Distributed Consensus and Diffuse Trust Systems

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https://github.com/SmithSamuelM/Papers/blob/master/presentations/Distributed%20Consensus.pdf

Why Distributed Consensus

- Distributed consensus enables diffuse trust systems for de-centralized computing infrastructure
- Diffuse trust allows secure infrastructure outside a firewall by distributing the attack surface.
- Diffuse trust systems can disruptively dis-intermediate centralized computing infrastructure.
- Diffuse trust systems enable new business models

  - Computation in the “fog” vs computation in the “cloud”

  - Distributed AI

  - Smart contracts

  - IOT

  - …. etc

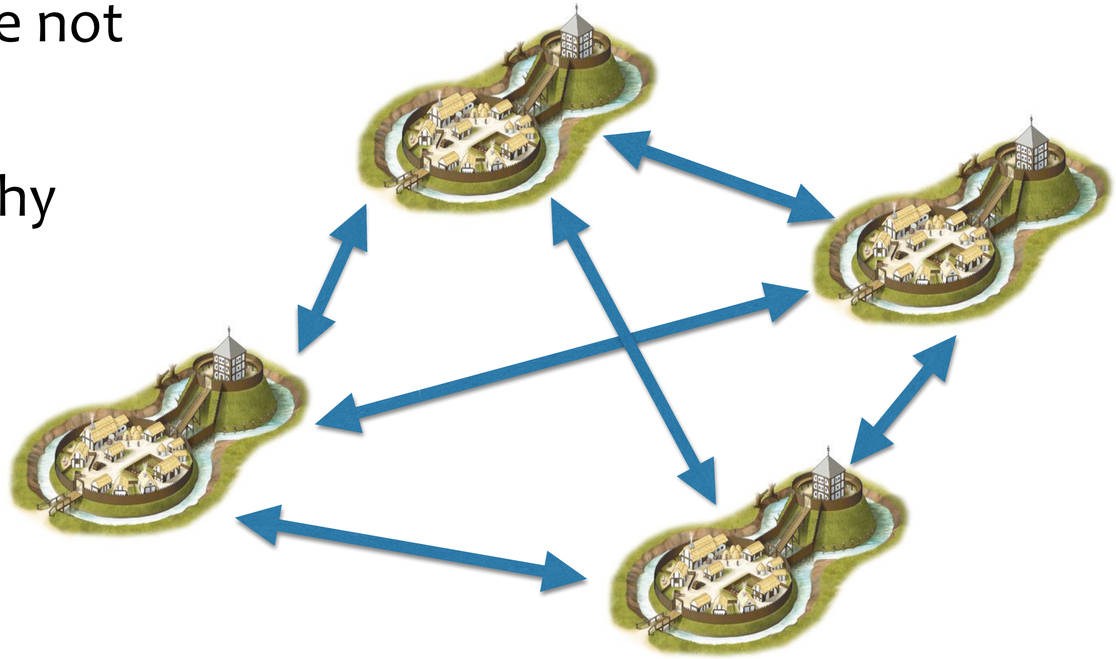
Diffuse Trust

- Cellular distributed topology.

  "Think clandestine spy ring or resistance organization"

- Defeating each node (cell, element) requires an independent exploit.
  - No single point of failure. *"Universal root privileges"*
  - No common mode failures. *"Exploit to attain root privileges"*
- As long as the majority or super majority of nodes are not exploited the system is trustworthy.
- Cooperation between peers vs. authoritarian hierarchy

VS



Distributed Consensus Types

- Proof of Work: Simple, highly inefficient, high latency, low throughput
- Proof of Stake: More complex, more efficient, lower latency, higher throughput (Asymmetric Proof of Work)
- Byzantine Agreement: Most complex, most efficient, lowest latency, highest throughput.
- Hybrid:

Distributed Consensus Components

- Governance
- Distributed Consensus Algorithm
- Data Structure
-

Permissioned Distributed Consensus
AKA XBFT

- Permissioned Distributed Ledgers
  Swanson 2105

  http://www.ofnumbers.com/wp-content/uploads/2015/04/Permissioned-distributed-ledgers.pdf

- Permissioned governance to address Sybil attack. Censorship.

- Higher speed application specific distributed consensus
  - Database
  - Open Storage
  - DHT
  - Transactions
  - Settlement
  - Smart Contracts
  - Identity
  - Reputation
  - etc …

BYZANTINE GENERALS

- Analogy to war in the Byzantine era.
- Historically Byzantine generals were prone to traitorous or duplicitous acts.
- The Byzantine Generals Problem:

  http://research.microsoft.com/en-us/um/people/lamport/pubs/byz.pdf

  Two separated generals agree to attack a third. If the two unite they both win. If either attacks alone he loses.

  The communication of intent to attack and confirmation of intent to attack is subject to delay and error.

- Byzantine agreement:

  A valid consensus is guaranteed despite a fraction of the participants behaving in a malicious and/or erroneous manner.

- Consensus despite "Byzantine" faults:

  Dropped packets, Erroneous packets, Malicious Packets, Partitioning, Sybil Attack

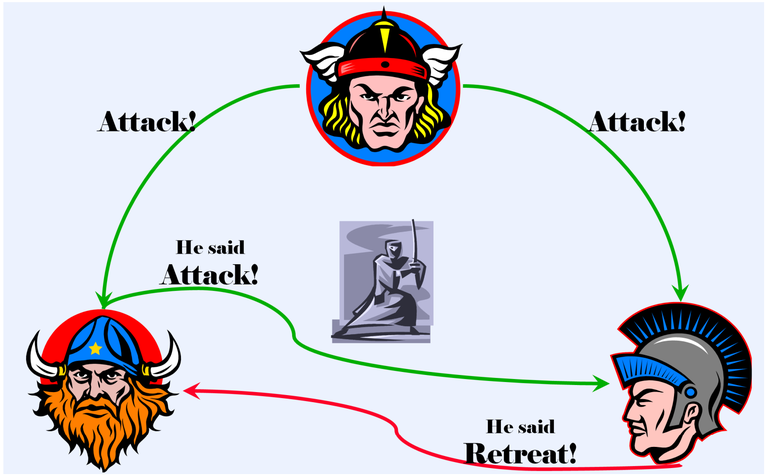
  A consensus algorithm that solves the Byzantine consensus problem in the presence of malicious and/or erroneous behavior is called Byzantine fault tolerant (BFT).

- There are two features of any BFT consensus solution:

  Liveness, that is, the non-faulty nodes make a joint decision in finite time.

  Safety, that is, the non-faulty nodes all make the same joint decision.

- All the solutions require that a majority or supermajority, of the nodes be non-faulty.
- The problem is usually couched as a problem of distributed replication of a sequence of states, that is, the non-faulty nodes will all replicate the same sequence of states (decisions).
- For example, the sequence of transactions entered into a shared public ledger or shared public database is the sequence of states.



Practical Byzantine Fault Tolerance (PBFT)

http://pmg.csail.mit.edu/~castro/osdi99_html/osdi99.html

Background

Synchronous Systems:

All steps proceed in rounds.
All message transmissions between nodes fully complete within each round.
Consensus at the end of each round.

Asynchronous:

Steps occur at varying times.
Message transmissions happen whenever.
Consensus?

Fundamental Constraint:

In an asynchronous system it is impossible to achieve consensus with one faulty node.
Impossibility of Distributed Consensus with One Faulty Process; Fischer, Lynch, Patterson, JACM Vol. 32, No. 2, April 1985, pp. 374-382.
https://groups.csail.mit.edu/tds/papers/Lynch/jacm85.pdf

Desirable Features

Sequential consistency among nodes:

Results of any execution is the same as if the operations on all the nodes were executed in some sequential order.

Linearizable:

Sequential consistency that respects the real time order of events.

State Machine Replication:

Lots of things can be expressed as a state machine

Goals:

Build a linearizable replicated state machine.
Agreement on operations and their order.
Replication to provide availability while preventing faults including malicious ones.

PBFT Features

Byzantine Faults:

Delay, Error, Stop, Duplicate, Reorder, Malicious Data.

Honest nodes:

Dishonest nodes:

Faulty nodes:

Liveness:

Quorum of non-faulty nodes make a joint decision in finite time.
Weak synchrony via timing bounds [h, H].
Delay does not grow faster than time. delay(t) = o(t)

Safety:

Quorum of non-faulty nodes all make the same joint decision.
Consensus despite byzantine faults on some of the nodes.
Consensus despite out of bounds delay on some of the honest nodes.

