Quorum Whitepaper

1 Introduction

Smart Contracts on a replicated, shared ledger hold the promise of improving efficiency and lowering costs compared with existing enterprise systems based on duplicated business logic and consensus by reconciliation. Existing smart contract systems on replicated shared ledgers are unable to provide data privacy; transactions and smart contract state data are exposed in the clear on the replicated shared ledger. A number of proposals to address the lack of data privacy with Smart Contracts are beginning to emerge involving methodologies such as homomorphic encryption, zero-knowledge proofs, secure multi-party computation, ledger segmentation, cryptographic protocols, etc. This paper outlines a simpler approach to privacy built on the Ethereum platform. Though the design is simple, the solution preserves many of the key attributes of Ethereum such as ensuring every node on the network participates in and increases the overall security of the entire network while only revealing the details of private transactions to those party to the transactions.

This paper focuses on the modifications to standard Ethereum in order to support the desired 'Enterprise' requirements. This paper assumes the reader is familiar with Ethereum and has read the Ethereum whitepaper[1].

2 Quorum

Quorum is a private/permissioned blockchain based on the official Go implementation of the Ethereum protocol[2]. Quorum uses a 'raft-based' consensus algorithm (a consensus model for faster blocktimes, transaction finality and on-demand block creation), and achieves Data Privacy through the introduction of a new "private" transaction type. One of the design goals of Quorum is to reuse as much existing technology as possible, minimizing the changes required to go-ethereum in order to reduce the effort required to keep in sync with future versions of the public Ethereum code base.

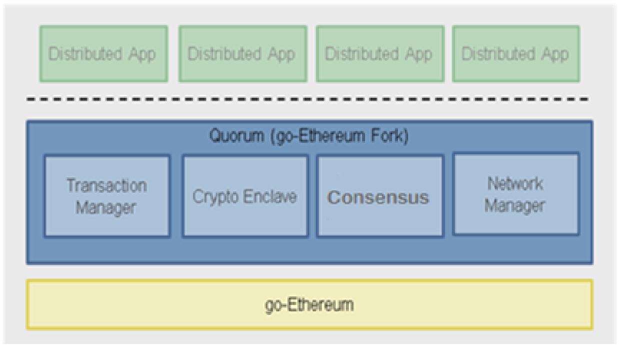
Much of the logic responsible for the additional privacy functionality resides in a layer that sits atop the standard Ethereum protocol layer. Figure 1 below provides a high-level overview of the Quorum blockchain platform and architectural components.

[1] https://github.com/ethereum/wiki/wiki/White-Paper
[2] https://github.com/ethereum/go-ethereum

Highlights

- **Built on Ethereum**
  - First mover advantage. In production since July, 2015.
  - 50,000+ unit tests, Security Audits, Bounty Program
  - Largest Ecosystem of Developers, Tools, Dapp's
  - Public Ethereum blockchain protects over $1B+ Ether'
- **Simple Privacy Design**
  - Supports both Public and Private transactions and smart contracts
- **Single Blockchain Architecture**
  - All public/private smart contracts and their state derived from a single, common, complete blockchain of transactions validated by every node in the network
  - Private smart contract state is updated for parties to contract only.
  - Best of both worlds… every node validating the list of transactions while only exposing details of private transactions and contracts to relevant parties
- **High Performance**
  - Able to process hundreds of transactions per second depending on system profiling.

Architecture



Components

- **Transaction Manager –** allows access to encrypted transaction data for private transactions, manages local data store and communication with other transaction managers.
- **Crypto Enclave** – responsible for private key management and encryption and decryption of private transaction data.
- **Consensus**
  - **Raft-Based -** consensus model for faster block time, on-demand block creation and better transaction finality
  - **Istanbul BFT** – Three Phase consensus, better fault tolerance , self verifiable blocks.
- **Network Manager** – controls access to the network, enabling a permissioned network of nodes to be created.

