless federated voting has confirmed every statement in prepared(b)

SCP prepare message

```
struct SCPPrepare {
  SCPBallot ballot;           // b
  SCPBallot *prepared;        // p
  SCPBallot *preparedPrime; // p'
  uint32 nC;                  // c.n
  uint32 nH;                  // h.n
};

union SCPStatement switch (SCPStatementType type) {
  case SCP_ST_PREPARE:
    SCPPrepare prepare;
  /* ... */
};
```

Prepare fields

`ballot.`*x* starts at 1, increases w. timeouts, msg receipt

`ballot.`*n* *b.x* from highest *b* for which prepared(b) confirmed (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`

`nH` *b.n* from highest *b* with confirmed prepared(*b*), else 0

`nC` if not 0 and `ballot.`$x = 1$, implies votes for commit $\langle nC, x\rangle$, commit $\langle nC + 1, x\rangle, \ldots,$ commit $\langle nH, x\rangle$

SCP confirm message

```
struct SCPConfirm {
    SCPBallot ballot;    // b
    uint32 nPrepared;    // p.n
    uint32 nCommit;      // c.n
    uint32 nH;           // h.n
};

union SCPStatement switch (SCPStatementType type) {
  case SCP_ST_CONFIRM:
    SCPConfirm confirm;
  /* ... */
};
```

Implies votes for all messages in the set $\{\textbf{accept}(\textbf{commit}\ b') \mid \texttt{nCommit} \le b'.n \le \texttt{nH}\ \textbf{and}\ b'.x = \texttt{ballot.x}\}$

Implies `SCPPrepare` **with ballot** $\langle \infty, \texttt{confirm.ballot}.x \rangle$**, prepared** $\langle \texttt{confirm.nPrepared}, \texttt{confirm.ballot}.x \rangle$**, and nH value** ∞**.**

SCP externalize message

```
struct SCPExternalize {
    SCPBallot commit;      // c
    uint32 nH;             // h.n
};

union SCPStatement switch (SCPStatementType type) {
  case SCP_ST_EXTERNALIZE:
    SCPExternalize externalize;
  /* ... */
};
```

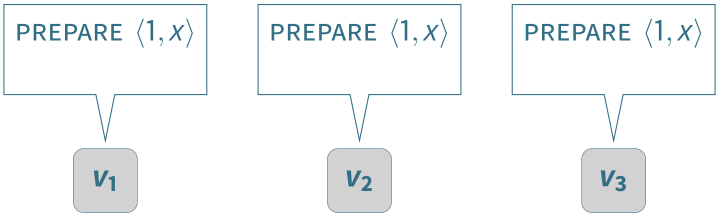
By the time you send this, already externalized `commit`.x

- Means you have confirmed committed a ballot with `commit`.x
- Goal is definitive record to help other nodes prove value/catch up

Implies `SCPConfirm` **with ballot** $\langle\infty,$ `externalize.commit`.$x\rangle$, **nPrepared** `externalize.commit`.n, **and nH** ∞

Implies `SCPConfirm` **with ballot** $\langle\infty,$ `externalize.commit`.$x\rangle$, **nPrepared** `externalize.commit`.n, **nH** `externalize.nH`, **and a special quorum slice declaration of only the sending node**

Balloting flow



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

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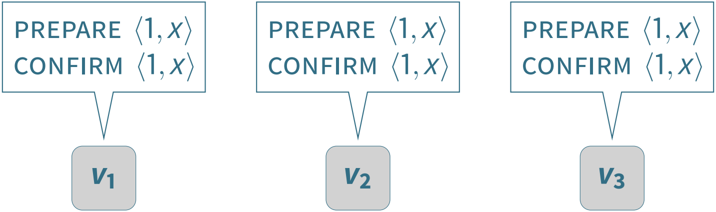

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