PBFT Assumptions

All messages between nodes are signed ():

Typically some combination of message authentication codes (MACs) with shared secrets and true digital signatures. Modern ECC digital signatures ameliorate many of the performance advantages of using MACS while enhancing security (nonrepudiation).

At most *f* faulty nodes during any step:

Honest nodes behave deterministically:

Honest nodes fail independently:

No systemic or common mode failures

Weakly synchronous:

Bounded time to respond

$N=cf+1$

N is the total number of nodes. f *is the number of allowed faulty nodes at a time (process step).*

$N=f+1$ Correct Agreement:

Given at most f faults or f faulty nodes, any agreement of $f+1$ nodes is correct because at least one of the $f+1$ nodes is honest. No guarantee that any set of $f+1$ nodes will ever be in agreement.

$N=2f+1$ Correct Majority Agreement:

Given $2f+1$ nodes at least $f+1$ are non-faulty ensuring a correct non-faulty majority. Guarantees that a correct majority of $f+1$ nodes will be in agreement. No guarantee that the agreement is live i.e. majority may not know that they are in agreement.

$N=3f+1$ Correct Majority Live Agreement:

Up to f honest nodes may no longer respond so need $3f+1 = 2f+1+f$ nodes to ensure in bounded time that a correct majority know that a correct majority were in agreement.

$N=3f+1$ Correct Majority Live Safe Agreement:

$N-f$ is *Quorum* size that ensures a *Quorum* is formed in bounded time.

$2f+1$ is minimum *Quorum* size to ensure correct majority.

Given *Quorum* size of $N-f = 2f+1$, find N for which the intersection of any two quorums will include at least one honest node i.e. intersection of of size $f+1$.

Partition Safety of Quorums

If any two pairwise quorums must be in agreement then all possible quorums will be in agreement.

$2f+1$ is minimum *Quorum* size to ensure correct majority agreement.

$N-f$ is constraint on *Quorum* size relative to N that ensures a *Quorum* is formed in bounded time.

Given *Quorum* size of $N-f \geq 2f+1$, find minimum N such that the intersection of any quorum partition includes at least one honest node.

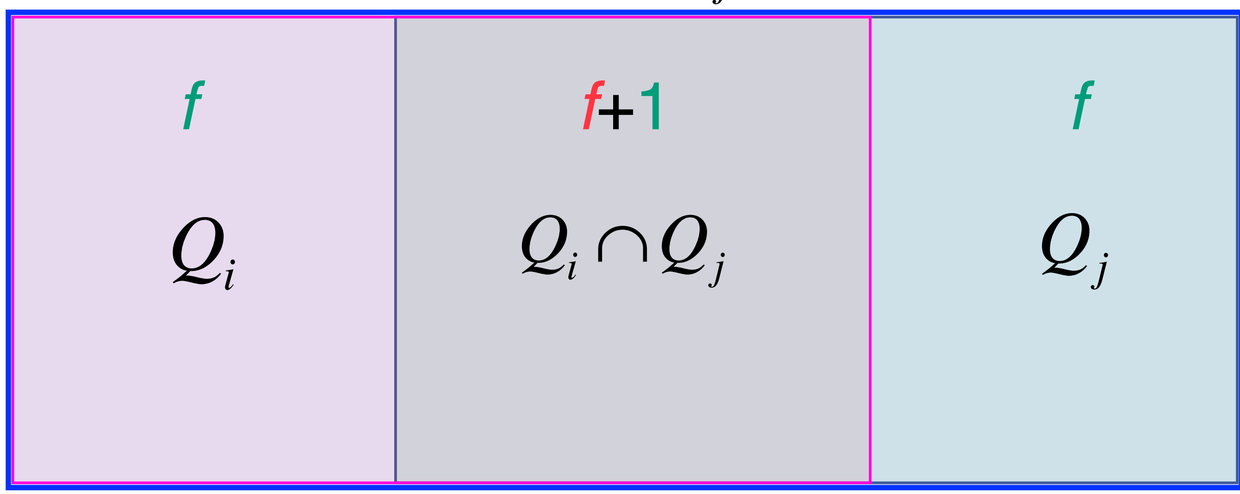
Intersection contains one honest node if size of intersection is $\geq f+1$

Overlapping Quorums $\left[Q_i, Q_j\right]$

For set S, the cardinality $|S|$ is the number of elements of S.

One honest node if:

$$\left|Q_i \cap Q_j\right| \geq f+1$$



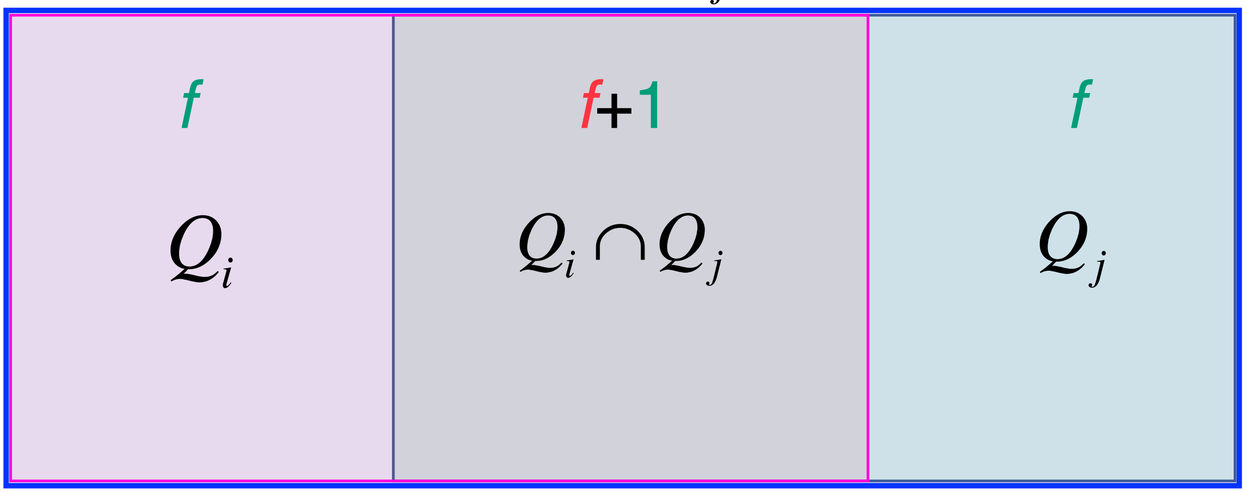
Proof of Quorum Size

For set S, the cardinality $|S|$ is the number of elements of S.

Phrased in terms of cardinality (size) of the quorums.

Overlapping Quorums $[Q_i, Q_j]$

$$Q_i \cup Q_j$$



One honest node if:

