distributed ledger technologies, blockchain and cryptocurrencies

a (largely incomplete) timeline

- 1999: first popular p2p service (Napster)
- 2008: Bitcoin: A Peer-to-Peer Electronic Cash System
- 2010: first real transaction
  - 2 pizzas for 10K BTC
- 2011: “Altcoins” begin to appear
  - Namecoin, Litecoin, etc.
- 2014: UK treasury commissioned a study on cryptocurrencies
- 2015: Ethereum: supporting smart contracts
- 2017:
  - BTC quotation about 16K$
  - Russia and Estonia announce plans for government backed cryptocurrency
  - blockchain (DLT) and cyrptocurrencies regarded as **game-changers**
- 2019:
  - BTC quotation 7K$
  - DLTs mainly regarded as a decentralized applicative platform
  - many pilot projects, a few real applications

Bitcoin, blockchain and DLT

- Bitcoin is a cryptocurrency...
- ...based on a technology called **blockchain**
- a number of variation of the blockchain are possible and many are used
- they collectively are called **Distributed Ledger Technologies (DLT)**

a DLT solves one fundamental problem

- many subjects need to agree on **transactions**...
- ...**without trusting each other**

- transactions are recorded on a **ledger**
- the ledger is **replicated**
  - each participant has a copy of it

- **consensus** on what is a “good copy” of the ledger is reached in a **distributed** manner
  - **no central authority** to be trusted

DLT for a cryptocurrency

- transactions are payments
- the ledger records payments
- a “good copy” conforms to plain accounting rules, e.g....
  – **no double spending** of money
  – controlled **money creation**
  – **no charge back**
  – conditions to unlock funds

  ...and many other technical rules

  – e.g. format of the records

ledgers and security

- a ledger is used by a community of *subjects* (or *parties* to transactions)
- it is updated for each transaction
- requirements
  - parties to a transaction need **guarantees about recording and consensus**
  - old transactions must be **immutable**
  - all involved nodes **see and agree on a single ledger status** at a certain instant
    - ...that conforms to all consensus rules
- DLTs fulfill these requirements without centralized trusted authority

potential applications of DLT

- real estate registry
- companies registry
- parcels delivery tracking
- civil registry
- financial transactions
- insurance
- medical records
- trial records
- ...

many have legal implications

(un)permissioned DLT

- unpermissioned DLT
  - anybody can contribute (with a new node) to run the DLT
  - large networks
  - slow
  - e.g., Bitcoin
- permissioned DLT
  - only authorized/trusted nodes can join
  - small networks
  - fast
  - typically belonging to industry/banking consortiums, but may run “public”

private/public DLT

- private DLT
  - only authorized subjects can access the ledger (either r/w or read-only)
    - “write” means send a transaction
  - nodes perform *access control*
- public DLT
  - any subject access the ledger and send transactions
    - no access control by nodes

subjects access the ledger by contacting nodes

DLT

		Who can run a node?	
		Permissioned	**Unpermissioned**
Who can access the ledger?	**Private**	set up by consortia for internal use (e.g. Ripple, inter-bank money transfers)	**-** this is possible from a technical point of view but unlikely to occur since no community would support a private objective
	Public	set up by consortia or industry association for providing public services (e.g. Sovrin, self sovereign digital identity)	community driven infrastructure to provide a public service (e.g. cryptocurrencies like Bitcoin, Ethereum, etc.)

cryptocurrencies elements

- **identifiers** of transaction parties, i.e. *users* (addresses)
- **ledger** content, format, consistency
  - many technical rules
- **p2p protocol** to broadcast accepted and pending transactions among *nodes* over an overlay network
  - nodes ≠ users
- **distributed consensus algorithm**
  - a way to reach consensus “securely”
- **incentives**
- **money creation and accounting constraints**

Distributed Ledger Technology (DLT)

- **identifiers**
- **ledger**
- **p2p protocol**
- **distr. consensus alg.**

DLT permissioned

- **incentives**

DLT unpermissioned

- **money creation and accounting constraints**

cryptocurrency

identifiers

- identification of subjects is done by private/public key pairs
- in unpermissioned DLT, subjects autonomously create private/public key pairs, possibly many of them
  - having many IDs improves confidentiality
- in permissioned DLT, subjects might be all well known to all nodes
  - shared subject directory and strictly regulated access

ledger

- essentially a log of *transactions*
  - *transactions*: some sort of state change request
  - state: can be just the log itself, or some other conceptual structure
    - e.g., current account for cryptocurrencies
- addition of transaction occur on a **block** basis
  - a block contains many transaction
  - transactions should respect certain "semantic rules" that are application-specific
    - e.g. for money: no double spending
  - **the order of transactions is fundamental!**
    - e.g. for money: can't spend before getting money
- most of the machinery of a DLT is about the addition of a block to the ledger

