COMPUTER SYSTEMS SECURITY

Chain of Blocks: basics

Bitcoin: A Peer-to-Peer Electronic Cash System

Goal

- Build «*... an electronic payment system based on cryptographic proof instead of trust, allowing any two willing parties to transact directly with each other without the need for a trusted third party*.» (Nakamoto, 2008)

Definition

- «*We define an electronic coin as a chain of digital signatures*.» (Nakamoto, 2008)
- type of **currency**, that is money, recognized value!
  - Bitcoin symbol: BTC
  - current value (as of March 2026): 1 BTC ≅ 60 300 EUR
  - 1 BTC = 100,000,000 satoshis[1]

1 also known as *sats*

Components

- Users
- Network (of Nodes)
- Nodes
- Chain (of Blocks)
- Blocks (of Transactions)
- Transactions

Users

- management of (their)
  - crytographic keys and digital money
- how: digital wallets
  - private (user controls everything) - software or hardware
  - custodial (control via broker - or bank!) - they have your private keys!
  - run their own machine/node (even for minting money!)

Network

- interconnection of peer machines (Nodes), of course, running over the Internet
- running Bitcoin open-source software
- exchanging messages (e.g. with Blocks) in a peer-to-peer, delivered on a best effort basis

Node

- any computer running Bitcoin software that participates in the Bitcoin network
- its role, in general:
  - enforcing of Bitcoin's rules
  - maintaining a copy of the Chain of Blocks (*Blockchain*) or part of it
  - validating Transactions and Blocks
  - relaying data to other nodes
- can be of different types (having varying capabilities)
  - Full nodes - copy of whole Bitcoin chain
  - Lightweight nodes - mostly, verification of Blocks
  - Mining nodes - as full nodes plus Mint facility!

Chain (of Blocks)[1]

- «*A chain of blocks with each block referencing the block that preceded it*.» (Developer-gloss, 2020)
- the Bitcoin digital bank: *just* a **global ledger** of the transactions!
- dynamic linear structure whose size does not cease to grow[2], supported by other structures (important, for instance, for efficiency)
- mantained by Nodes

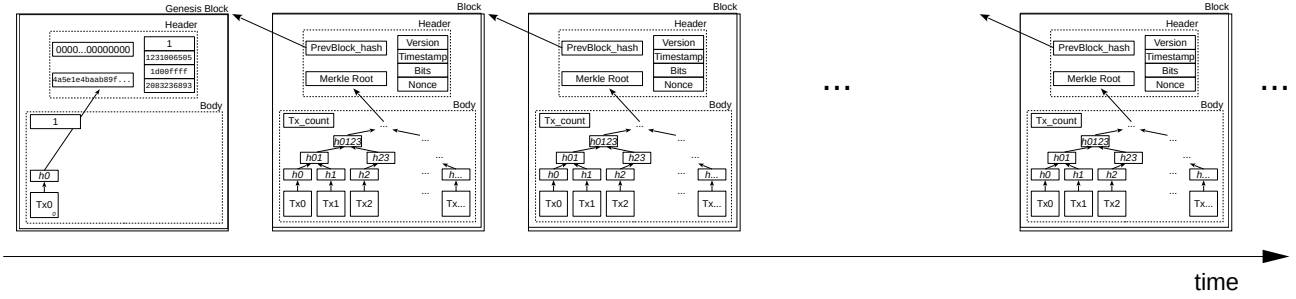


Fig. Bitcoin's Chain of Blocks.

1 usually abreviated to (the overused) *blockchain*
2 as of March 2026, the Bitcoin blockchain has a number of blocks (block height) of, approximately, 942,000, taking about 726 GiB.