$$|Q_i \cap Q_j| \geq f + 1$$

$$|Q_i| = N - f$$

$$|Q_j| = N - f$$

$$|Q_i \cup Q_j| = N$$

$$|Q_i| + |Q_j| = |Q_i \cup Q_j| + |Q_i \cap Q_j|$$

$$|Q_i| + |Q_j| - |Q_i \cup Q_j| = |Q_i \cap Q_j| \geq f + 1$$

$$(N - f) + (N - f) - N \geq f + 1$$

$$N - 2f \geq f + 1$$

$$N \geq 2f + f + 1 \geq 3f + 1$$

$$\min(N) \rightarrow N = 3f + 1 \rightarrow N - f = 2f + 1$$

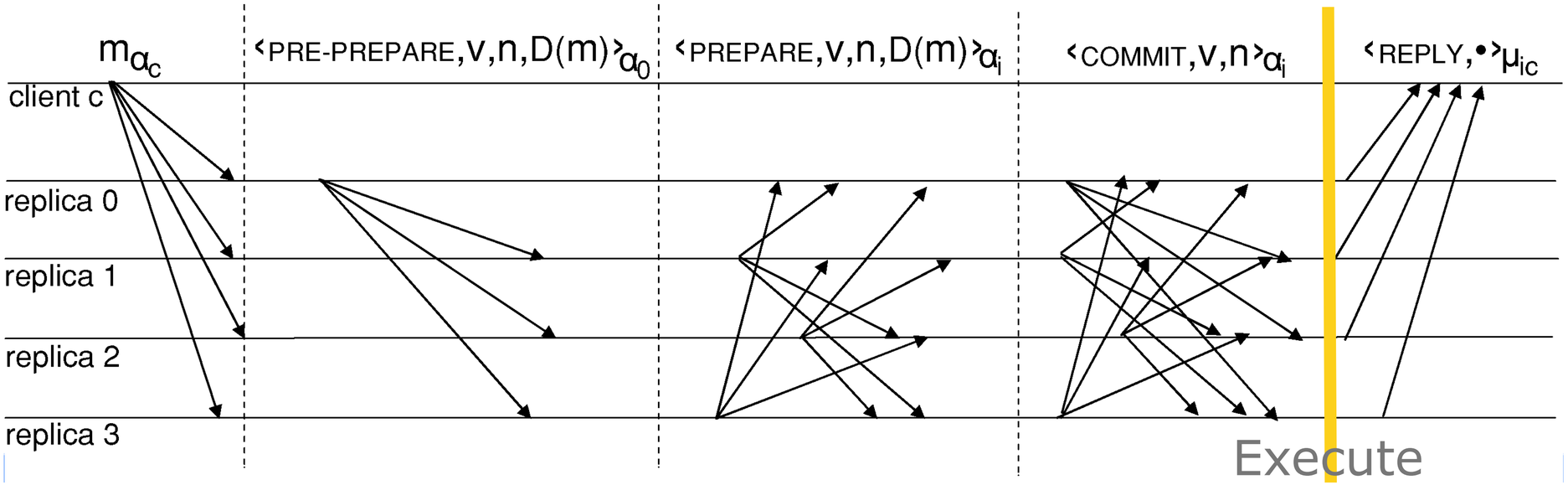
Fundamental Rule for Stepwise Live Agreement

Given that f of the nodes that come to agreement in the current step may become unavailable in the next step, then at least $2f+1$ nodes must come to agreement in the current step to ensure that at least $f+1$ of those nodes will remain available to correctly carry that agreement into the next step.

Therefore all steps but the last step must have at least $2f+1$ nodes in agreement.

Given that at most f nodes may be faulty during any step, newly non-faulty nodes in the current step may have been faulty in the previous step and vice-versa.