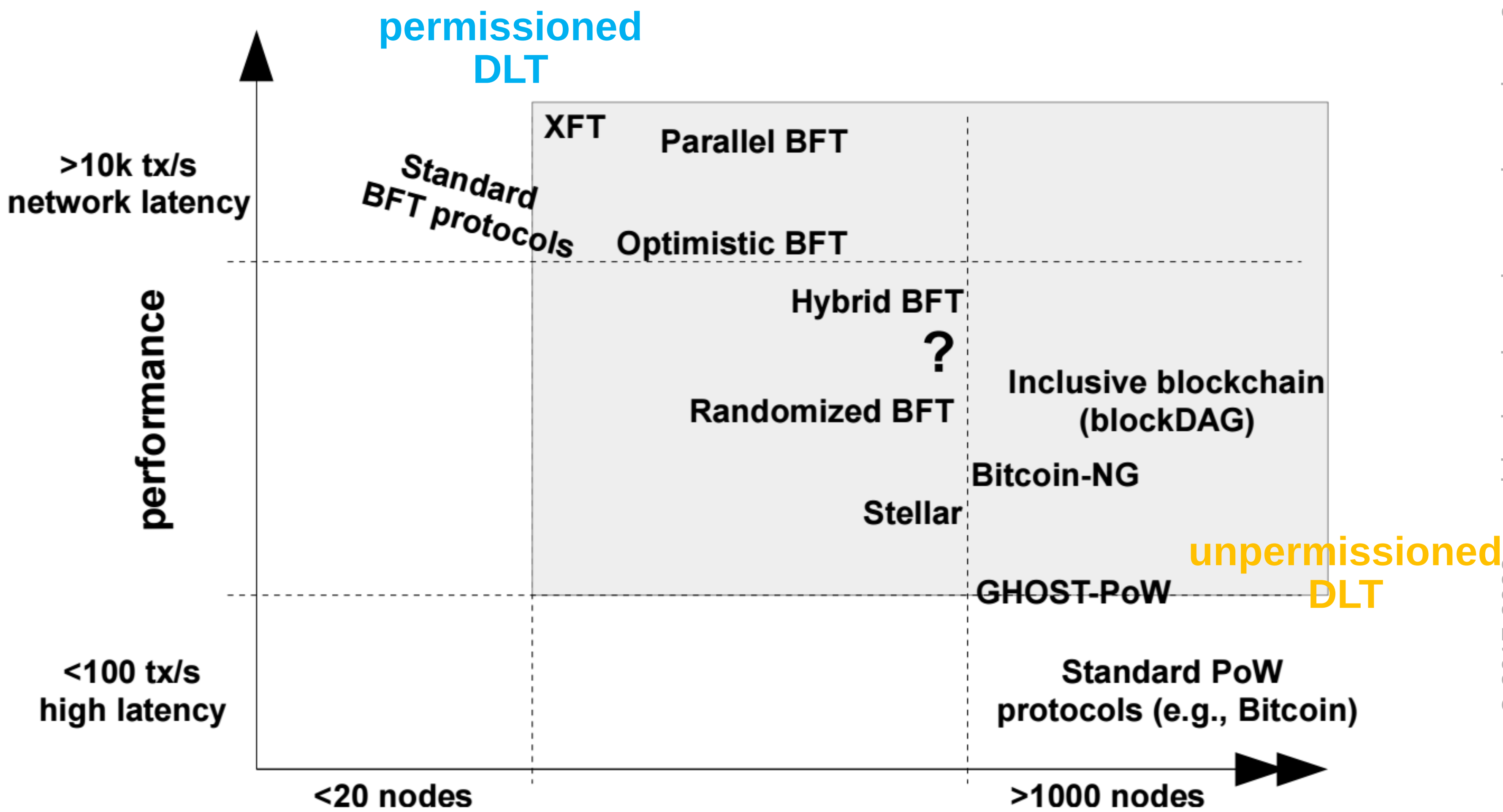
p2p protocol

- nodes discovery
  - what is the first node to connect to?
- node interconnection
  - peer-to-peer overlay network
- broadcasting
  - by *gossip protocol*
    - each node resends to neighbors received messages (only one time)
- each new/pending transaction is broadcasted
  - these are not yet accepted into the ledger
- a block that contains new accepted transactions for ledger is broadcasted