Figure 1 - Quorum Overview

The basic idea behind Quorum is to use cryptography to prevent all except those party to the transaction from seeing sensitive data. The solution involves a single shared blockcain and a combination of smart contract software architecture and modifications to Ethereum. The smart contract architecture provides segmentation of private data. Modifications to the go-ethereum codebase include modifications to the block proposal and validation processes. The block validation process is modified such that all nodes validate public transactions and any private transactions they are party to by executing the contract code associated with the transactions. For other "private transactions", a node will simply skip the contract code execution process.

This will result in a segmentation of the state database, i.e. the state database is split into a private state database and a public state database . All nodes in the network are in perfect state consensus on their public state. The private state databases will differ. Even though the client node state database no longer stores the state of the entire global state database, the actual distributed blockchain and all the transactions therein are fully replicated across all nodes and cryptographically secured for immutability. This is an important distinction relative to other segmentation strategies based on multiple block chains and adds to the security and resiliency of the design (see figure 2 below).

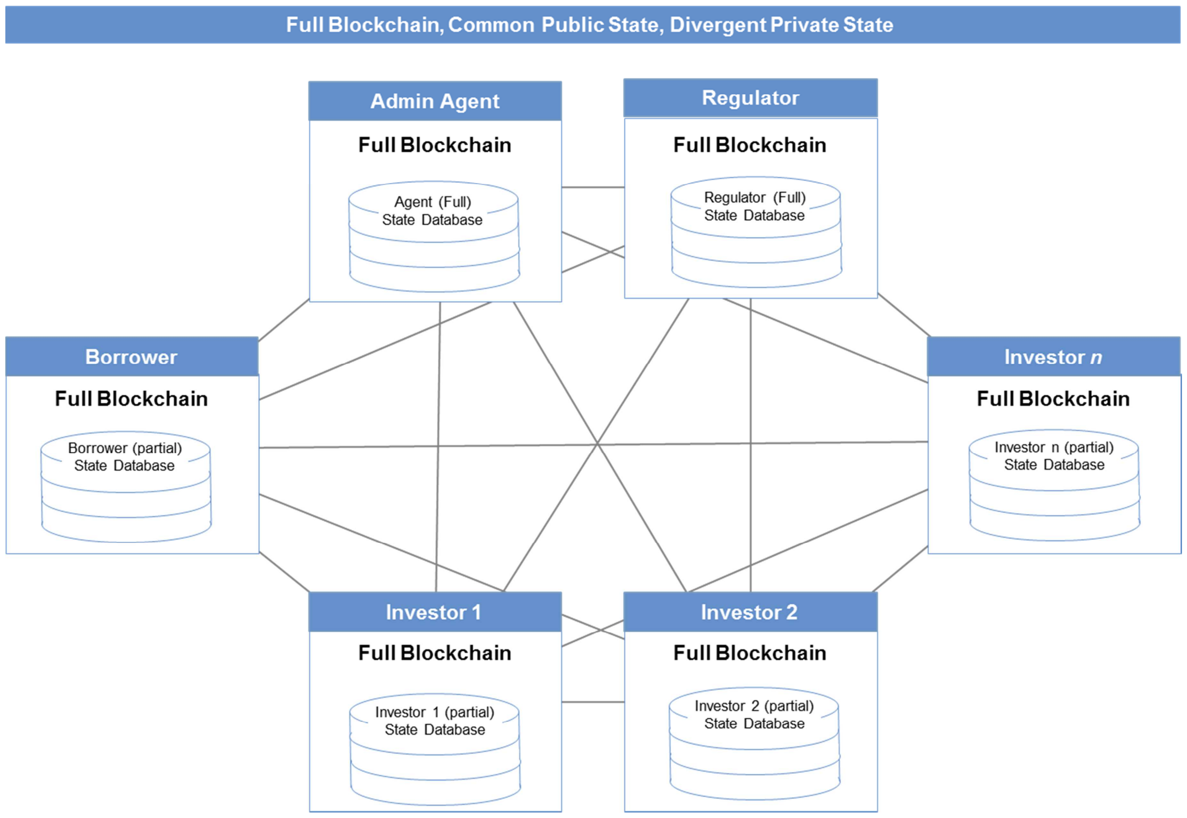

Full Blockchain, Common Public State, Divergent Private State
Admin Agent
Full Blockchain
Agent (Full) State Database
Regulator
Full Blockchain
Regulator (Full) State Database
Borrower
Full Blockchain
Borrower (partial) State Database
Investor n
Full Blockchain
Investor n (partial) State Database
Investor 1
Full Blockchain
Investor 1 (partial) State Database
Investor 2
Full Blockchain
Investor 2 (partial) State Database