Client Request



Client multicasts request to replicas

Primary initiates 3 phase commit

Client collects replies from replicas,

f+1 correct replies before timeout indicates success

- Valid signature
- Distinct *f*+1 replicas *i* but same *t* and *r*

Each replica accepts request

- Verifies signature
- logs request

$$\text{REQUEST} < o,t,c > \sigma_c \qquad REPLY < v,t,c,i,r > \sigma_i$$

o = operation

t = request timestamp

c = client id

σ_c = client signature

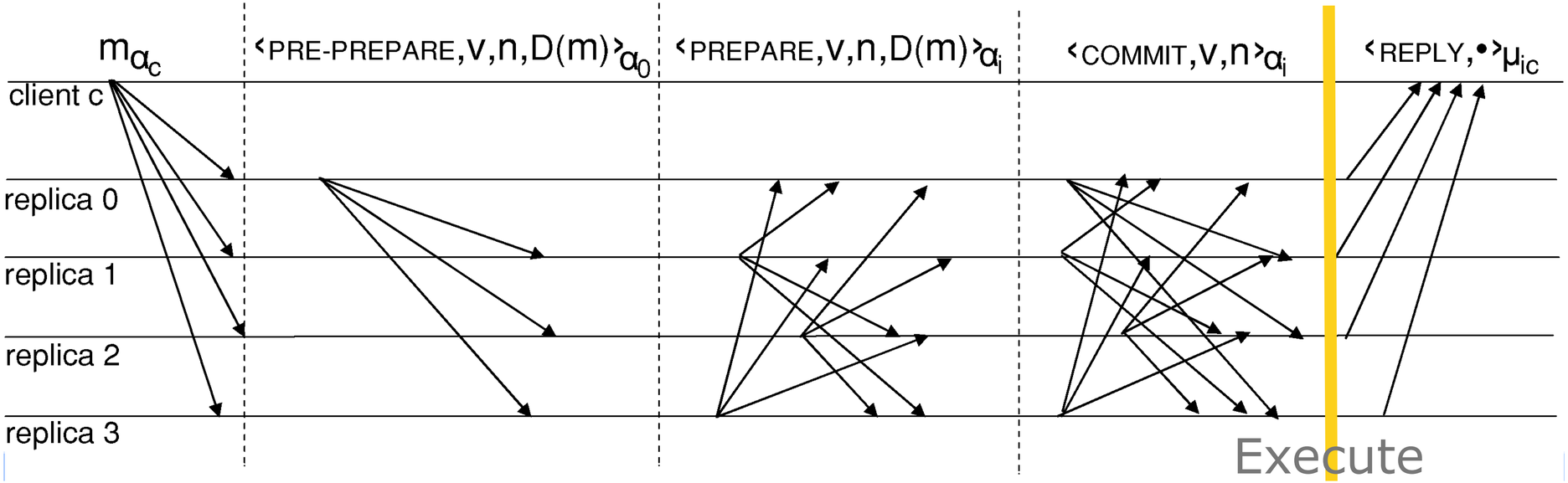
v = view number

i = replica id

r = result of o

σ_i = replica i signature

Pre-Prepare



Primary replica initiates 3 phase commit

Multicasts pre-prepare with proposed order n

Backup replicas accept and log pre-prepare

Verify signature and digest of request

Verify backup is in same view

Verify not accepted different request for n

Enter prepare phase

$$PREPREPARE < v,n,d(m) > \sigma_p$$

$v = \text{view number}$

$n = \text{sequence number}$

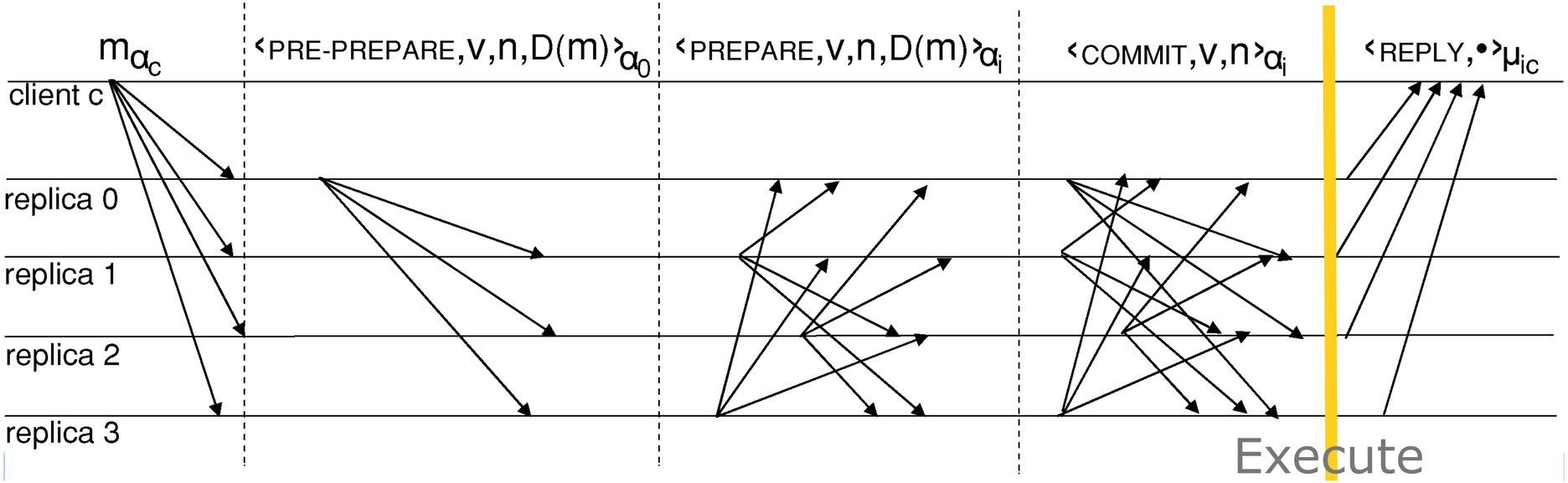
$d = \text{digest}$

$m = \text{request message}$

$p = v \bmod N$

$\sigma_p = \text{primary replica signature}$

Prepare



Backups initiate prepare phase

Multicast prepare to all replicas

Backup replicas accept and log prepare

Verify signatures and *v,n,d* match

Backup *i* is prepared IFF

pre-prepare and 2*f* matching prepares

knows a safe quorum agrees on n for m in v

If prepared(*m,v,n,i*) is True, Then prepared(*m,v,n,j*) is False for *i≠j*

$$PREPARE < v,n,d(m),i > \sigma_i$$

v = view number

i = replica id

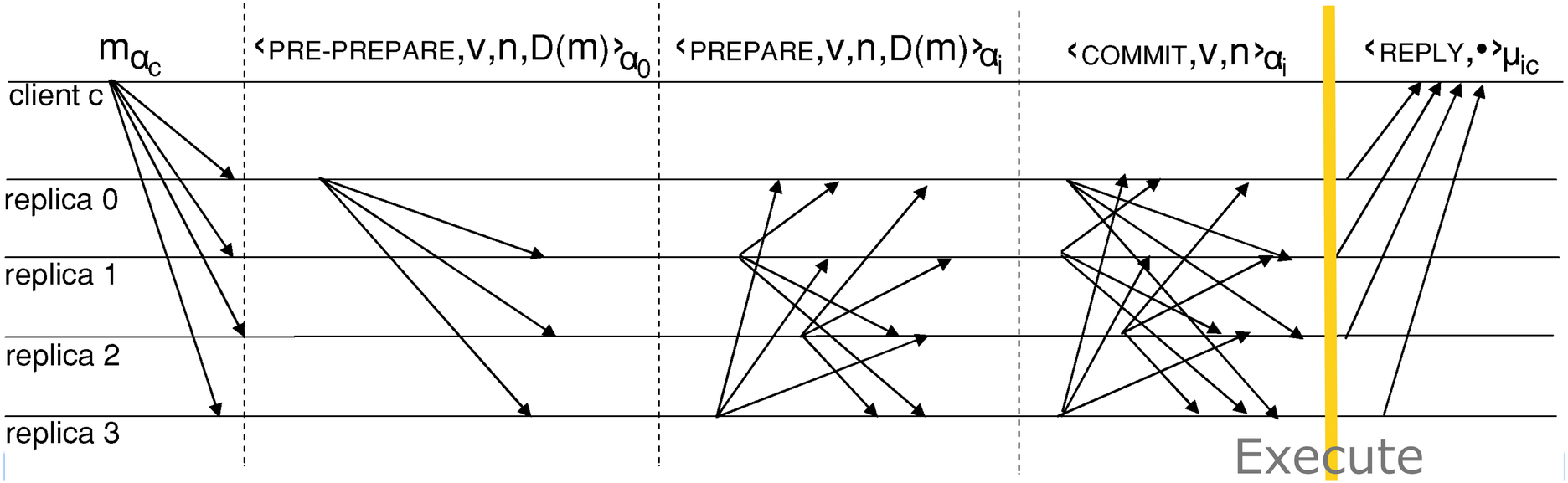
n = sequence number

d = digest

m = request message

σ_i = replica i signature

Commit



Backups initiate commit phase

- Multicast commit to all replicas

Backup replicas accept and log commit

Backup i performs operation o IFF

- Prepared
- 2*f*+1 matching commits including own (quorum)
- lower order n operations have been performed

$$COMMIT < v,n,i > \sigma_i$$

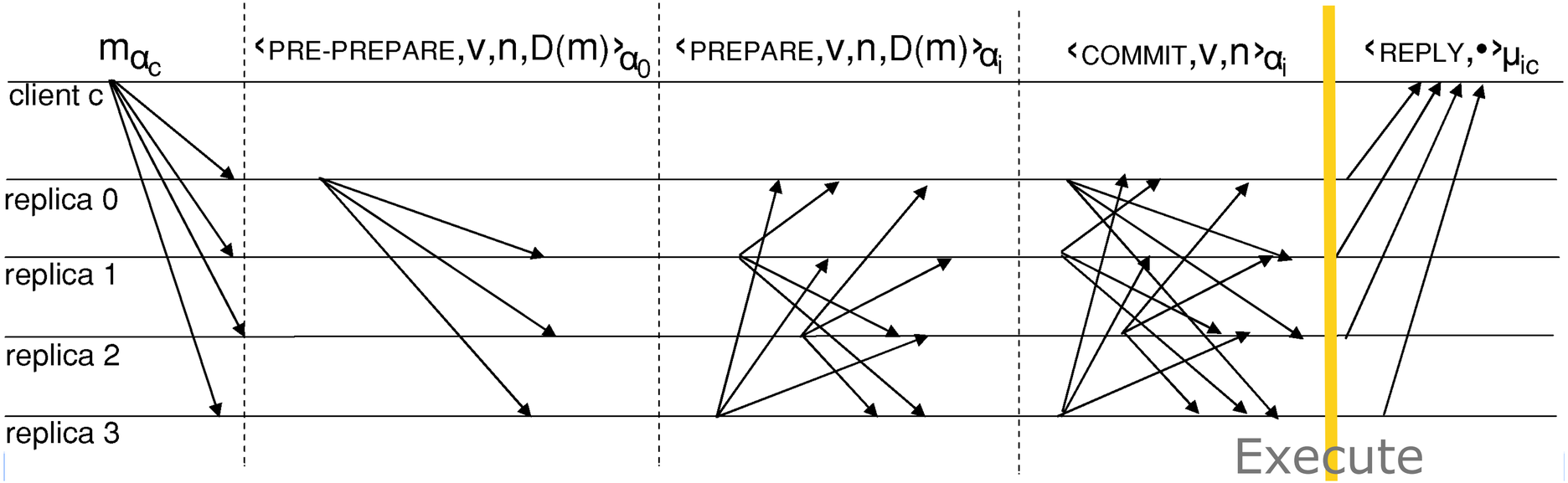
$$v = \text{view number}$$

$$n = \text{sequence number}$$

$$i = \text{replica id}$$

$$\sigma_i = \text{replica } i \text{ signature}$$

Reply



Backups reply to client

$$REPLY < v,t,c,i,r > \sigma_i$$

$v = \text{view number}$

$i = \text{replica id}$

$r = \text{result of o}$

$\sigma_i = \text{replica } i \text{ signature}$

Log Checkpointing

Infinite log

Checkpoint Log state periodically

- Digest of log state
- Multicast digest of log state to other replicas
- $2f+1$ digests of matching state is quorum
  - Checkpoint and discard older log entries

$$CHECKPOINT < d(s), i > \sigma_i$$

$$d = \text{digest}$$

$$s = \log \text{state}$$

$$i = \text{replica id}$$

$$\sigma_i = \text{replica } i \text{ signature}$$

View Changes

Faulty Primary

Primary deterministic $p = v \bmod N$

Views may overlap

Restart view by re-issuing pre-prepares from failed view.

View change request triggered by

- Client Timeout rebroadcast request which starts replica timer
- Replica Timeout generates view change request

If primary given by $v+1$ receives $2f$ view change plus own

$$VIEWCHANGE < v+1, n_s, C, P, i > \sigma_i$$

v = faulty view number

n_s = sequence number of last stable checkpoint s

C = set of $2f+1$ checkpoint messages

P = set of sets P_m for each m prepared at i with $n_m > n_s$

P_m = 1 preprepare+ $2f$ prepare

m = request message

i = replica id

σ_i = replica i signature

New View

If primary given by *v*+1 receives 2*f* view change plus own

- Multicasts new view to replicas
- O set of pre-prepare messages
  - After last stable checkpoint
  - Contained in a least one *P* of view-change messages
  - Use no-op for sequence number gaps

$$NEWVIEW < v+1, V, O > \sigma_p$$

$$v = \text{faulty view number}$$

$$p = (v+1) \bmod N$$

$$V = \text{set of view change messages}$$

$$O = \text{set of pre-prepare messages}$$

$$\sigma_p = \text{primary replica signature}$$

Performance

PBFT BFS about 10- 20% slower than NFS under normal operation

90% performance degradation for fault recovery view change.