distributed consensus algorithm

- it is a way to accept a new block
- mandate that "all" accept the same block(s)
  - eventually they will have the same view of the ledger
- **check for format rules and other rules**
  - these are called **consensus rules**
  - **the most important aspect is to state which sequences of transactions can be accepted!**
- contrast "byzantine" (malicious) behavior of nodes...
  - ... which might pretend to subvert the rules
  - hard
- many solutions, a few very famous
  - Proof-of-Work – for unpermissioned DLTs
    - slow but it scales to high number of nodes
  - Byzantine-Fault-Tolerant – for permissioned DLTs
    - fast but feasible only for a small number of nodes
  - Proof-of-Stake – mainly for unpermissioned DLTs
    - fast, scales but some security concern

distributed consensus algorithms overview



source: M. Vukolić. The Quest for Scalable Blockchain Fabric: Proof-of-Work vs. BFT Replication. iNetSec 2015 (adapted)

incentive

- needed only for unpermissioned DLT
- anybody can join the DLT with a new node
  - usually, it is better to have a large number of nodes (for higher security and democracy)
- people have to get an advantage to join
  - joining means sharing resources with a community
- the advantage is usually some form of "money" (*tokens*)
  - that is, even not strictly money-related DLT have their own form of currency that can be exchanged for real money

consensus rules: “money semantic”

- creation
  - mining, premining, minting, etc.
  - tightly related with the incentive problem
- accounting rules
  - no double spending
  - no charge back
  - transaction fees
- unlocking of funds
  - proving ownership (by cryptographic means)
  - possibly complex rules (smart contracts)

consensus rules: general semantic

- the consensus algorithm can enforce very general semantic
- smart contracts
  - the semantic is the correct execution of program in a certain “virtual machine”
  - essentially the DLT user states what are the rules to be enforced

bitcoin

relevant concepts

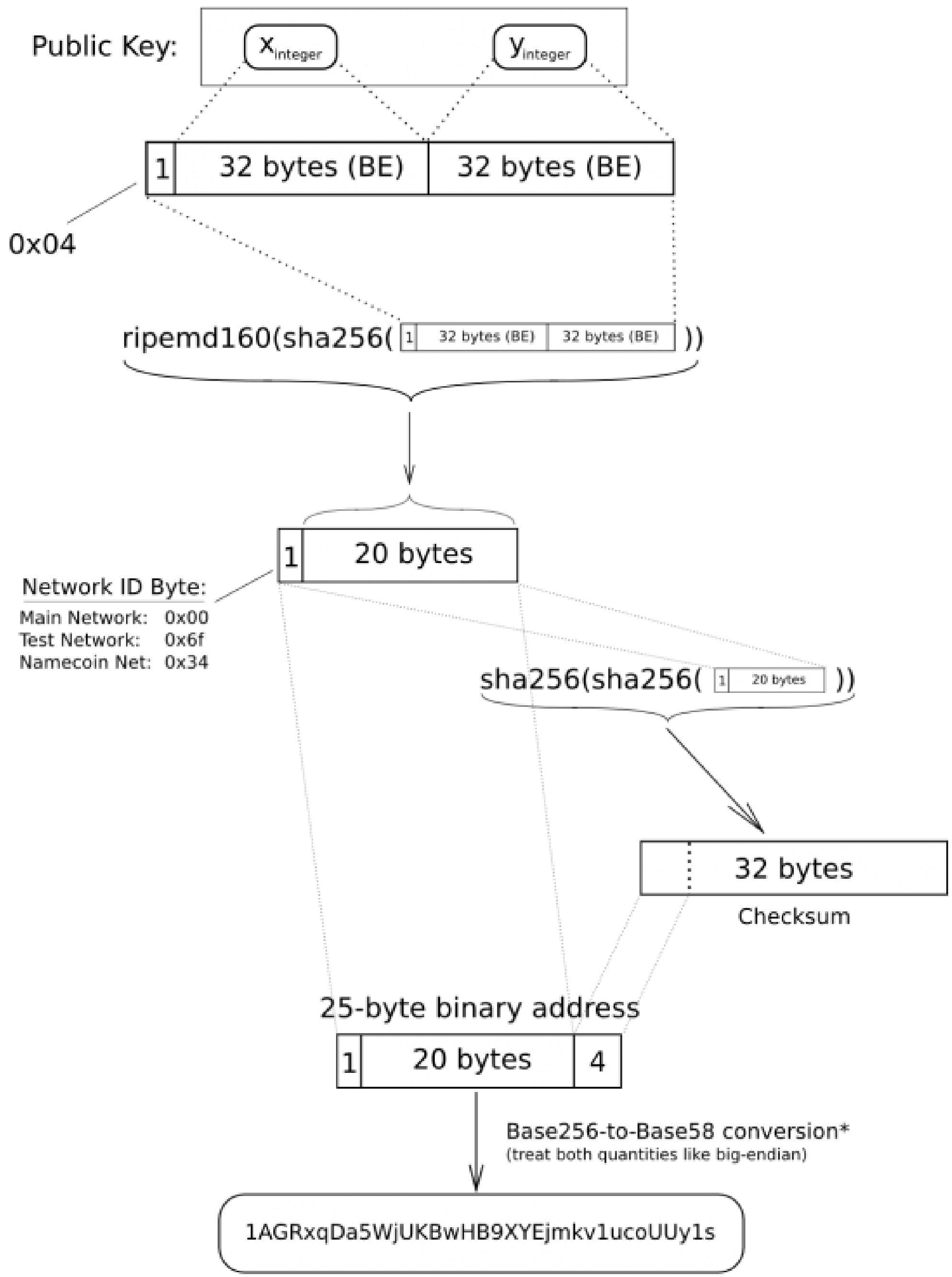
- addresses
- transactions
  - txin, txout, utxo, fees
- blocks
- blockchain
- proof-of-work

