ITU Workshop on "Security Aspects of Blockchain" (Geneva, Switzerland, 21 March 2017)

Blockchain, cryptography, and consensus

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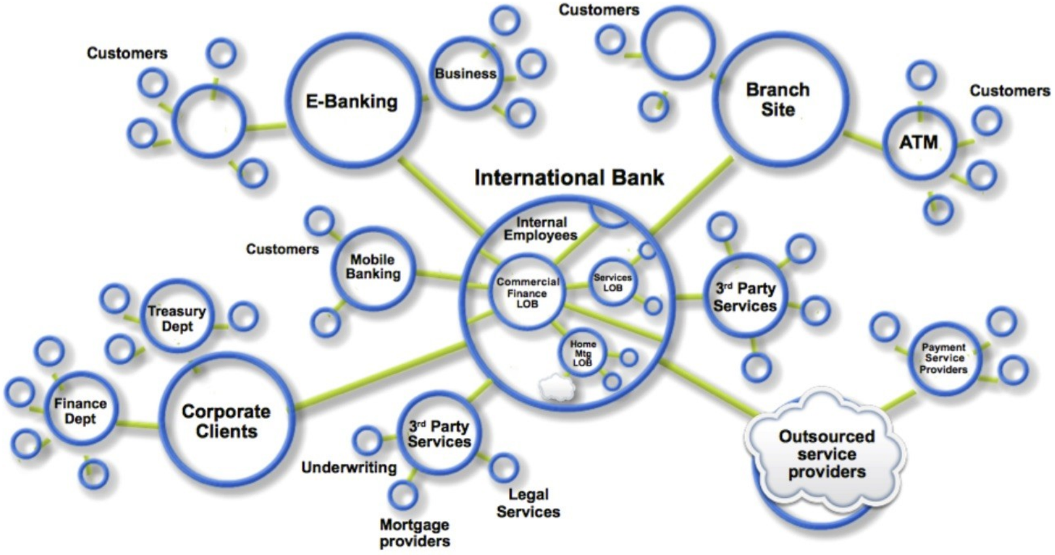
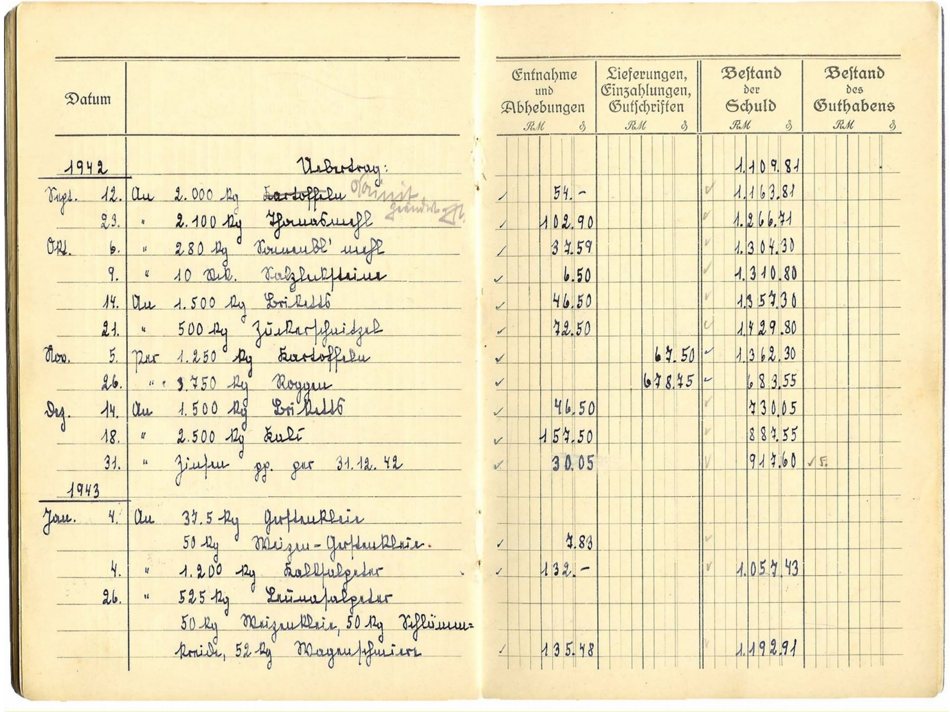
Connected markets

- Networks connect participants
  - Customers, suppliers, banks, consumers
- Markets organize trades
  - Public and private markets
- Value comes from assets
  - Physical assets (house, car ...)
  - Virtual assets (bond, patent ...)
  - Services are also assets
- Transactions exchange assets