Block

- «*One or more transactions prefaced by a block header and protected by proof of work. Blocks are the data stored on the block chain*.» (Developer-gloss, 2020)
- «*As miners construct a new block, they add unverified transactions from ... [a] pool to the new block and then attempt to prove the validity of that new block, with the mining algorithm (Proof-of-Work)*.» (Antonopoulos, 2014)
- So, a block is meant to contain a group of Transactions, each representing the movement of the digital money (from "hand to hand")

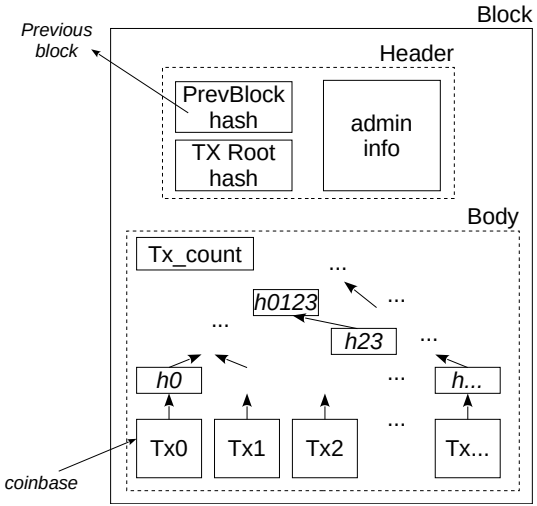


Fig. Basic block. Tx0, first transaction of block, is called *coinbase* transaction and is where new money appears, mined and owned by the builder of the block.

Transaction

- «*Transactions are the most important part of the bitcoin system. Everything else in bitcoin is designed to ensure that transactions can be created, propagated on the network, validated, and finally added to the global ledger of transactions (the blockchain).*» (Antonopoulos, 2014)
- operation by means of which Bitcoin's money changes hands[1]:
  - atom of Bitcoin system's structure, but
  - cannot be "standalone": must be connected to other transactions

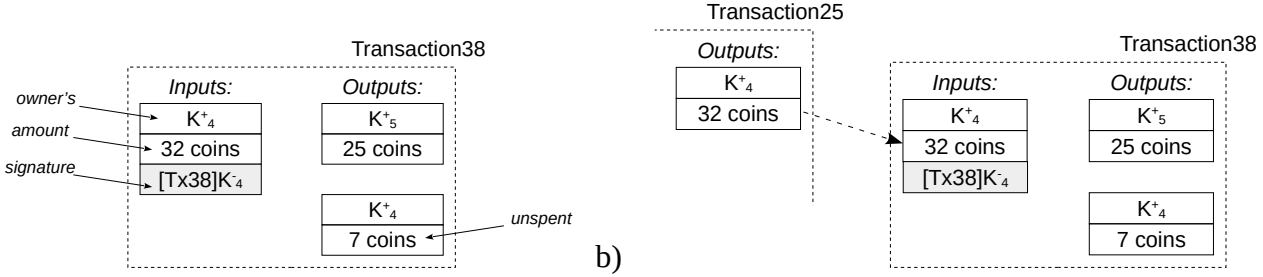


Fig. Basic transaction pictured very simplified-A.
a) main data with a single input owner; b) dashed arrow shows where money is coming from!

1 owners!

...Components: Transaction...