addresses

- created off-line by your wallet software
  - as many as you want
- private/public key pair
- **an address is a cryptographic hash of the public key**

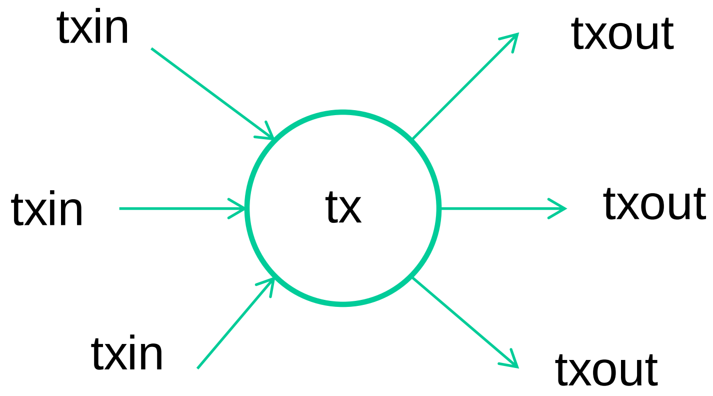
- ECDSA standard is used
- notable properties:
  - private keys are random numbers
  - the public key are derived from the private one
  - password based wallet with no explicit key storage are possible
    - Hierarchical Deterministic wallets

address derivation details



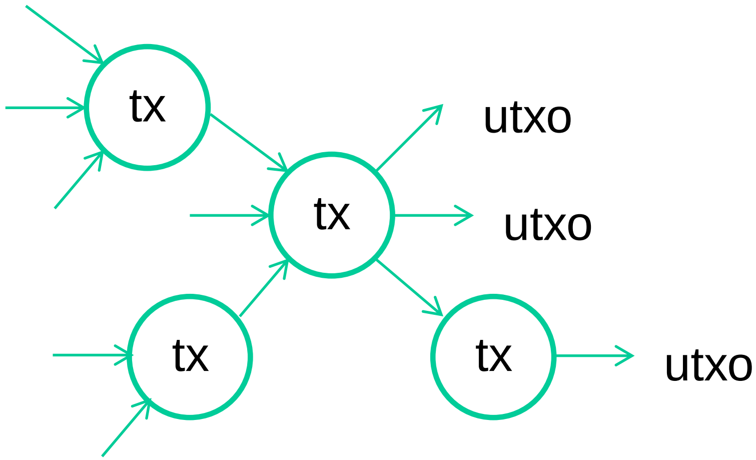
- this is the most common kind of address
- it is called “pay to public key hash” (p2pkh)

transactions (TXs)