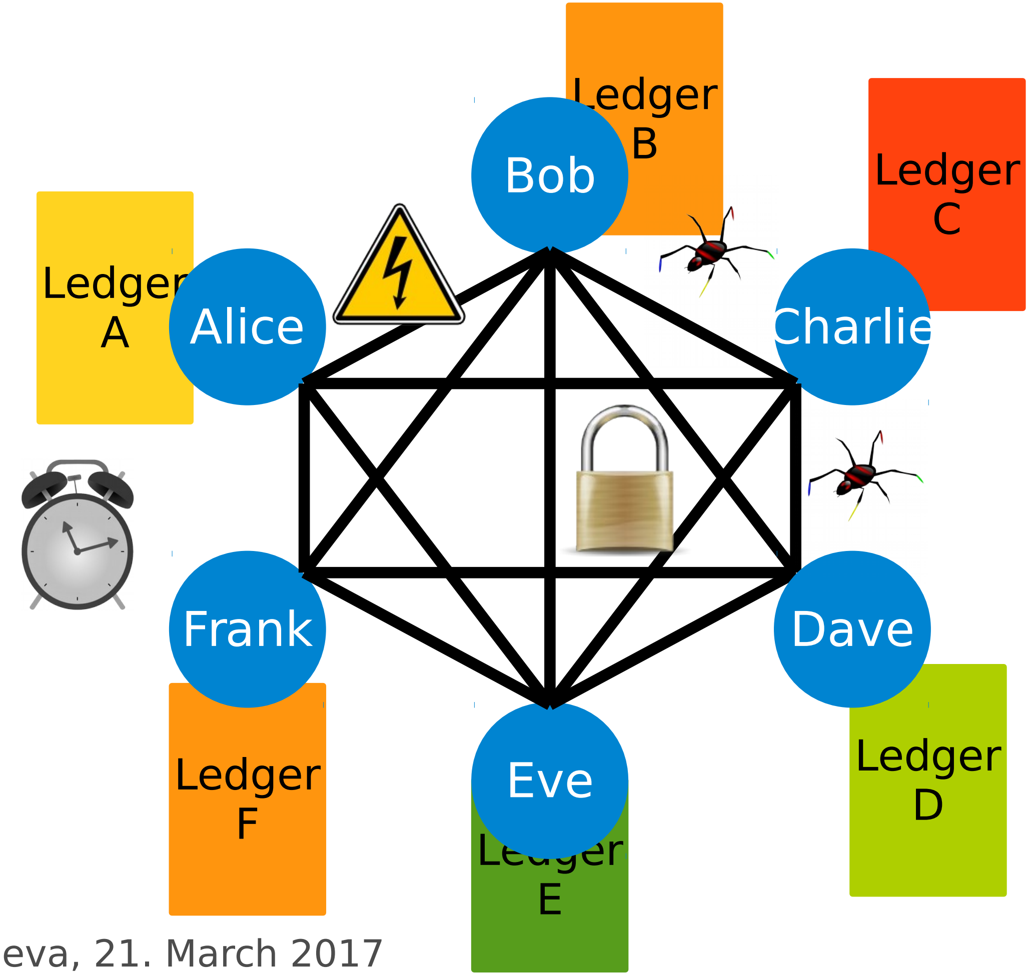


Ledger



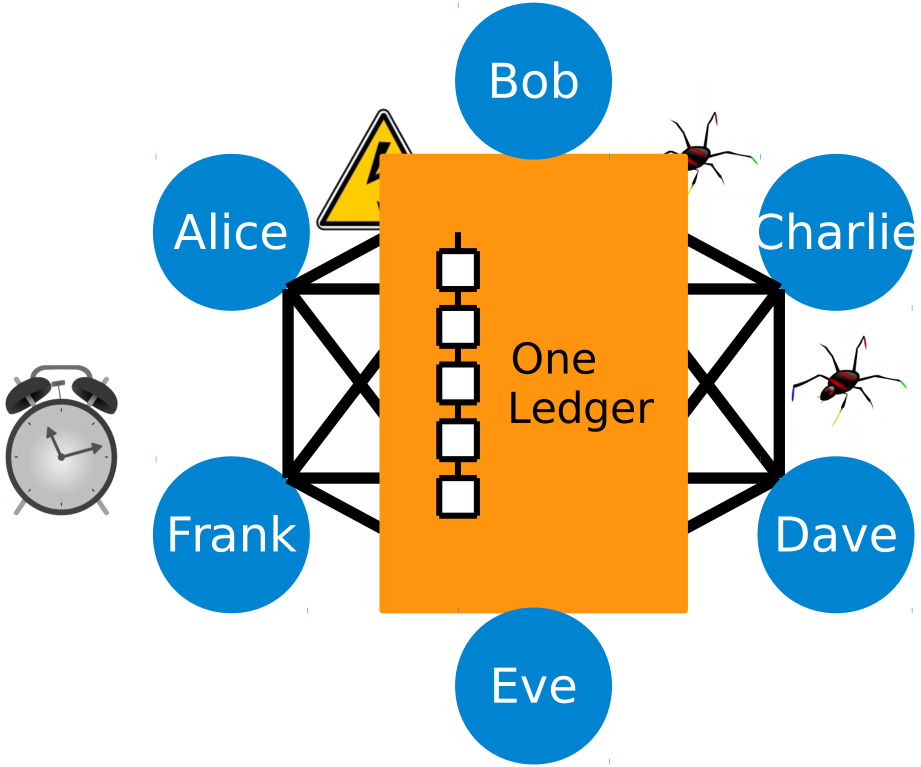
- Ledger records all business activity as transactions
  - Databases
- Every market and network defines a ledger
- Ledger records asset transfers between participants
- Problem — (Too) many ledgers
  - Every market has its ledger
  - Every organization has its own ledger