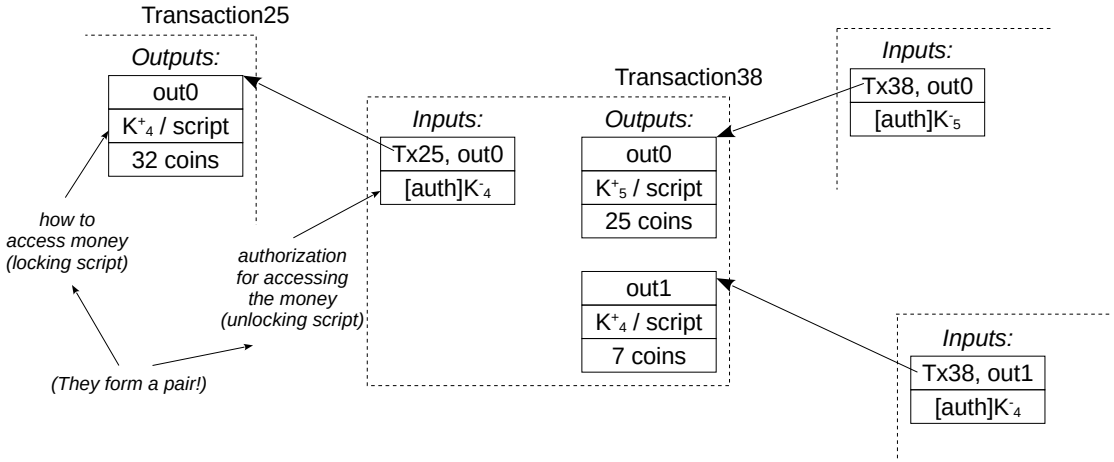
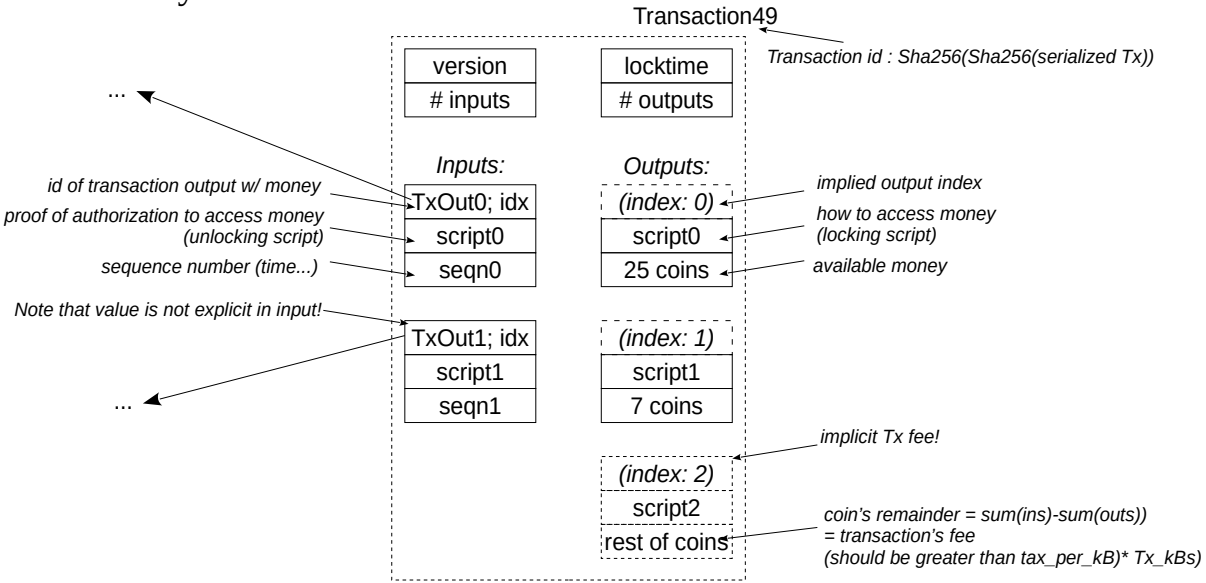


Fig. Transaction pictured a bit less simplified.

Transaction

Structure

- more realistically:



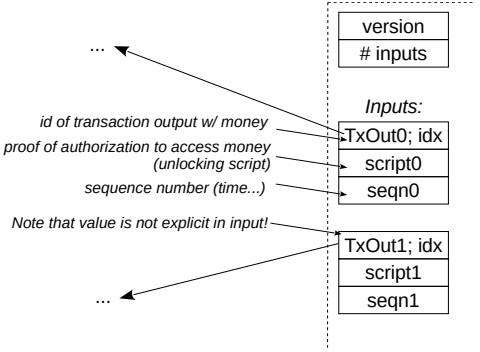
Types

- coinbase
  - 1st transaction in a block
  - always created by a miner
  - no Input, one Output
- general - identified by their address types (inputs and outputs) -> see below
  - Pay-to-Public-Key (P2PK)
  - Pay To Public Key Hash (P2PKH)
  - Pay To Script Hash (P2SH)
  - ...