- transactions form a directed acyclic graph
- txout is associated with...
  - an **amount**
    - espressed in satoshi
    - 1 satoshi = 10^-8 BTC, i.e., about 0.0001$
  - a **destination address**
    - actually a script typically checking for the address
    - dest. addresses may or may not belong to the same subject

utxo



- a txout can be...
  - **spent**, i.e. attached to a txin of another transaction
  - **unspent**, called **unspent tx output (utxo),** i.e., no txin attached
- currently “existing” bitcoins are those “stored” at utxo
  - ... and at addresses associated with current utxo
- **a txin always spends the whole utxo amount**
- partial spending is realized by adding a txout with a “change address”
  - i.e. returning money to addresses that belong to the same subject owning addresses involved in txin

transaction (un)balance and fees

- sum of amounts for txin's should be greater than the sum of amount of txout's
- the difference is the transaction fee
  - it is implicitly specified by the unbalance

$$Fee = \sum TxIn - \sum TxOut \geq 0$$

- the fee goes to the node that succeeds in putting the transaction in the blockchain
- nodes pick transactions with the highest fees!
  - block size is limited to 1MB! (see after)
  - your transaction might never be accepted due to low fee

txid

- a txid is a cryptographic hash of a transaction
- it is “almost” an id
- “almost”?
  - a design mistake
  - security problems was fixed
  - you can safely consider it as an ideal id

transactions: getting money out of a utxo

- txout are ordered
- each txin specifies a txout by...
  - txid (the transaction)
  - the index (i.e., the order) of the txout in that transaction
- each txin provides a **cryptographic proof** that the tx creator has the private key for the destination address of the txout

getting money out of a utxo: cryptographic proof

- this is like a challenge response protocol
- txin of a transaction tx provides...
  - public key whose hash should match the address in txout
  - **signature** with private key of a challenge string X derived from tx
- X is a string derived from...
  - tx where signatures are omitted
    - signing the signature is clearly impossible!
  - the destination address contained in referred txout
    - actually a string derived from the *script* containing the destination address!
  - it is a quite tricky procedure
    - see https://en.bitcoin.it/wiki/OP_CHECKSIG

lifecycle of a transaction

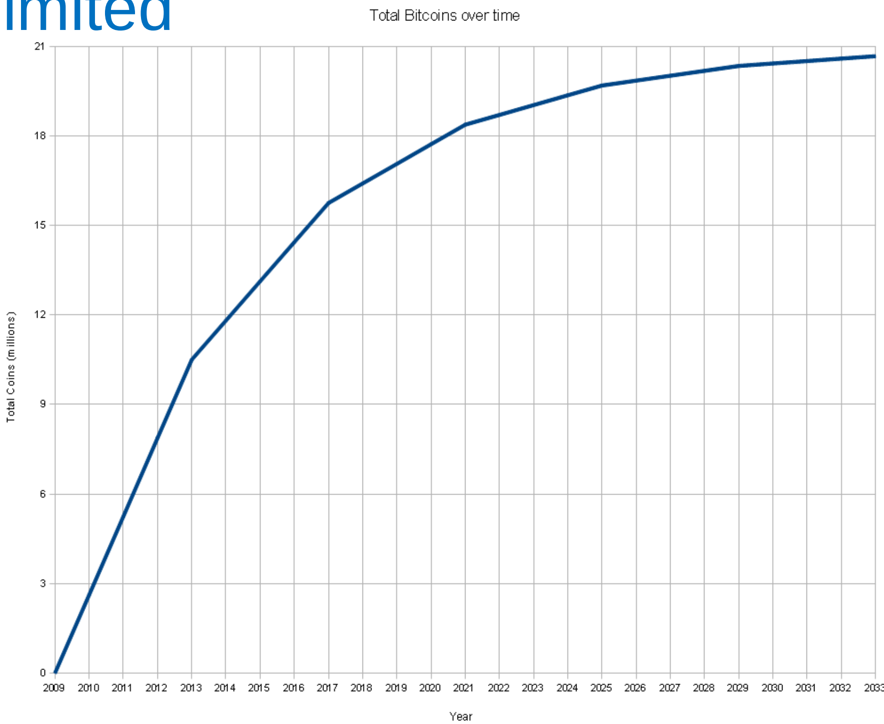
- a user *u* creates a tx locally
  - it computes all signatures proving private key possession
  - the user should know all previous transactions
    - It may ask nodes for them, *wallet apps* do this
- *u* sends tx to any node *n*
- *n* send it in broadcast
- the nodes that receives tx check it for its validity (just syntactically)
- all nodes puts tx into a “pool” of pending transactions
- all nodes try to put tx in the **blockchain**

blockchain

- this is the ledger of bitcoin
- it is made of **blocks**
- a block contains many of transactions
- blocks are chained in a sort of authenticated singly linked list
  - hence, blocks are strictly ordered and numbered (depth of a block)
- adding a block is...
  - difficult (proof-of-work approach)
  - provides the node with a reward (incentive) of newly created bitcoins and transaction fees

reward (Bitcoin creation)