Implementations

Tendermint http://tendermint.com/docs/tendermint.pdf

Aardvark 2009 http://usenix.org/events/nsdi09/tech/full_papers/clement/clement.pdf

Fast Byzantine Consensus 2006 https://www.cs.utexas.edu/~lorenzo/papers/fab.pdf

Ripple https://ripple.com/consensus-whitepaper/

Stellar 2015 https://www.stellar.org/papers/stellarconsensusprotocol.pdf

https://www.bigchaindb.com/whitepaper/

https://www.hyperledger.org

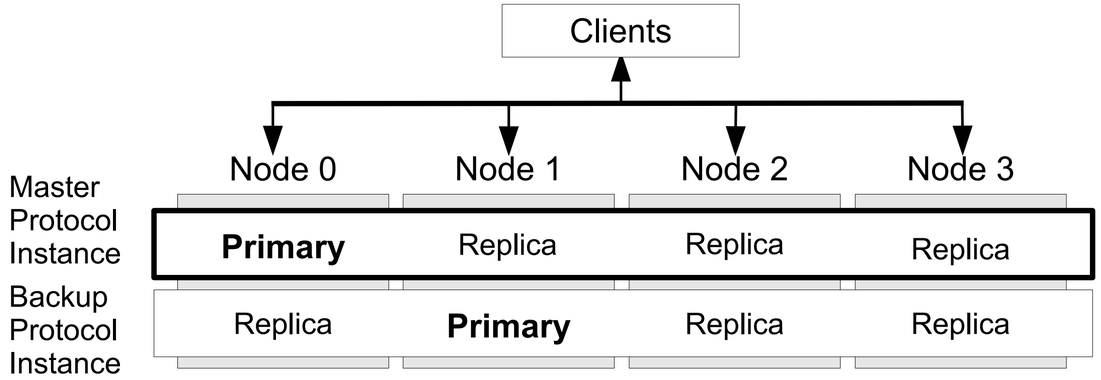
Redundant BFT (RBFT)

Redundant Byzantine Fault Tolerance 2013

http://pakupaku.me/plaublin/rbft/report.pdf)

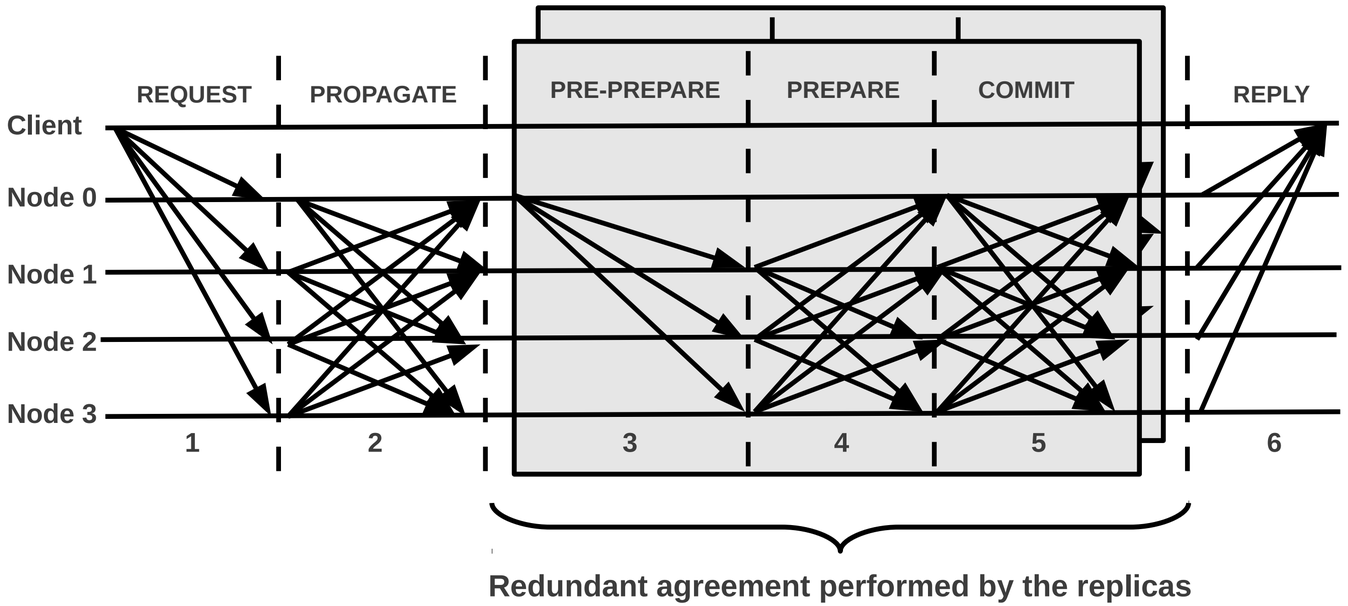
700 BFT Protocols, 2014

http://www.eurecom.fr/~vukolic/tocs-700.pdf



Little performance degradation for fault recovery, 5%.

About 10-20% lower performance under normal conditions.