Signing & Scripting

Signing (1st part)

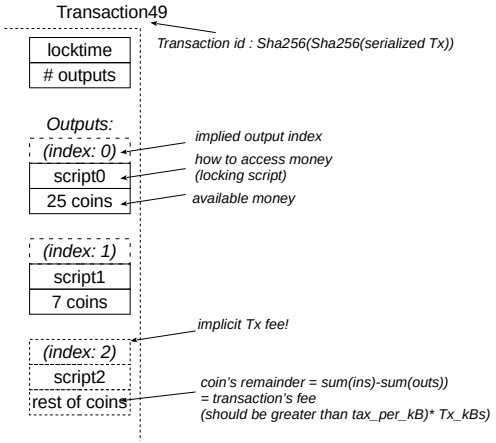
- «*Digital signatures are applied to messages, which in the case of bitcoin, are the transactions themselves. The signature implies a commitment by the signer to specific transaction data. In the simplest form, the signature applies to the entire transaction, thereby committing all the inputs, outputs, and other transaction fields. However, a signature can commit to only a subset of the data in a transaction...*» (Antonopoulos, 2014)
- a signature:
  - proves that some unspent money (from a previous transaction) can be spent in the current transaction)[1]
  - so, it should connect to the previous transaction
  - it is put in each input's *Unlocking Script*
  - *...continues...*



1 It is an *authorization* for spending the money, proving ownership of it.

...Signing (cont.)...

- a signature (cont.):
  - specifies the relevant outputs of the current transaction (to where the spent money will go)
  - who can use (or how can be used) that money[1]
  - covers the common parts of the transaction (version, locktime, ...)
  - uses double SHA256 hashing of the serialized data[2]
  - is made with (of course) the private key of owner of input money

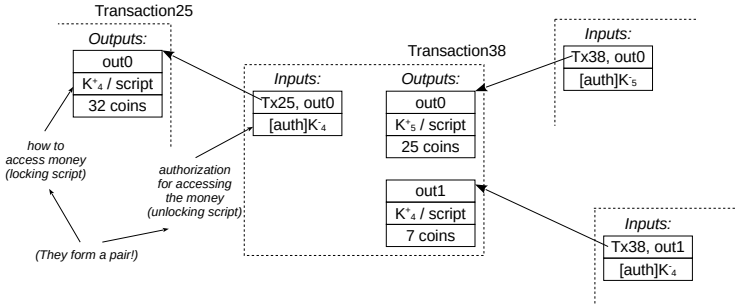


1 by means of the Locking Scripts, one in each output
2 sha256d (x)= SHA256 (SHA256 (x))

Scripting

- Scripts are what gives flexibility (power?...) to bitcoin transactions
- each transaction needs both of two types of scripts (they make a "pair"):
  - *Output Script* (*Pubkey Script*, *scriptPubKey*, *Lock Script*)
    - define the conditions for spending money; live in Outputs
  - *Input Script* (*Signature Script*, *scriptSig*, *Unlock Script*)
    - try to) satisfy of the conditions for spending money; live in Inputs
- for spending some money on current TX, the script's pair is:
  - *scriptPubKey* of previous TX
  - *scriptSig* of current TX

---> see a previous picture:



Types of scripts

- P2PK
  - normal
  - multisig
- P2PKH
  - normal
- P2SH
  - normal
  - multisig
- Null Data
- ...

Types explained

- P2PK - Public Key or Pay-to-Public-Key[1]
  - initial form of payment
  - normal
    - input contains recipient's signature
    - output contains recipient's pubkey
  - (bare) multisig
    - input contains *m* (up to *n*) signatures (of different recipients)
    - output contains *n* (greater or equal to *m*) signatures (of different recipients)

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1 dated...

...Scripting: types (cont.)...