Figure 2 - Quorum Network

3 Consensus

Quorum currently implements 2 consensus mechanisms – Raft (default) & Istanbul BFT. Enabling one or the other is done via flags passed at start up time to the node client.

3.1 Raft

This implementation is useful for a closed-membership/consortium setting where Byzantine fault tolerance is not a requirement, i.e. where there is leader/follower model and forking is disallowed ensuring transaction finality. There is a single leader for the entire cluster through which all log entries will flow through. There is a one-to-one correspondence between Raft and Ethereum nodes (i.e. a Raft node is also an Ethereum node) and the leader (“minter”) is the only node that should mint new blocks. The minter bundles transactions into a block without presenting a POW (proof of work).

The leader is elected after a period of voting and during that period all nodes assume the role ‘candidate’. Once a leader is elected by majority , the node which won the election takes the ‘leader’ role and all other nodes take a ‘follower’ role. When the leader/minter creates a block, the block is set to be the new head of the chain only after the block has has been verified by the majority of Raft nodes. All nodes will then extend the chain together. This differs from Ethereum where the block is written to the database and immediately considered the new head of the chain.

For more details on Raft-based consensus, please refer to the Raft Consensus Documentation.

3.2 Istanbul BFT (Byzantine Fault Tolerance)

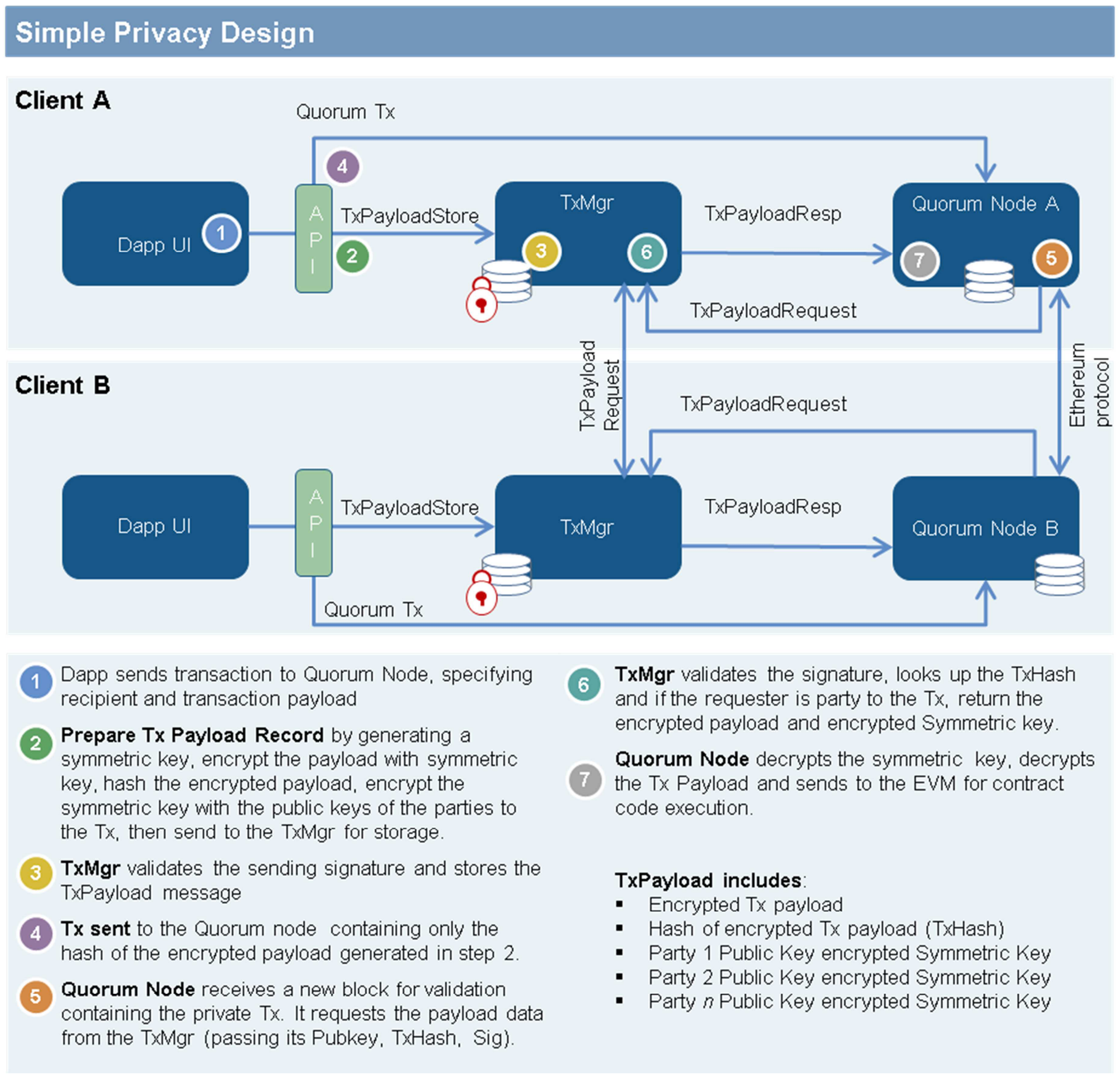
Istanbul-BFT consensus is a three-phase consensus: PRE-PREPARE, PREPARE and COMMIT. Through this consensus the system can tolerate up to one-third of all block 'validator' nodes in the network being faulty, yet still ensure transaction finality. Nodes which are elected as block 'validators' pick a 'proposer' node to propose a new block in a consensus round. The proposer will then propose a new block proposal and broadcast it along with the PRE-PREPARE message. Upon receiving the PRE-PREPARE message from the proposer, validators enter the state of PRE-PREPARED and then broadcast a PREPARE message. This step is to make sure all validators are working on the same sequence and the same round. After receiving the PREPARE message from two-thirds of the network nodes, the validator enters the state of PREPARED and then broadcasts a COMMIT message. This step is to inform its peers that it accepts the proposed block and is going to add the block to the chain. Lastly, validators wait for two-thirds of the COMMIT messages to enter the COMMITTED state and then insert the block to the chain.