Multiple ledgers



- Every party keeps its own ledger and state
- Problems, incidents, faults
- Diverging ledgers

Blockchain provides one virtual ledger



- One common trusted ledger
- Today often implemented by a centralized intermediary
- Blockchain creates one single ledger for all parties
- Replicated and produced collaboratively
- Trust in ledger from
  - Cryptographic protection
  - Distributed validation

Four elements characterize Blockchain

Replicated ledger

- History of all transactions
- Append-only with immutable past
- Distributed and replicated

Cryptography

- Integrity of ledger
- Authenticity of transactions
- Privacy of transactions
- Identity of participants

Consensus

- Decentralized protocol
- Shared control tolerating disruption
- Transactions validated

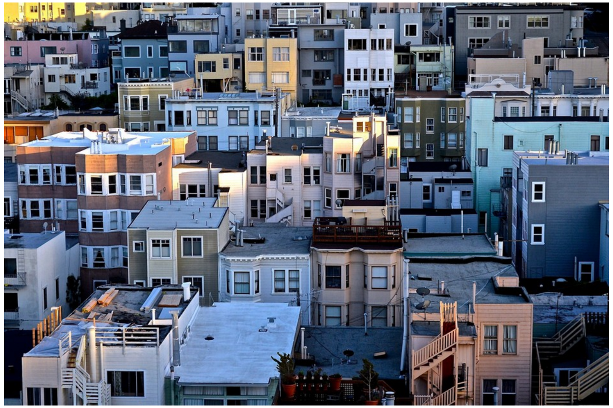
Business logic

- Logic embedded in the ledger
- Executed together with transactions
- From simple "coins" to self-enforcing "smart contracts"

Blockchain simplifies complex transactions

Logistics

Real-time visibility
Improved efficiency
Transparency & verifiability
Reduced cost



Property records

Digital but unforgeable
Fewer disputes
Transparency & verifiability
Lower transfer fees

Capital markets

Faster settlement times
Increased credit availability
Transparency & verifiability
No reconciliation cost

Why blockchain now?

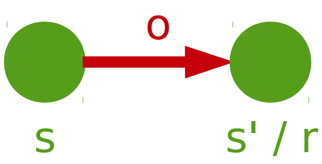
- Cryptography has been a key technology in the financial world for decades
  - Payment networks, ATM security, smart cards, online banking ...
- Trust model of (financial) business has not changed
  - Trusted intermediary needed for exchange among non-trusting partners
  - Today cryptography mostly secures point-to-point interactions
- Bitcoin started in 2009
  - Embodies only cryptography of 1990s and earlier
  - First prominent use of cryptography for a new trust model (= trust no entity)
- The promise of Blockchain – Reduce trust and replace it by technology
  - Exploit advanced cryptographic techniques

What is a blockchain?

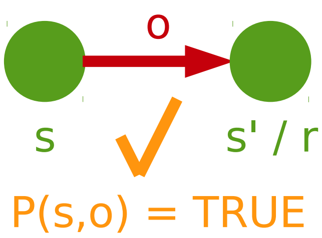
A state machine

- Functionality F
  - Operation o transforms a state s to new state s' and may generate a response r

$(s', r) \leftarrow F(s, o)$

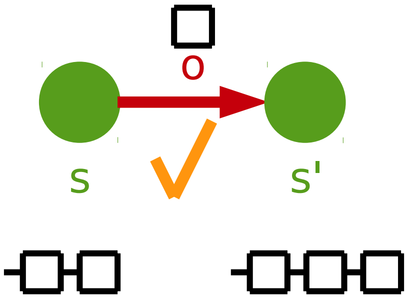


- Validation condition
  - Operation needs to be valid, in current state, according to a predicate P()



Blockchain state machine

- Append-only log
  - Every operation o appends a "block" of valid transactions (tx) to the log



- Log content is verifiable from the most recent element

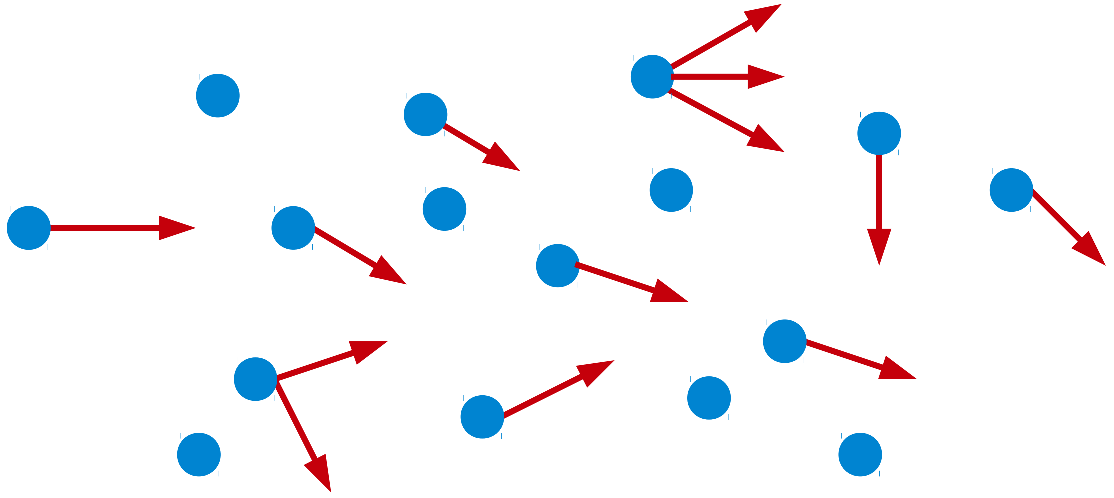
- Log entries form a hash chain

  $h_t \leftarrow \text{Hash}(\ [tx_1, tx_2, \ldots\ ]\ ||\ h_{t-1}\ ||\ t)$.