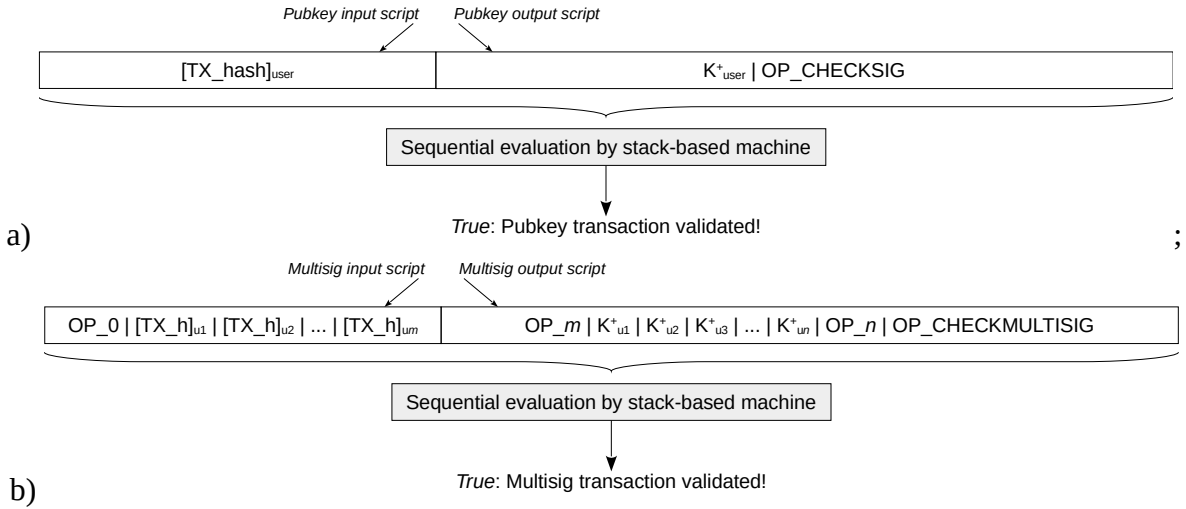

Fig. Pubkey type of scripts: a) normal (simple); b) multisig.
Note: $[TX]_{user}$ means *signature of TX by user* (with K^-_{user}, of course).[1]

1 In reality, there is an additional byte appended: the sighash type. So, really, it should be: $[TX]_{user}$ ---> $[TX]_{user}$ | sighash_type.

- P2PKH - Pay To Public Key Hash
  - enhanced form of payment:
    - more resistance to attacks and privacy
    - shorter addresses (recipient's of money transfer)
    - built-in error-detection (via checksums)
  - normal
    - input contains recipient’s pubkey and a recipient's signature of TX (including previous output’s scriptPubKey)
    - output contains recipient’s pubkey hash
      - Hex: `76a914 <20-byte pubKeyHash> 88ac`

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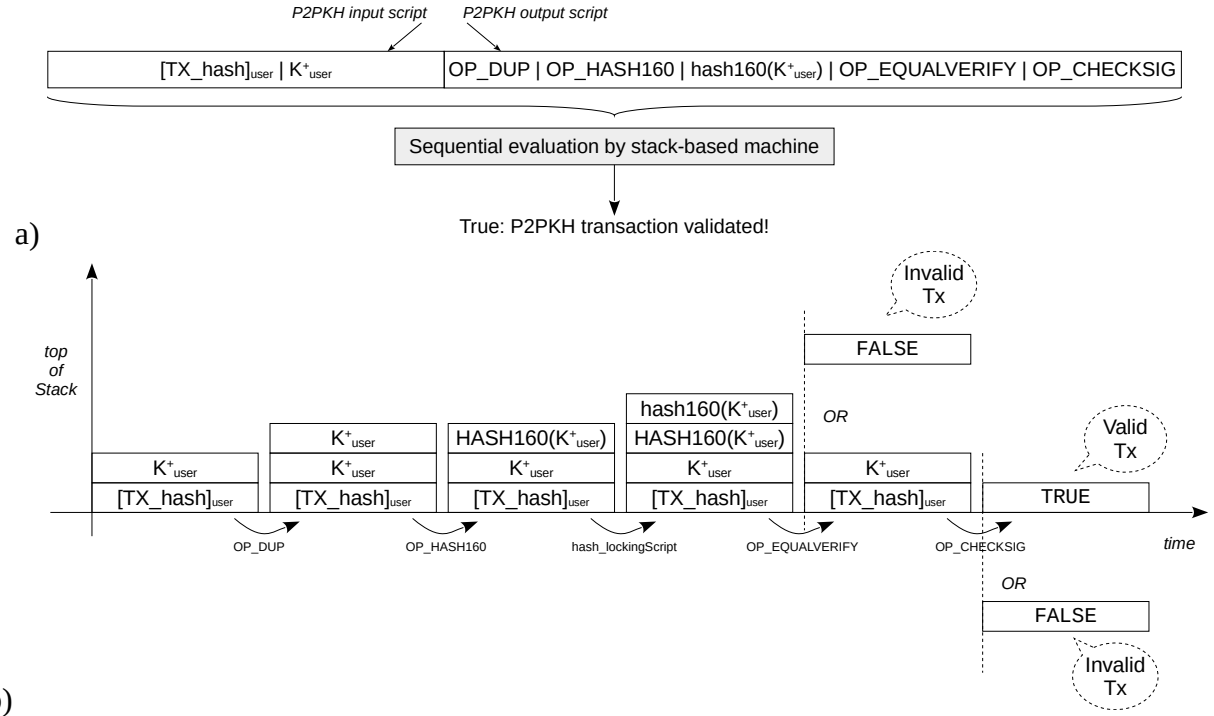