Blocks commited using this consensus protocol are final which means no forking. To prevent a faulty node from generating a totally different chain from the main chain, each validator appends the received commit signature to an 'extradata' field in the block header thereby making all blocks self-verifiable.

For more details on Istanbul BFT consensus, please refer Istanbul BFT Consensus Documentation.

4 Data Privacy

Data privacy in Quorum is achieved through cryptography and segmentation. Cryptograhy is applied to the data in transactions (which everyone sees on the blockchain). Segmentation is applied to each node's local state database (which contains the contract storage and is only accessible to the node). Only nodes party to private transactions are able to execute the private contract code associated with the transactions, which results in updating the private contract data storage in the local state database. The result is that each node's local state database is only populated with public and private data they are party to. Figure 3 below outlines the high-level logical design of the Quorum privacy solution.



1. Dapp sends transaction to Quorum Node, specifying recipient and transaction payload
2. **Prepare Tx Payload Record** by generating a symmetric key, encrypt the payload with symmetric key, hash the encrypted payload, encrypt the symmetric key with the public keys of the parties to the Tx, then send to the TxMgr for storage.
3. **TxMgr** validates the sending signature and stores the TxPayload message
4. **Tx sent** to the Quorum node containing only the hash of the encrypted payload generated in step 2.
5. **Quorum Node** receives a new block for validation containing the private Tx. It requests the payload data from the TxMgr (passing its Pubkey, TxHash, Sig).
6. **TxMgr** validates the signature, looks up the TxHash and if the requester is party to the Tx, return the encrypted payload and encrypted Symmetric key.
7. **Quorum Node** decrypts the symmetric key, decrypts the Tx Payload and sends to the EVM for contract code execution.