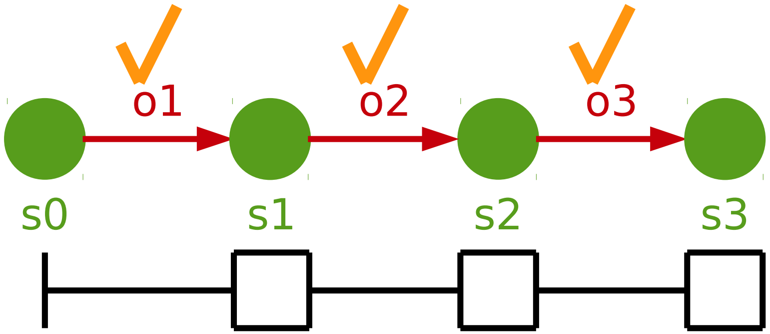
Example – The Bitcoin state machine

- Bitcoins are unforgeable bitstrings
  - "Mined" by the protocol itself (see later)
- Digital signature keys (ECDSA) own and transfer bitcoins
  - Owners are pseudonymous, e.g., 3JDs4hAZeKE7vER2YvmH4yTMDEfoA1trnC
- Every transaction transfers a bitcoin (fraction) from current to next owner
  - "This bitcoin now belongs to 3JDs..." signed by the key of current owner
  - (Flow linkable by protocol, and not anonymous when converted to real-world assets)
- Validation is based on the global history of past transactions
  - Signer has received the bitcoin before
  - Signer has not yet spent the bitcoin

Distributed p2p protocol to create a ledger



Nodes
produce
transactions



Nodes run a
protocol to
construct the
ledger

Blockchain protocol features

- Only "valid" operations (transactions) are "executed"

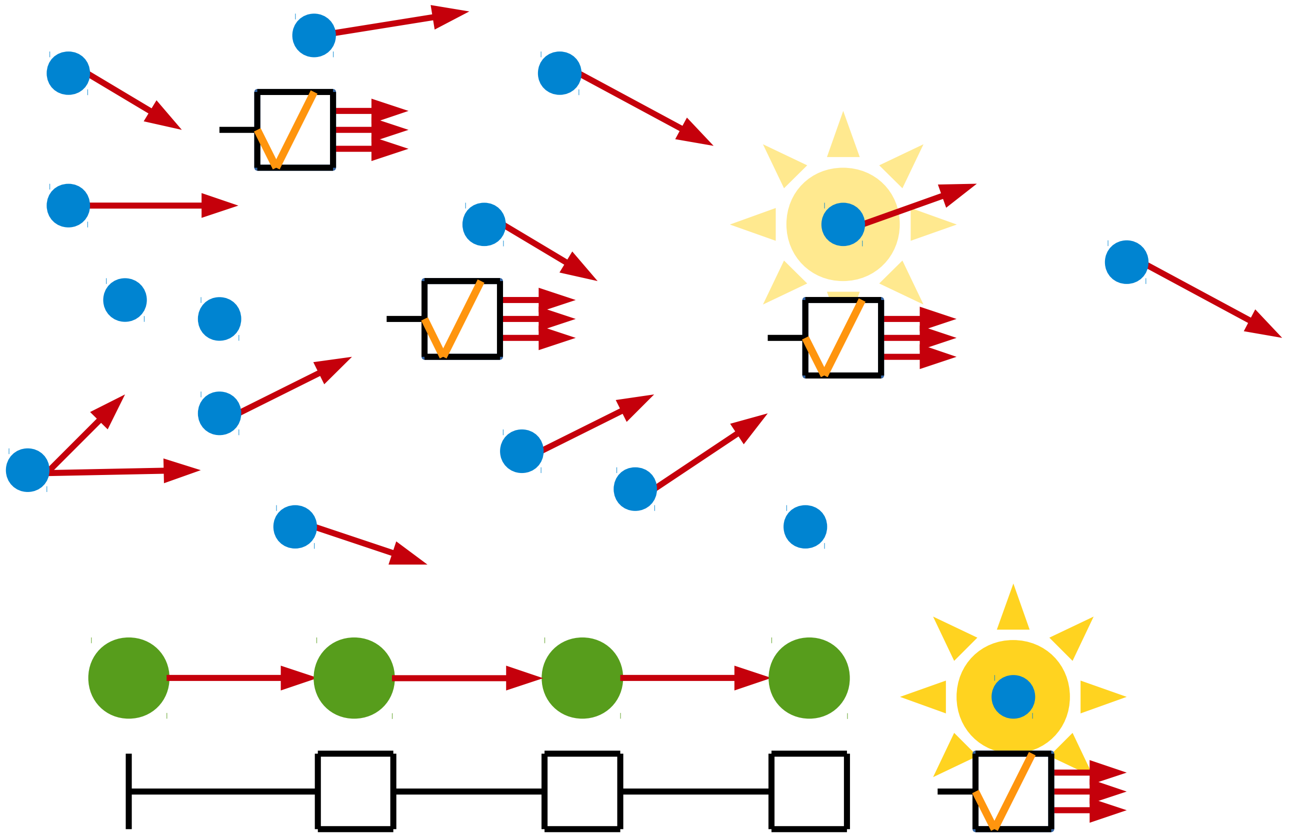
- Transactions can be simple
  - Bitcoin tx are statement of ownership for coins, digitally signed
    "This bitcoin now belongs to K2" signed by K1