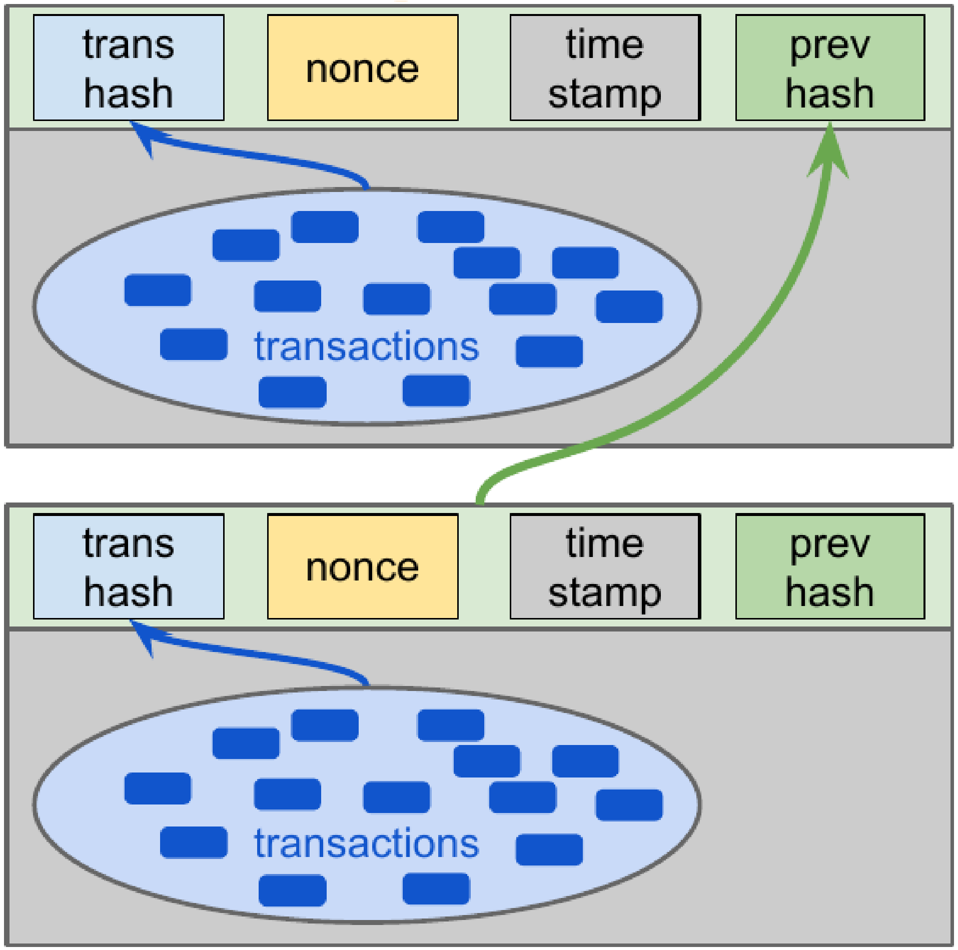
- each block create a new amount of bitcoin
  - called “coinbase”
- started at 50BTC/block
- halved every 210000 blocks (about 4 years)
  - total number of BTC is limited
- as of Dec 2017 it is 12.5BTC/block (about 200K$)
- it is represented as a special transaction
  - the first of each block, no txin, only one txout

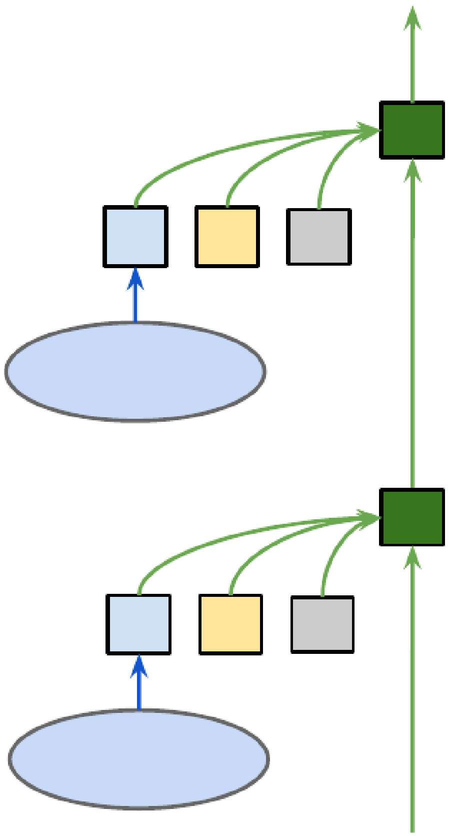


block content

- payload, i.e., the transactions
  - block size is limited to 1MB
  - nodes pick transactions with the highest fees! your transaction might never be accepted due to low fee
- header
  - timestamp (very roughly approximated)
  - hash of all transactions
    - **a root hash of a Merkle hash tree** of all transactions in the payload
  - the hash of the header of the previous block of the blockchain
  - a nonce
    - this is the solution of the puzzle for the proof-of-work approach
  - other stuff