TxPayload includes:
- Encrypted Tx payload
- Hash of encrypted Tx payload (TxHash)
- Party 1 Public Key encrypted Symmetric Key
- Party 2 Public Key encrypted Symmetric Key
- Party *n* Public Key encrypted Symmetric Key

Figure 3 - Simple Privacy Design

4.1 Private Transactions and Private Contracts

Private transactions are facilitated through an API exposed to the Dapp that originates the transaction. A private contract is simply a contract created by a private transaction.

During the block construction and validation process the node party to the private transaction will decrypt the transaction data prior to sending it to the EVM. The EVM therefore does not need to support encryption/decryption operations. The private state data of a private contract is stored in the clear in the local state database of the nodes party to the transaction.

4.1.1 Private Transactions

A Private Transaction is a transaction that only carries a 256-bit hash in the data field. It is also identified by the parameter ‘v’ of the transaction object being 37 or 38 (in contrast to Ethereum’s usual 27 or 28).

In addition to the basic data a typical Ethereum sendTransaction accepts, the new API takes a list of public keys that identify the parties to the transaction (privateFor). With this data a standard Ethereum transaction is generated where the payload is simply the hash of the encrypted private data. This newly formed Ethereum transaction carrying only the cryptographic hash is sent to the Quorum node where it is distributed out to all the nodes in the network as a pending transaction.

A Quorum transaction contains:

- The recipient
- Signature identifying the sender
- The amount of ether
- An optional “privateFor “ (identifies the transaction as private and lists the parties privy to the transaction)
- An optional data field (a 256-bit hash in the case of a private transaction)

Figure 3 illustrates the basic steps in producing and sending private transactions.

4.1.2 Private Contracts

A private contract is a contract that was created by a private transaction. The state of private contracts are represented as their own separate Patricia-Merkle trie. One cannot create a private contract with a public transaction because the state of the contract created with a public transaction is recorded in the separate public state Patricia-Merkle trie.

4.2 Block Validation and State Consensus

Standard Ethereum block validation includes a step to confirm the global state of all contracts match the global state hash included in the block header. This is the cryptographic proof that every node in the network has the exact same state database, a provable replica.

The Quorum state database is split into two, a private state and a public state. These are represented in memory as two separate Patricia-Merkle trees. Quorum block validation only matches on the public state.

Private state consensus is passed up to the application layer and is supported by a new *storageRoot* RPC API. When parties to a private contract require cryptographic state consensus evidence, the application can retrieve the private contract state hash for a specified block and share this value with the parties to the contract either off-chain or through an on-chain transaction. It should be noted that a specific application design may not require or infact expect parties to the same contract to have different state (see section 5.1 Payments for an example). It should also be noted that if public state consensus is achieved, it should be impossible for parties to a private transaction to be out of consensus. This is because:

1. Validating a block includes global transaction hash consensus and public state consensus and a few other checks.
2. The EVM is deterministic – the same inputs always generate the same outputs.
3. The inputs are the same because we’re confirming consensus on the list of transactions.

4. We know we're using the same blockchain of transactions because we are achieving public state consensus.
5. If we have the same blockchain of transactions and the public transactions result in public state consensus and since the EVM is deterministic then it should be impossible to have the EVM produce a different state of a private contract by processing a private transaction.

In public Ethereum, in practice, the only time blocks are invalidated is due to a fundamental configuration problem, for example if your genesis block is misconfigured. Once you are properly connected to the network and syncing blocks with your peers, you never actually fail blocks because of a global consensus break. Occasionally in the public network a malicious node(s) will attempt to send bad blocks. Of course the threat of a malicious node is more real in the public Ethereum network so it's critically important to validate global consensus but in reality, because everyone knows that a malicious node would be detected and their blocks rejected no one bothers with that attack vector.