- Transactions can be arbitrary code (smart contracts)
  - Embody logic that responds to events (on blockchain) and may transfer assets in response
  - Auctions, elections, investment decisions, blackmail ...

Consensus

Decentralized – Nakamoto consensus/Bitcoin

- Nodes prepare blocks
  - List of transactions (tx)
  - All tx valid
- Lottery race
  - Solves a hard puzzle
  - Selects a random winner/leader
  - Winner's operation/ block is executed and "mines" a coin
- All nodes verify and validate new block
  - "Longest" chain wins



Decentralized = permissionless

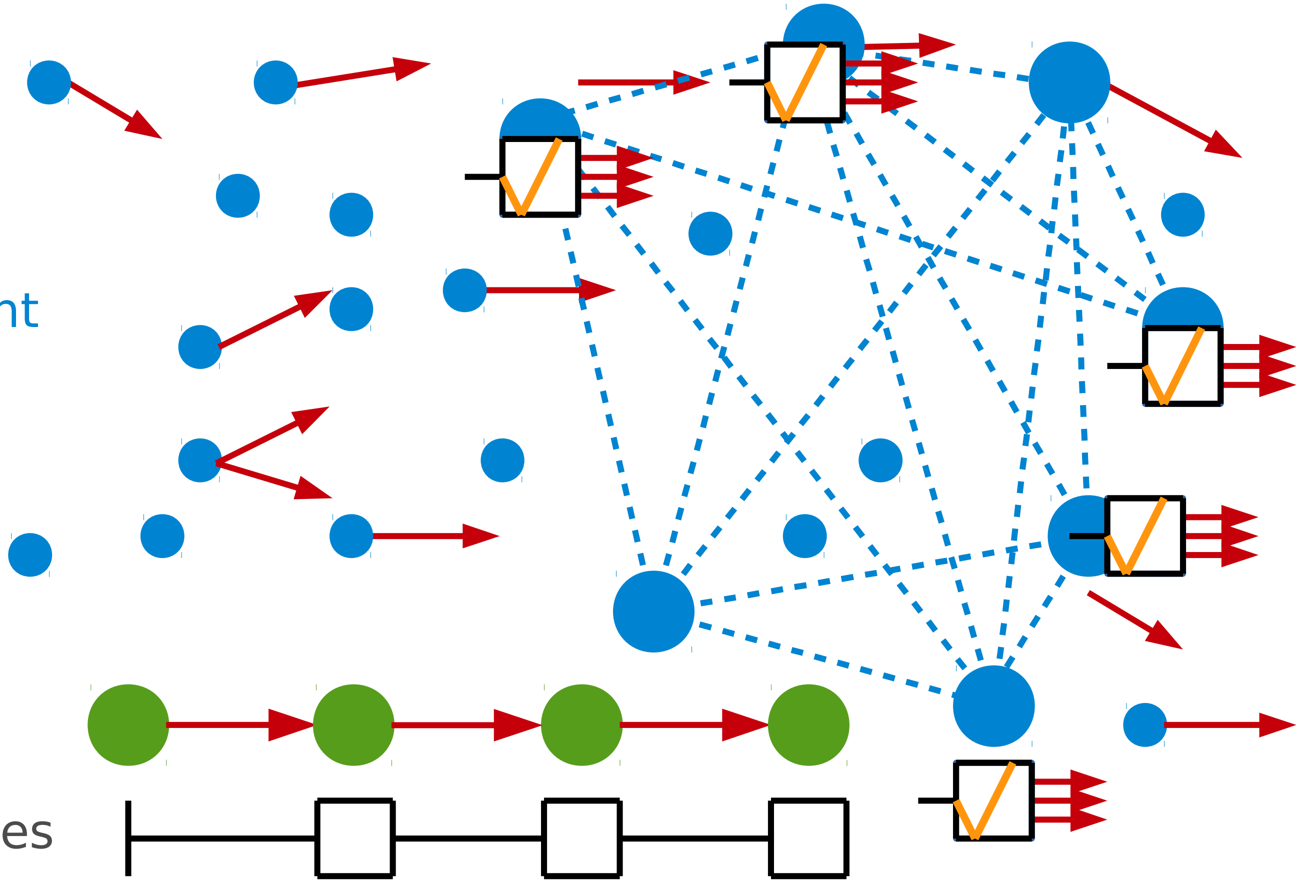
- Survives censorship and suppression
  - No central entity
- Nakamoto consensus requires proof-of-work (PoW)
  - Original intent: one CPU, one vote
  - Majority of hashing power controls network
  - Gives economic incentive to participate (solution to PoW is a newly "mined" Bitcoin)
- Today, total hashing work consumes a lot of electricity
  - Estimates vary, 250-1000MW, from a major city to a small country ...
- Protocol features
  - Stability is a tradeoff between dissemination of new block (10s-20s) and mining rate (new block on average every 10min)
  - Decisions are not final ("wait until chain is 6 blocks longer before a tx is confirmed")