block content





courtesy of G. Di Battista and R. Tamassia

consensus

- adding a block requires to solve a cryptographic puzzle (proof-of-work, PoW)
  - by enumeration approach
- **in PoW consensus is implicit**
  - **a node that works for the next block is accepting all previous ones**
- **forks** may happen:
  - two nodes solve the next block at roughly “same time”
    - with two distinct solutions
  - the two block are broadcasted (fork)
    - actually some nodes see only one of them (non instantaneous broadcast), others see both and choose one
  - the two chains might grow independently for a while

fork resolution
the longest chain rule

- a node that sees more chains **chooses the longest one**
  - transactions that are in a discarded block are put in the pending transaction pool again
  - they might not be accepted any more
    - … and definitely discarded after a timeout
    - depends on the consensus rules and previous transactions
    - possible double spending!
- which chain grows faster is random
- the longest chain has more work done on it
  - in terms of computation performed

transaction confirmation

- **confirmed: stored in an immutable block, forever**
- PoW does not provide “mathematical guarantee” of confirmation

- a transaction is considered confirmed if it is enough deep in the blockchain!
- “enough” depends on the criticality of the transaction
- usual confirmation depths are 1 to 6

consensus attacks general objectives

- changes to old blocks already accepted by at least some nodes
  - it is about integrity of the blockchain: important for all DLTs
  - might allow chargeback, double spending, and illegitimate change other parameters of the network

- DoS: denial of acceptance of certain transactions

consensus attacks and confirmation depth

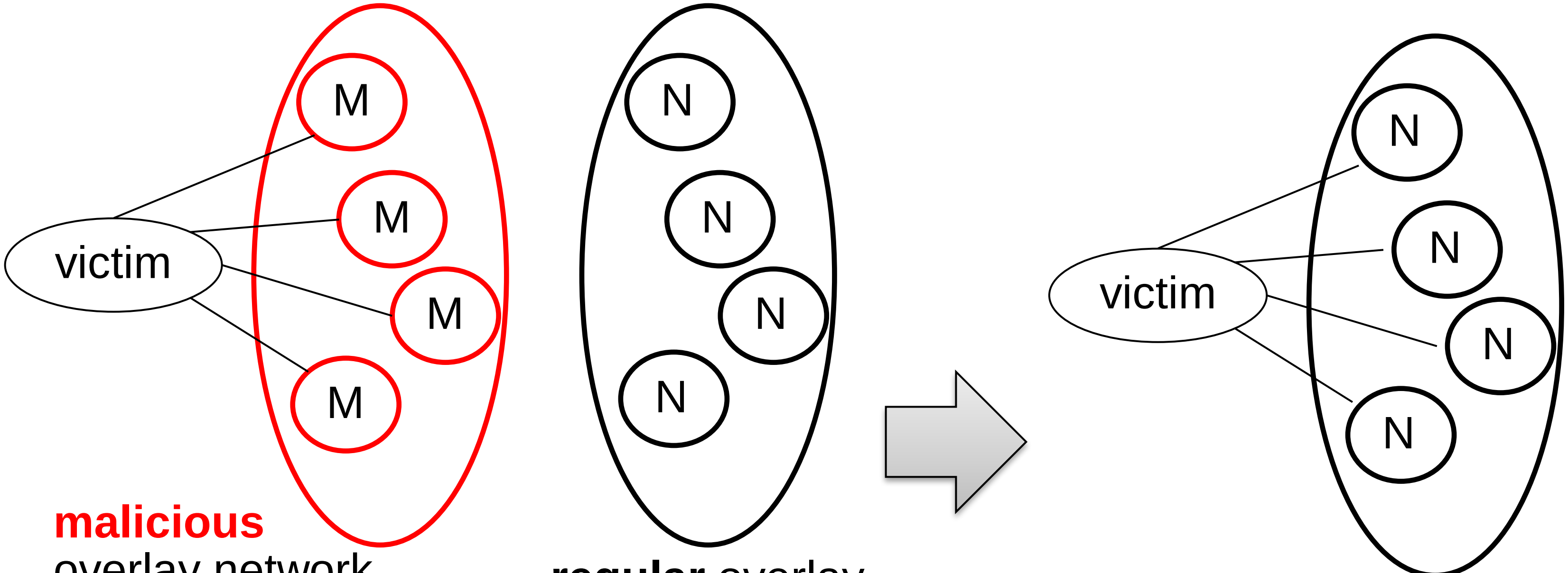
- changing of a deep block *b...*
- ...requires the attacker to solve again all blocks above *b*
- the attacker needs a huge amount of computing power to reach and surpass the legitimate chain