In permissioned Quorum, the same sort of thing occurs in that if you have a fundamental configuration problem, you will quickly see blocks not validating and syncing with the network. If you are able to get blocks to sync by only looking at public state (and don't forget every block has public transactions for block voting) then there is no fundamental configuration problem and nodes party to the same private transactions and contracts will deterministically arrive at the same private state for those contracts. Throwing in the failsafe detection of comparing private contract state hashes (at the application layer) is a simple and easy way and a good practice to detect malicious nodes if that's what your design calls for.

4.3 Privacy through Sharding?

It's worth mentioning that the Quorum privacy design exhibits several properties of sharding techniques that have been proposed to enhance the performance and throughput of blockchain networks. Sharding basically segments the validation of transactions such that not every node in the network is validating every transaction. In Quorum, a node is only processing transactions that are public or private transactions that they are party to.

5 Performance

Tests of Quorum have demonstrated throughput of dozens to hundreds of transactions per second depending on system configuration. No specific code changes were required; the block gaslimit parameter enabling the node to pack in many more transactions per block was simply updated. The gating factor on throughput is the rate at which the Quorum node is able to validate blocks in which the processing of transactions must be serial.

6 Applications

Financial applications come first to mind when considering the requirements for privacy. In a consortium network of multiple financial institutions, it is essential to ensure the details of transactions between financial institutions are not revealed to other financial institutions that are not party to the transactions. This is for both client privacy concerns as well as meeting legal and regulatory requirements. Several financial application use cases have been considered during the design of the privacy solution of Quorum. From various (simple, high throughput) payment applications to derivative and securities use cases.

It's important to understand the Quorum privacy design does impose constraints on the application design. For example, updating a public contract state from a private contract is not permitted. Also, a private contract may not create a public contract. In general, private transactions cannot change public state as doing so would break the block validation/consensus algorithm.

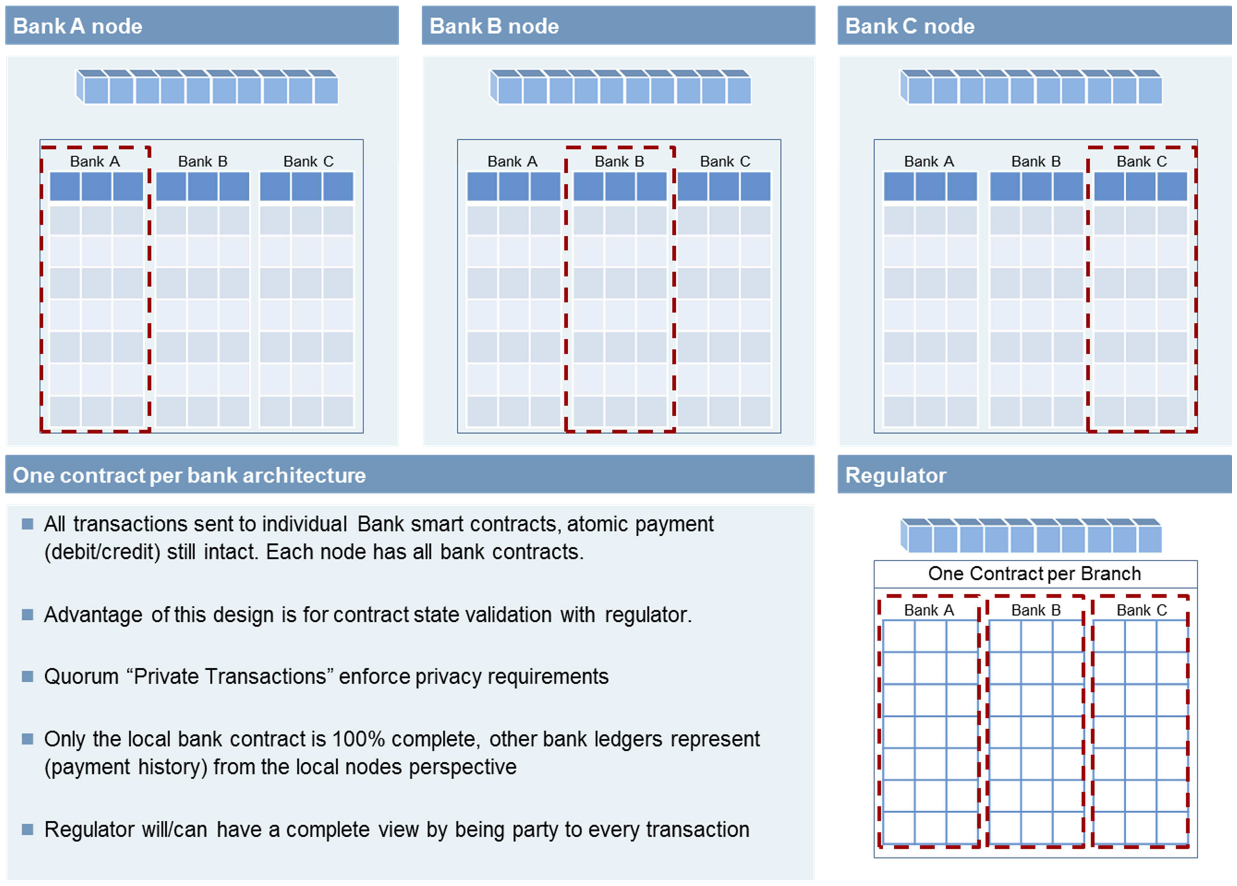
Nevertheless, these constraints have not been unsurmountable in finding an application/smart contract design for the financial use cases considered to date.