Decentralized – deployment

- Bitcoin
  - Many (100s? 1000s?) of alt-coins and blockchains
- Ethereum
  - First digital currency with general-purpose smart contract execution
- Sawtooth ledger (Intel contribution to Hyperledger)
  - PoET consensus (proof of elapsed time)
    - Nodes run PoET program in "trusted execution environment" (Intel SGX)
    - PoET waits a random amount of time (say, E[wait] = 10min)
    - Creates an attested proof of elapsed time
    - Rest like in Bitcoin protocol

Consortium consensus (BFT, Hyperledger)

- Designated set of homogeneous validator nodes
- BFT/Byzantine agreement
  - Tolerates f-out-of-n faulty/ adversarial nodes
  - Generalized quorums
- Tx sent to consensus nodes
- Consensus validates tx, decides, and disseminates result



Consortium consensus = permissioned

- Central entity controls group membership
  - Dynamic membership changes in protocol
  - Membership may be decided inline, by protocol itself
- Well-understood problem in distributed computing
  - BFT and consensus studied since ca. 1985
    - Clear assumptions and top-down design
    - 700 protocols and counting [AGK+15]
    - Textbooks [CGR11]
    - Open-source implementations (BFT-SMaRT)
  - Many systems already provide crash tolerant consensus (Chubby, Zookeeper, etcd ...)
  - Requires $\Omega(n^2)$ communication (OK for 10-100 nodes, not > 1000s)
- Revival of research in BFT protocols
  - Focus on scalability and communication efficiency

Consortium consensus – under development

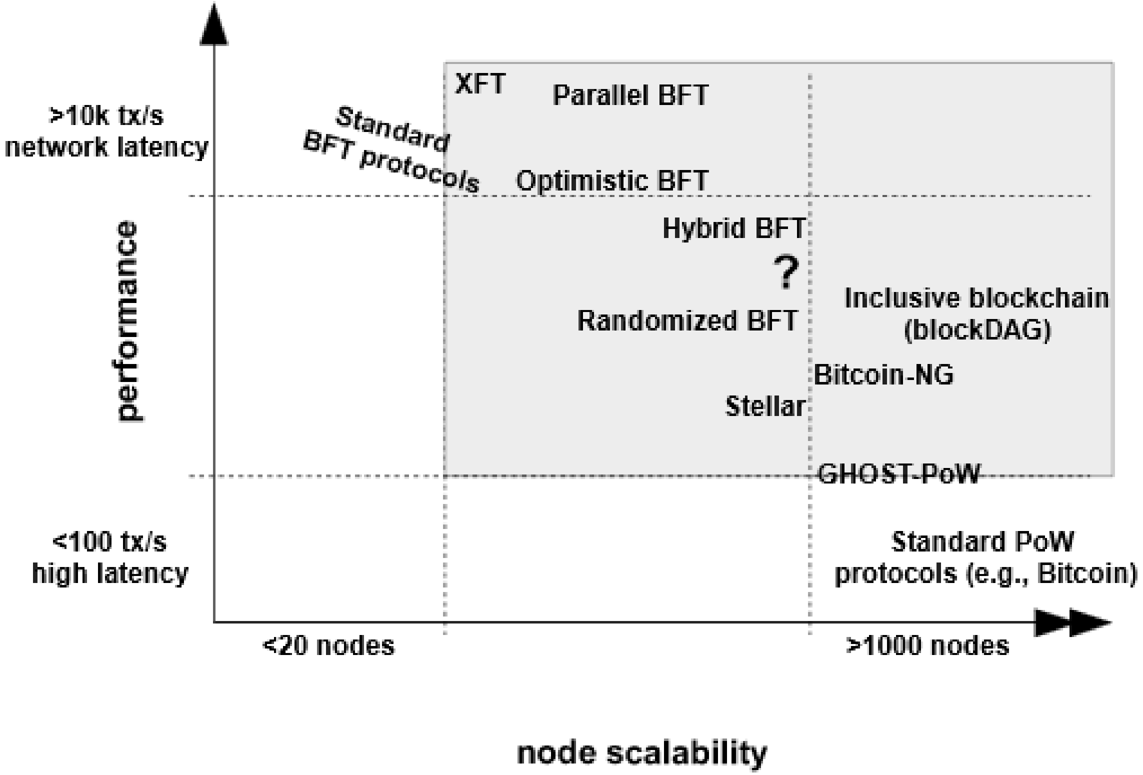
- Hyperledger fabric (IBM's contribution to Hyperledger)
  – Includes PBFT protocol [CL02]