Plenum RBFT Python Implementation

PLenum RBFT https://github.com/evernym/plenum

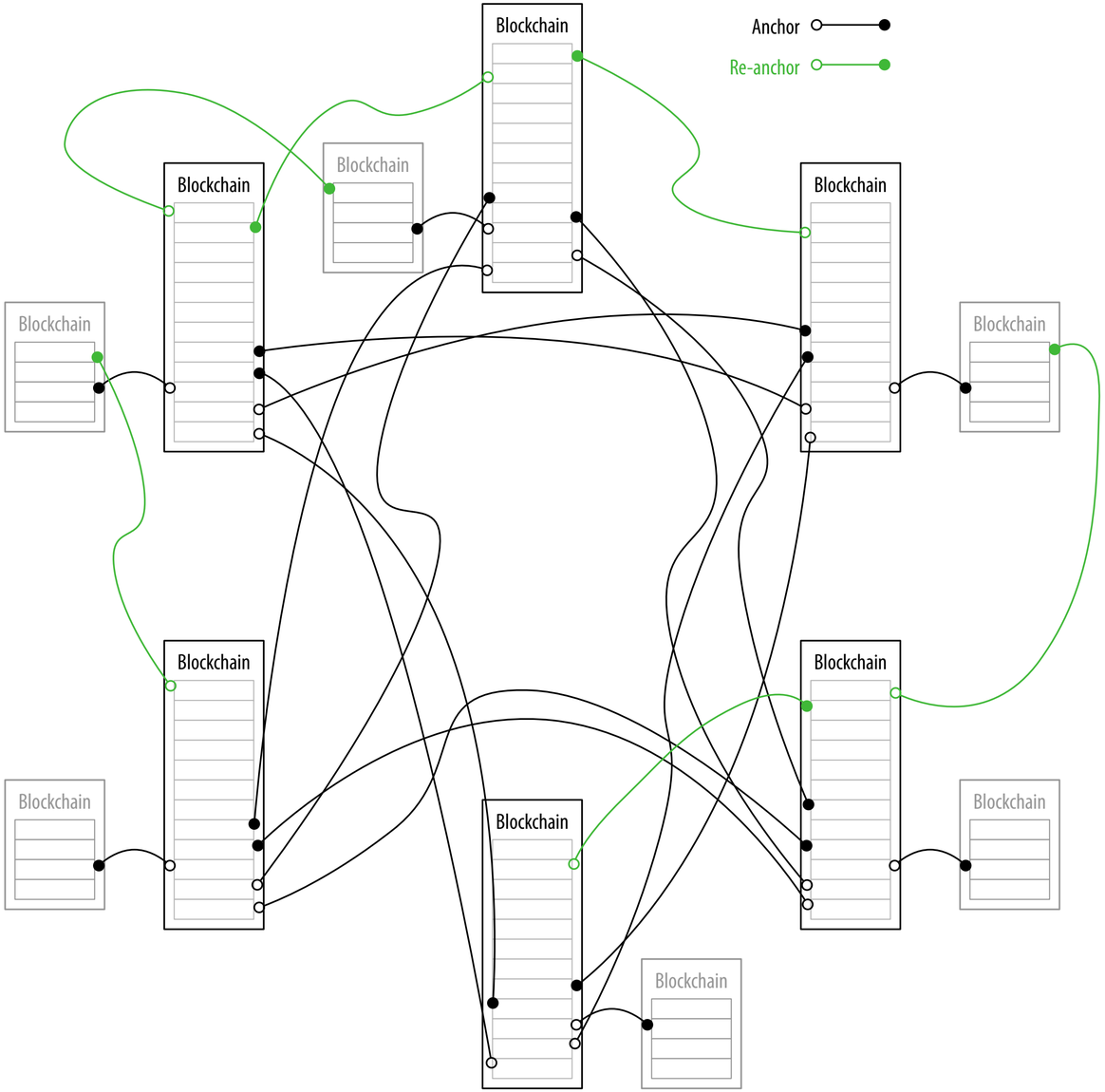
https://github.com/evernym/plenum/wiki

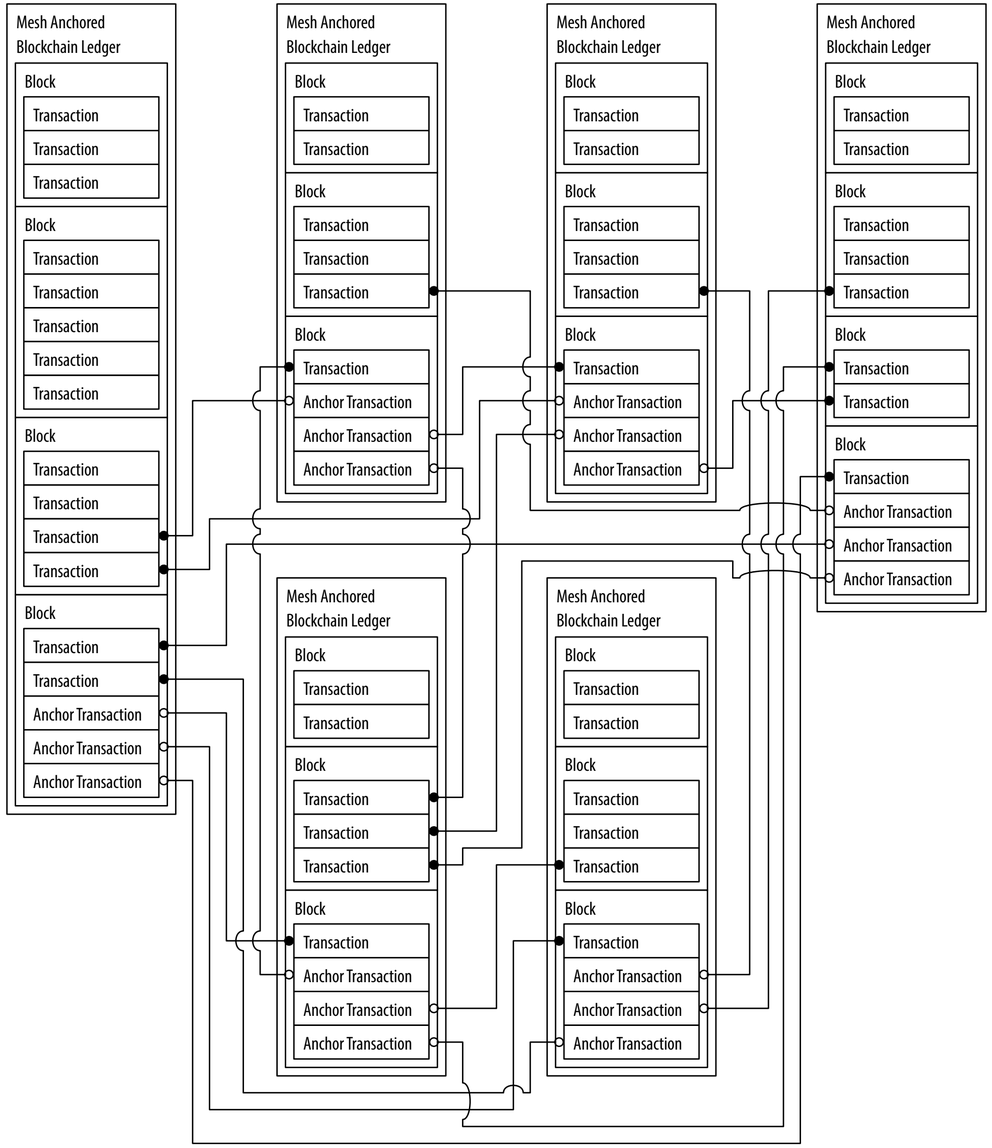
Uses RAET (Reliable Asynchronous Event Transport) protocol

https://github.com/RaetProtocol/raet

Digital Signatures (no Macs) so don’t need digests.

Chainmail or Mesh Anchoring

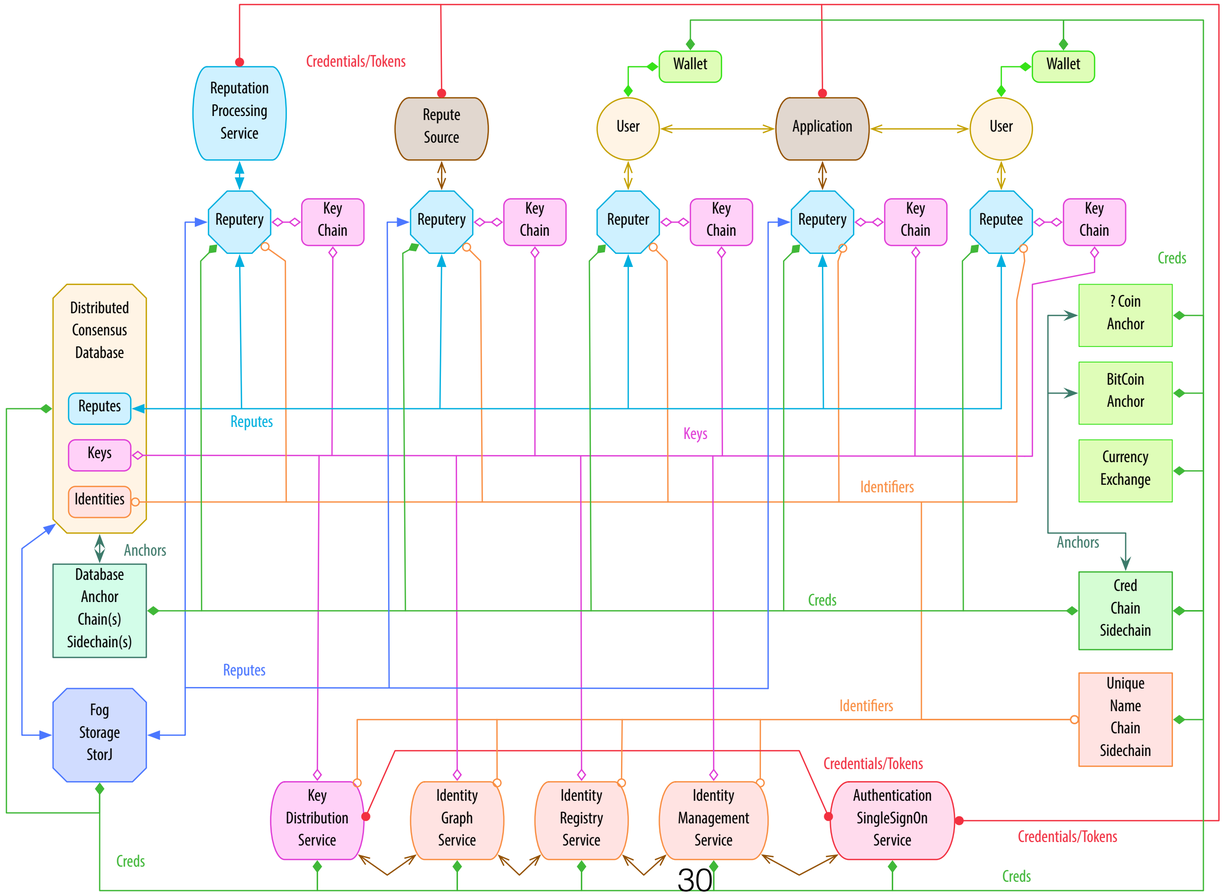




Reputation and Identity

https://openreputation.net/open-reputation-low-level-whitepaper.pdf

http://evernym.com/assets/doc/Identity-System-Essentials.pdf?v=0825630653



BACKUP SLIDES

View Change

What if the primary is faulty?