6.1 Payments

Various payment type use cases are useful proxies for many other financial applications. The simplest form of payment use case does not even require the use of smart contracts. The consenus critical information can be represented entirely in the data of the transaction itself and the blockchain of transactions.

Other types of payment applications may choose to use smart contracts to keep track of balances in lines of credit. Having the flexibility to manage private state consensus at the application layer is a powerful tool to help find designs to solve for the functionality and privacy requirements of many use cases. For example, consider an inter-bank payment use case where a payment from an account at Bank A is made to an account at Bank B. Bank C is not party to the payment and should not be able to know any information associated with this payment. It is the goal of the application design to ensure that sufficient balance exists in accounts to cover the payment.

One particular design calls for the creation of a 'Bank' contract for each bank as illustrated in Figure 4. In this design each Quorum node in the network would have 3 contracts, one for each Bank A, B, and C. In addition, a regulator node would be part of the network and would be party to all payment transactions. It is a further design requirement that payment transfers between accounts and banks be atomic operations, i.e. a single transaction must update both Bank contracts, all or nothing. In this design, the state of contract Bank A would only be in consensus with the Regulator node (and other Bank A nodes). The Bank A contract on Bank A's node would see all debits and credits between itself and all the Banks in the network. From Bank B's perspective, the state of Contract Bank A would only reflect the debits and credits between Bank A and Bank B, it would not know of any payments between Bank A and Bank C. In this design, the application would seek to confirm state consensus of its own Bank contract with only the regulatory node. By design, the state of the same contract on different Bank nodes would not be in state consensus.



- All transactions sent to individual Bank smart contracts, atomic payment (debit/credit) still intact. Each node has all bank contracts.
- Advantage of this design is for contract state validation with regulator.
- Quorum "Private Transactions" enforce privacy requirements
- Only the local bank contract is 100% complete, other bank ledgers represent (payment history) from the local nodes perspective
- Regulator will/can have a complete view by being party to every transaction

Figure 4 - Sample Payments contract design

7 Conclusion

The Quorum design outlined in this paper demonstrates how the seminal Ethereum platform can be extended to meet the key requirements of enterprise and in particular, financial institutions in preserving privacy in a distributed, decentralized blockchain consortium network. By building on Ethereum, Quorum inherits the maturity of the production hardened go-ethereum code base as well as helps unite the public and enterprise development communities on a common protocol.