- Tendermint, Juno/Kadena, JPMC Quorum, Axoni, Iroha, Chain and others

- HoneyBadgerBFT [MXC+16]
  – Revisits practical randomized BFT [CKPS01], including amoritzation

- Many existing BFT libraries predate blockchain
  – BFT-SMaRT, Univ. Lisbon (github.com/bft-smart/library)
  – Prime, Johns Hopkins Univ. (www.dsn.jhu.edu/byzrep/prime.html)

Scalability–performance tradeoff



M. Vukolic: The Quest for Scalable Blockchain Fabric: Proof-of-Work vs. BFT Replication. Proc. iNetSec 2015, LNCS 9591.

Validation

Validation of transactions – PoW protocols

- Recall validation predicate P on state s and operation o: P(s, o) ✓

- When constructing a block, the node
  - Validates all contained tx
  - Decides on an ordering within block

- When a new block is propagated, all nodes must validate the block and its tx
  - Simple for Bitcoin – verify digital signatures and that coins are unspent
  - More complex and costly for Ethereum – re-run all the smart-contract code

- Validation can be expensive
  - Bitcoin blockchain contains the log of all tx – 97GB as of 1/2017
    (https://blockchain.info/charts/blocks-size)

Validation of transactions – BFT protocols

- Properties of ordinary Byzantine consensus
  - Weak Validity: Suppose all nodes are correct: if all propose v, then a node may only decide v; if a node decides v, then v was proposed by some node.
  - Agreement: No two correct nodes decide differently.
  - Termination: Every correct node eventually decides.
- Standard validity notions do not connect to the application!
- Need validity anchored at external predicate [CKPS01]
  - External validity: Given predicate P, known to every node, if a correct node decides v, then P(v); additionally, v was proposed by some node.
  - Can be implemented with digital signatures on input tx

Public validation vs. private state

- So far everything on blockchain is public – where is privacy?
- Use cryptography – keep state "off-chain" and produce verifiable tx
  - In Bitcoin, verification is a digital signature by key that owns coin
  - In ZeroCash [BCG+14], blockchain holds committed coins and transfers use zero-knowledge proofs (zk-SNARKS) validated by P
  - Hawk [KMS+16] uses verifiable computation (VC)
    - Computation using VC performed off-chain by involved parties
    - P checks correctness of proof for VC
- Private computation requires additional assumption (MPC, trusted HW ...)

Security and privacy

- Transactional privacy
  - Anonymity or pseudonymity through cryptographic tools
  - Some is feasible today (e.g., anonymous credentials in IBM Identity Mixer)
- Contract privacy
  - Distributed secure cryptographic computation on encrypted data
- Accountability & non-repudiation
  - Identity and cryptographic signatures
- Auditability & transparency
  - Cryptographic hash chain
- Many of these need advanced cryptographic protocols

Hyperledger Fabric

Geneva, 21. March 2017

Hyperledger project

- Open-source collaboration under Linux Foundation
  - www.hyperledger.org
  - Hyperledger unites industry leaders to advance blockchain technology (Dec. '15)
  - 100 members in Jan. '17

HYPERLEDGER PROJECT

- Develops enterprise-grade, open-source distributed ledger technology

- Code contributions from several members

- Fabric is the IBM-started contribution – github.com/hyperledger/fabric/
  - Security architecture and consensus protocols from IBM Research - Zurich

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Geneva,

Hyperledger Fabric

- Enterprise-grade consortium blockchain and distributed ledger framework
  - A blockchain implementation in the Hyperledger Project
- Developed open-source, by IBM and others (DAH, LSEG ...)
  - github.com/hyperledger/fabric
  - Initially called 'openblockchain' and donated by IBM to Hyperledger project
  - Actively developed, IBM and IBM Zurich play key roles
- Technical details
  - Implemented in GO
  - Runs smart contracts ("chaincode") within Docker containers
  - Implements consortium blockchain using traditional consensus (BFT, Paxos)

Hyperledger Fabric details (V0.6)