Fig. Pay To Public Key Hash (P2PKH) type of scripts: a) scripts structure; b) Sequential Evaluation of Input Script by stack-based machine.

...Scripting: types (cont.)...

- P2SH - Pay To Script Hash
  - normal
    - input contains recipient's *Redeem Script* and a signature
    - output contains recipient's *Redeem Script* hash
  - multisig pubkey script (most used)
    - similar to P2PK's (bare) multisig, e.g. scripts' evaluation, by stack machine[1]
  - all this is similar to P2PK and P2PKH main formats
    - but, here, owner's info is revealed only later (when spending)
    - the *locking script* (in the outputs) has only the hash of the owner's identities
  - textual data could be stored on *Redeem Scripts*, but is not ideal in many aspects
    - scripts must still be correct and evaluate to TRUE
    - script size is limited to ~500 B per "push"[2] up to ~10kB in total

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1 However, transaction's fees will be higher for a buyer, as unlocking script is potentially larger than locking's.
2 each instruction in script that results in adding an amount of data onto the stack-based machine evaluator

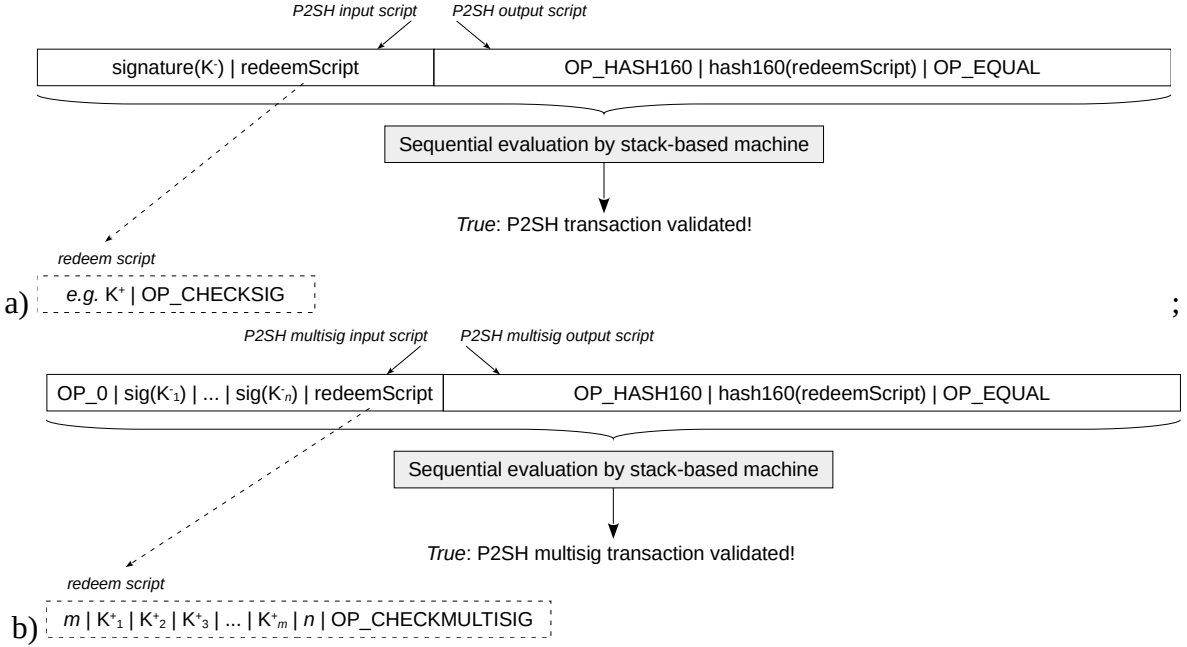

Fig. Pay To Script Hash (P2SH) type of scripts: a) normal (simple); b) multisig.

...Scripting: types (cont.)...

- Null Data (OP_RETURN or Data carrier)
  - «*adds arbitrary data to a provably unspendable pubkey script that full nodes don't have to store in their UTXO*[1] *database*» (Antonopoulos, 2014)