- the more *b* is deep the more is "confirmed"

consensus attacks: eclipse

- who controls a large number of nodes can isolate a “victim” node
- the victim see a different blockchain where she can get “malicious payments”
- the malicious payment disappear when the attack terminates and legitimate chain is broadcasted
  - chargeback, double spending
- can be detected by observing an anomalously low “hash power”

consensus attacks: eclipse



malicious overlay network where payment is recorded

the victim assume payment was correctly finalized

regular overlay network, that is screened by the malicious one, where **no** payment is recorded

when malicious nodes go away, the victim connects to the regular overlay network and see no payment

consensus attack: 51% a.k.a. Sybil attack

from "Sybil: The True Story of a Woman Possessed by 16 Separate Personalities" –F. R. Schreiber - 1973

- who controls more than 50% of the computational power can...
  - disconfirm recently confirmed blocks
    - by surpassing with its chain all other forks
  - get 100% of the rewords
    - by keeping adding blocks
- it can also impact certain consensus rules
  - e.g., creating blocks that signal support for certain features that activates over a certain threshold, and "orphaning" nodes that do not

proof-of-work: the puzzle

- find a block whose header hash is below a certain **target threshold**
  - SHA256(SHA256(Block_Header))<threshold
  - lower is harder
  - difficulty = maxthreshold/threshold
- target threshold is “given”
- a node can search for a solution varying...
  - nonce
  - timestamp (within certain limits)
  - the set of transactions

target threshold adjustment

- the target threshold at a certain instant is fixed for all nodes
  - current target is stored in the last block
- it is adjusted so that time for solving the puzzle is 10 minutes on average
  - the average tx acceptance delay tend to be 5 minutes
- it is a feedback control loop
  - inputs: the time needed for last 2016 blocks and current threshold
  - output: new threshold
- adjustment happen every 2016 blocks
  - two weeks on average
  - only the node that solve the k*2016th block can change it (it is a consensus rule)

maximum theoretical transaction acceptance **throughput**

- maximum size of the block is 1MB
- minimum useful tx size is 226 bytes
  - tx with p2pkh addresses, two outputs (one for change), one input
- 1 [MB/block] / 226 [B/tx] / 600 [s/block] =

7.32 [tx/s]

- current average about 3.5 [tx/s]

bitcoin policy: the block length dilemma

- larger block size
  - lower fees
    - more txs in a block
  - harder to be a miner
    - more bandwidth, more ram, etc.
  - less democracy
    - limited number of miners can easily decide on the future of Bitcoin: easier to agree to change rules, easier to collude to reach 51% computing power
- smaller block size
  - higher fees
  - easier to be a miner
  - more democratic governance

segregated witness (SegWit)

- a soft fork activated on August 24, 2017
- strip signatures from transactions in the block
  - note that signatures are not relevant for replaying the history of the blockchain
    - it is enough to be sure that someone checked them in during consensus
  - they can be outside the block and possibly forgotten
  - similar approach also in other blockchains
- new address format (SegWit address)
  - transaction should get money from new segwit addresses to “weight less”
  - slow adoption
- equivalent to have about 2MB of block size

Simplified Payment Verification

(thin clients or light clients)

- thin clients do not store the whole blockchain
- they store just block headers
  - 80 bytes, about 4MB/year
- when transaction information is needed an untrusted full node is contacted
  - Merkle tree! proof used for integrity check against the root hash stored in the trusted header

the blockchain (scalability) trilemma

first stated by V. Buterin (Ethereum founder)

- desirable properties: **decentralization, scalability, security**
- trilemma: you cannot fulfill all the three completely
- any DLT is a compromise
  - current unpermissioned DLT: no scalability
  - permissioned DLT: no decentralization
  - plain p2p technologies: no security
- it is not a theorem
  - research is ongoing for the perfect solution!