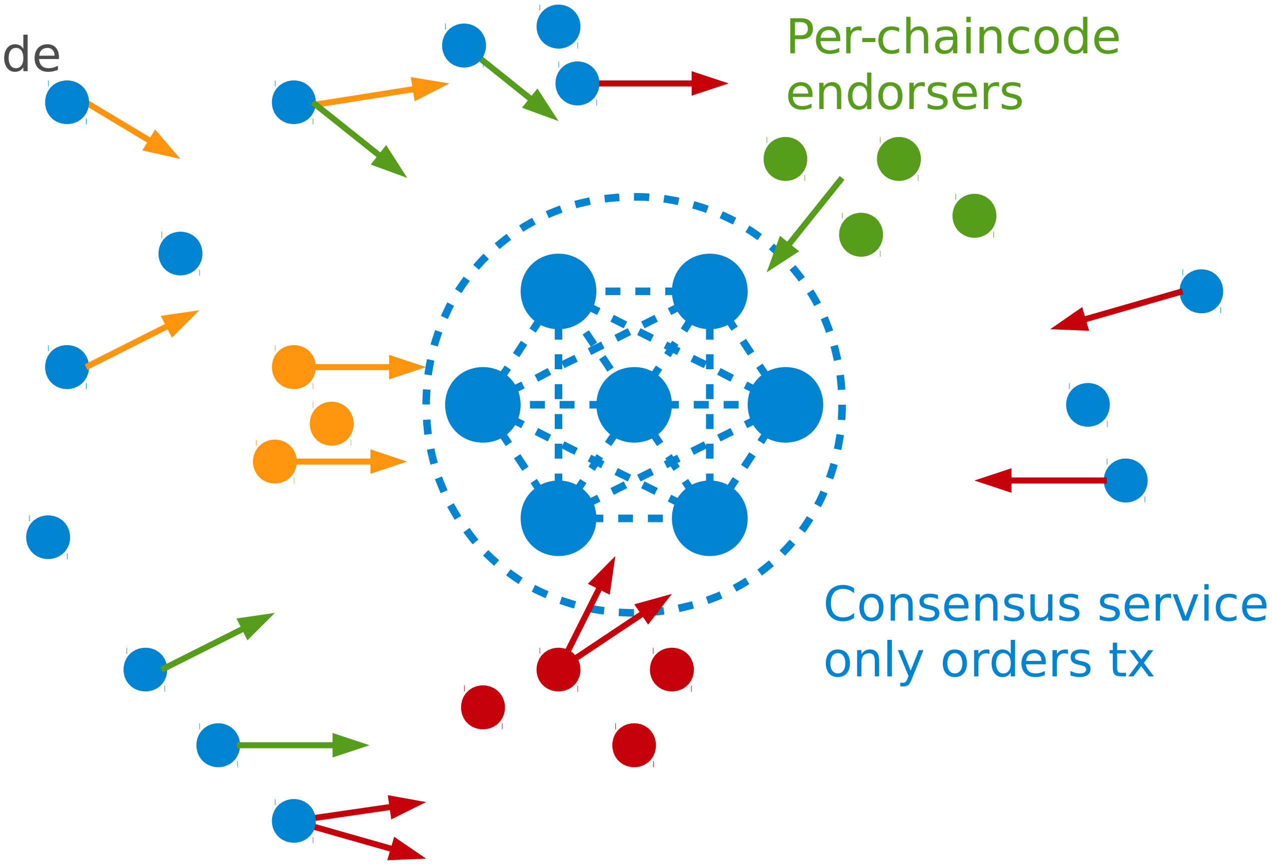
- Peers (validating peers and non-validating peers)
  - GO and other languages, gRPC over HTTP/2
  - Validating peers (all running consensus) and non-validating peers
- Membership service issues identity-certificates and transaction-certificates
- Transactions
  - Deploy new chaincode / Invoke an operation / Read state
  - Chaincode is arbitrary GO program running in a Docker container
- State is a key-value store (RocksDB)
  - Put, get … no other state must be held in chaincode
  - Non-validating peers store state and execute transactions
- Hash chain computed over state (and possibly transactions)

Towards Hyperledger Fabric V1

- Separate the functions of nodes into endorsers and consensus nodes
  - Every chaincode may have different endorsers
  - Endorsers have state, run tx, and validate tx for their chaincode
  - Chaincode specifies endorsement policy
  - Consensus nodes order endorsed and already-validated tx
  - All peers apply all state changes in order, only for properly endorsed tx
- Functions as replicated database maintained by peers [PWSKA00, KJP10]
  - Replication via (BFT) atomic broadcast in consensus
  - Endorsement protects against unauthorized updates
- Scales better – only few nodes execute, independent computations in parallel
- Permits some confidential data on blockchain via partitioning state
  - Data seen only by endorsers assigned to run that chaincode

Separation of endorsement from consensus

- Validation is by chaincode
- Dedicated endorsers per chaincode
- Consensus service
  - Only communication
  - Pub/sub messaging
  - Ordering for endorsed tx
- State and hash chain are common
  - State may be encrypted



Transactions in Fabric V1

- Client
  - Produces a tx (operation) for some chaincode (smart contract)
- Submitter peer
  - Execute/simulates tx with chaincode
  - Records state values accessed, but does not change state → readset/writeset
- Endorsing peer
  - Re-executes tx with chaincode and verifies readset/writeset
  - Endorses tx with a signature on readset/writeset
- Consensus service
  - Orders the endorsed tx, produces ordered stream of tx
  - Filters out the not properly endorsed tx, according to chaincode endorsement policy
- All peers
  - Disseminate tx from consensus service with p2p communication (gossip)
  - Execute state changes from readset/writeset of valid tx, in order

Modular consensus in Fabric V1

- "Solo orderer"
  - One host only, acting as specification during development (ideal functionality)
- Apache Kafka, a distributed pub/sub streaming platform
  - Tolerates crashes among member nodes, has Apache Zookeeper
  - Focus on high throughput
- SBFT - A simple implementation of Practical Byzantine Fault Tolerance (PBFT)
  - Tolerates $f < n/3$ Byzantine faulty nodes among n
  - Focus on resilience

Conclusion

Conclusion

- Blockchain enables new trust models

- Many interesting technologies
  - Distributed computing for consensus
  - Cryptography for integrity, privacy, anonymity

- We are only at the beginning

- Blockchain = Distributing trust over the Internet

  - www.hyperledger.org
  - www.ibm.com/blockchain/
  - www.research.ibm.com/blockchain/