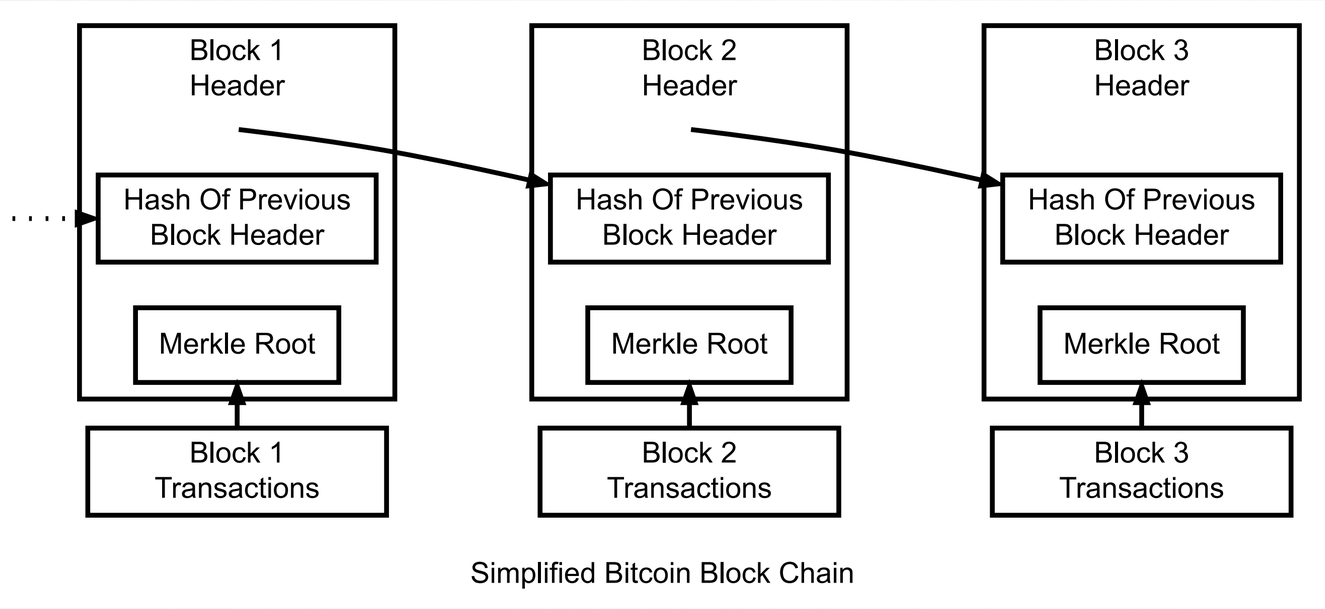
- The client uses a timeout. When this timeout expires, the request is sent to all replicas.
- If a replica already knows about the request, the rebroadcast is ignored.
- If the replica does not know about the request, it will start a timer.
- On timeout of this second timer, the replica starts the view change process.

- If a replica's timer expires, it sends a view change message.
- This message contains the system state (in the form of archived messages) so that other nodes will know that the replica has not failed.
- If the current view is *v, node v+1 (mod n) waits for 2f valid view-change messages.*

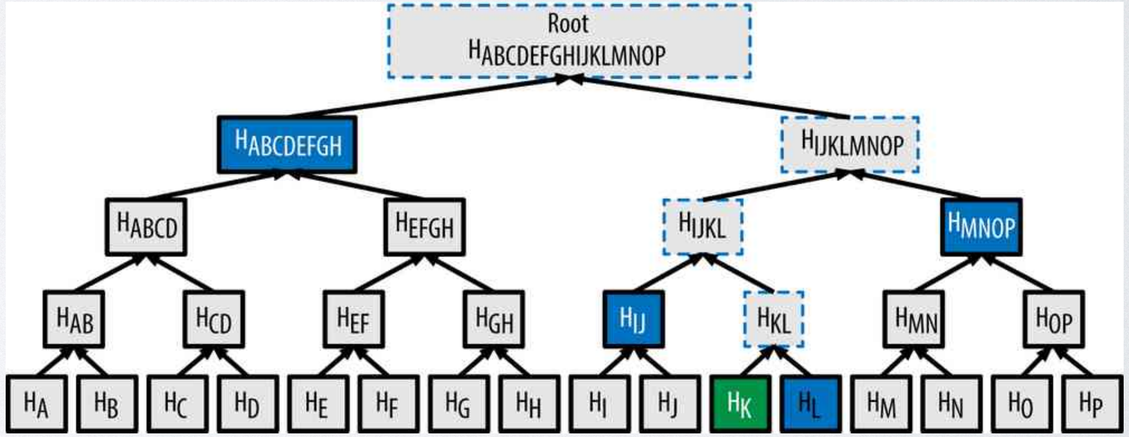
- Once *v+1 has seen 2f view-change messages, it multicasts a new-view message*
- *This message contains all the valid view change messages received by v+1 as well as a set O of all requests that may not have been completed yet (due to primary failure).*
  - *After a replica receives a valid view-change message, it enters view v+1 and processes O*
  - *While view change is occurring, no new requests are accepted.* 24

BlockChain 1: CryptoCurrency

- BitCoin: A Peer-to-Peer Electronic Cash System https://bitcoin.org/bitcoin.pdf
- Solved in a logically simple but computationally inefficient way the double-spend problem on a distributed ledger with uncensored hosts
- Proof of Work: Do the work up front. Fastest worker (miner) wins. Solve cryptographic hash proof.
- Validation: All the workers (miners) validate. Majority rules.



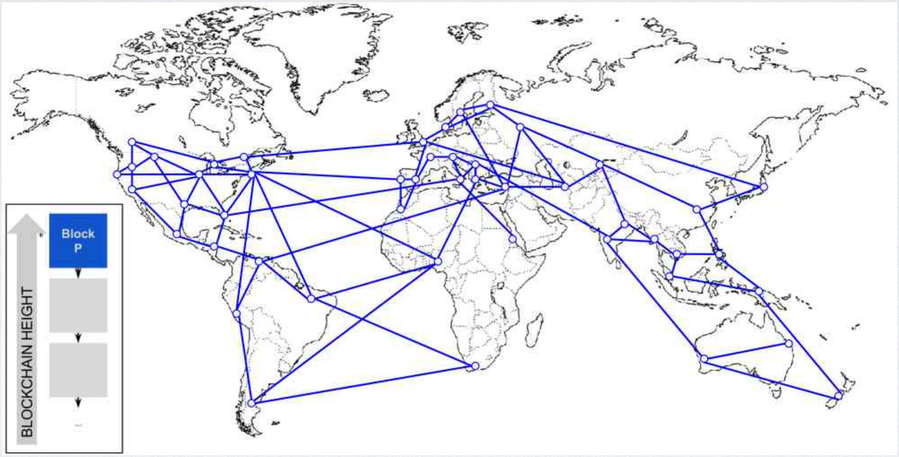
Simplified Bitcoin Block Chain

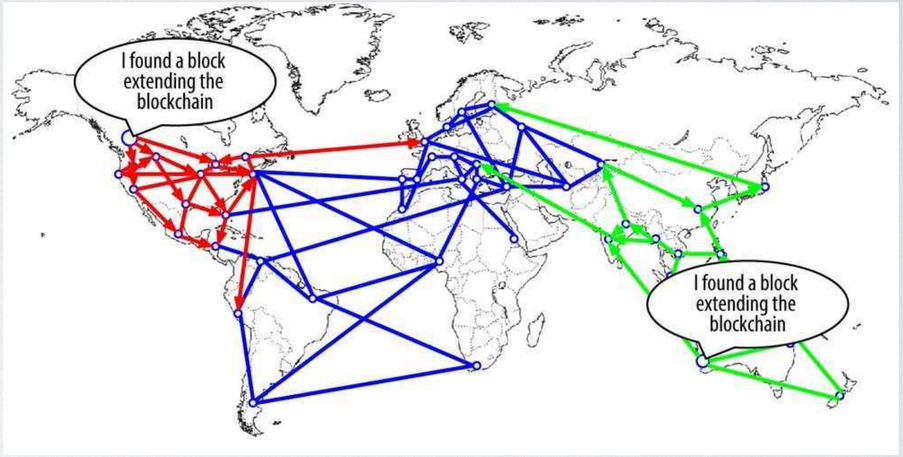


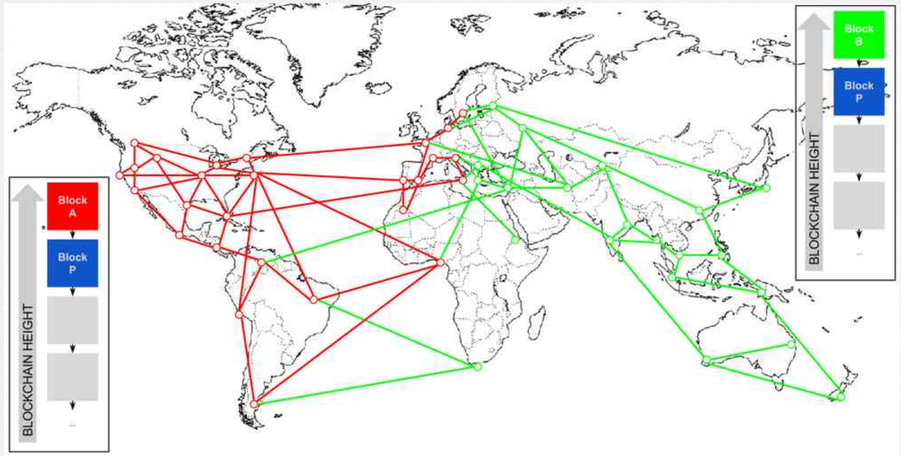
BlockChain 1: Proof of Work

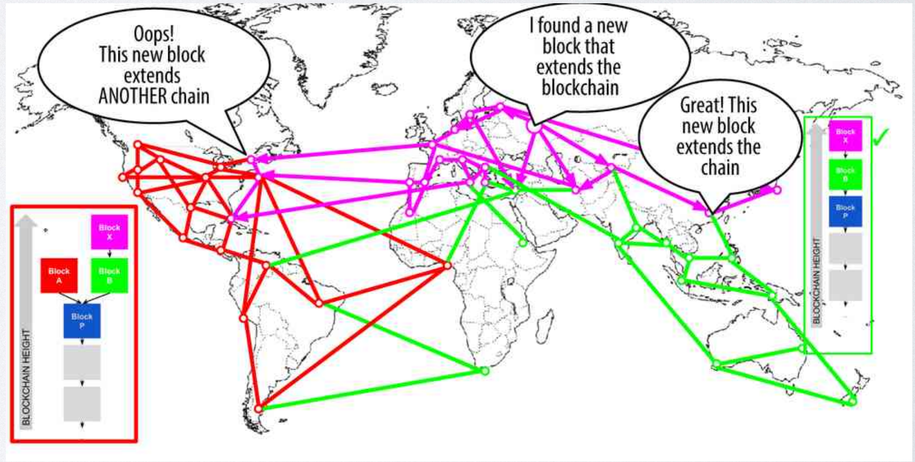
- Every new block requires proof of work.
- To change a block down in the chain requires reworking all the blocks above it.
- Deep enough blocks become exponentially difficult to change.
- In order to double spend, one must control a majority of the compute power to create a forked chain and then collude with spenders to reverse and then respond prior spends.
- Transactions made by other spenders cannot be double spent.

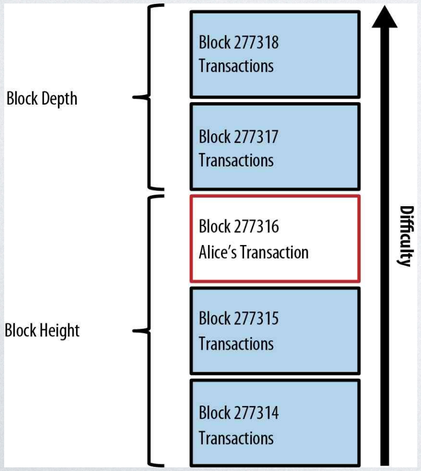
- Multi Billions of currency outside of any firewall. Safe from attack











Elliptic Curve Cryptography

- Fast, efficient, most secure.
- Both encryption/decryption and signing/validation
- Public Private Key exchange
- Secret Sharing
- Key Blinding
- End to End Encryption with Authentication after Encrypt

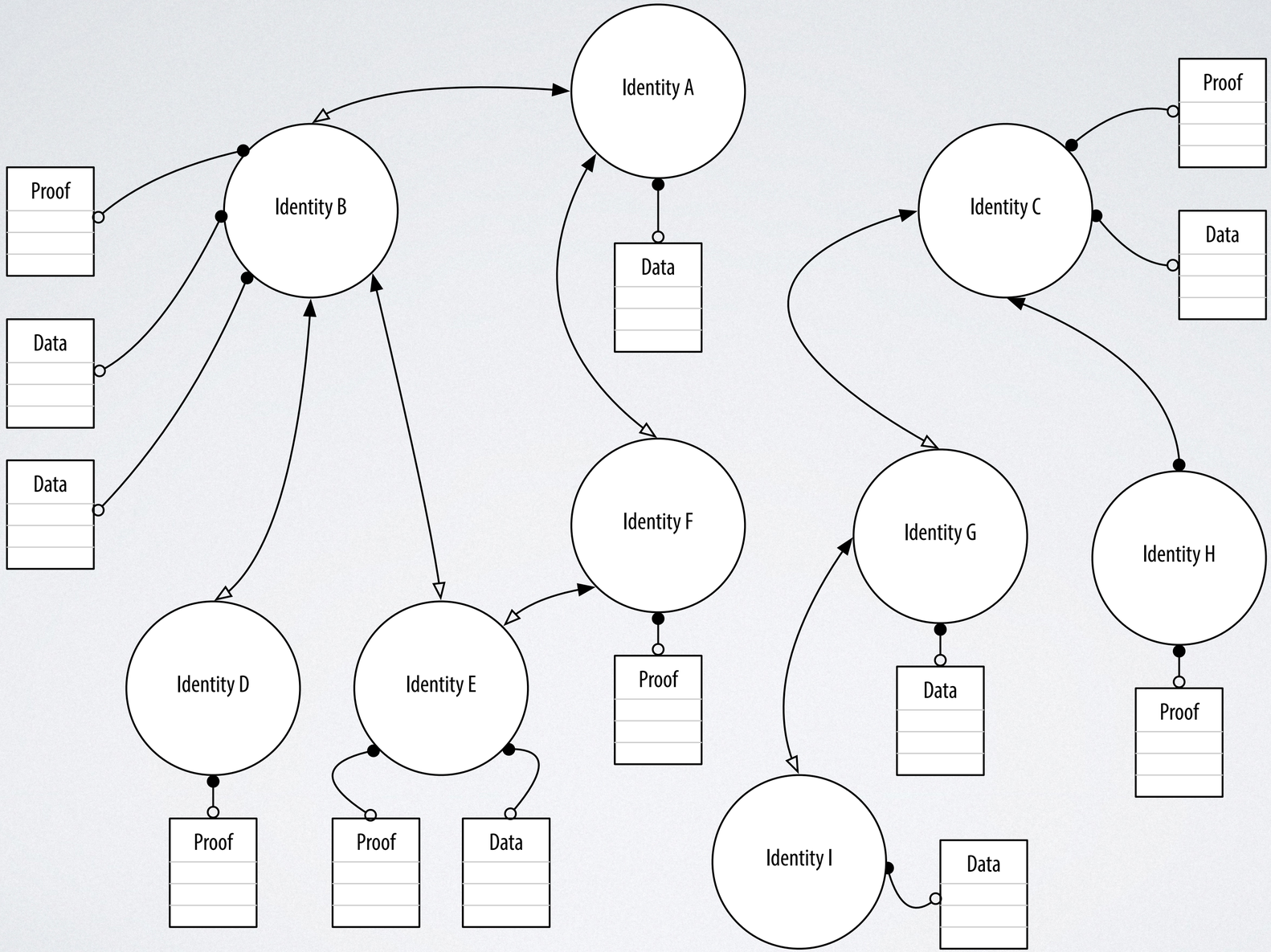
BlockChain 2

- Smart Contracts:
  - Terms and conditions codified in the ledger.
  - Distributed consensus enforces terms and conditions
- Other assets managed by distributed consensus
- Identity managed by distributed consensus
- Distributed Autonomous Organizations and Services.

IDENTITY

- Entity: Uniquely Identifiable, Individual or Group
- Identifier: Symbol uniquely associated with an entity
  - Cryptonym: Globally unique cryptographic key
  - Aliases: Human friendly globally unique string
  - Email
  - Phone number
  - URL
  - Self certifying URL
- Proofs: Verifiable information that associates an identifier with an entity
- Data: Relevant information about entity
- Identity Graph: Relationships between identifiers, proofs, and descriptors
- Identity: Data structure: Identity graph, proofs, data
- Hierarchical Deterministic Cryptonyms

Identity Graph



PRIVACY

- Three Degrees of Privacy:
  - Full Public: Public (non-anonymous) Identifiers and Public (unencrypted) Descriptors/Proofs
  - Semi-Private: Public (non-anonymous) Identifiers and Private (encrypted) Descriptors
  - Full Private: Private (anonymous) Identifiers and Private (encrypted) Descriptors
- Group Privacy: Class or Attribute Identifiers
  - Identifier associates entity as a member of a group of entities essentially anonymizing the entity
  - Allows sharing of data without correlation
  - Principle only share enough data to enable the transaction and no more
- Controllability, Observability, Traceability

Key Management

- Multi-Signature
- Hierarchical Deterministic Keys
- Key Recovery
- Secret Sharing
- Group Keys