  - there is no *Unlocking Script*, as there is no money to spend!
  - *Output Script* has arbitrary data with limited size (~80 B)
  - allows storing of textual data on the blockchain![2]

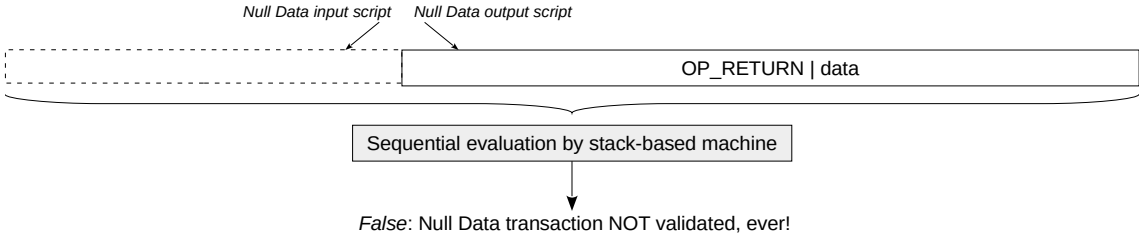

Fig. Null Data type of script. Data is of limited size. Script always evaluate to FALSE!

1 UTXO - Unspent Transaction Output
2 Without "polluting" the UTXO set!

Signing (2nd part)

Procedure

- for signing a Transaction:[1]
  - supposing the transaction's fields are filled out (excepto for the *Unlocking Scripts*)
  - for each input:
    - make a copy of the transaction
    - clear its input scripts[2]
    - in current input script put the *scriptPubKey* of UTXO of (previous) transaction
    - select inputs and outputs to be signed, depending on sighash type[3]
    - serialize the transaction into bytes
    - append sighash type
    - compute (double) hash[4]
    - sign hash with private key of owner of input money

2 *Locking Script*

3 see below

4 sha256d (TX_serialized | sighash)

1 This applies to legacy transactions' signing; SegWit transactions (BIP 141) differ slightly.

- inputs and outputs covered by signature (FIG)
  - specified in strict or more relaxed ways by means of flag *sighash*
  - `SIGHASH` applies to outputs; `ANYONECANPAY` applies to inputs

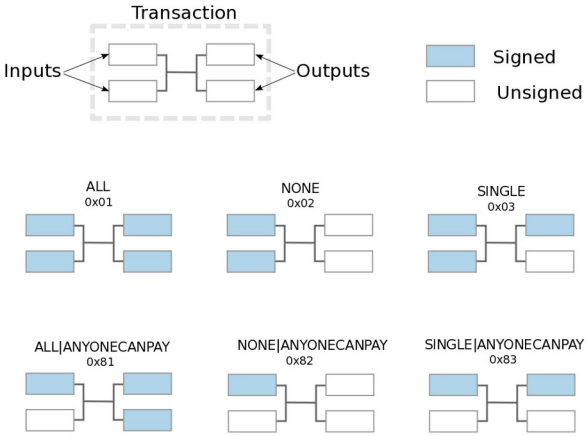

Fig. `SIGHASH` flag variants (`ALL`, `NONE`, `SINGLE`) and `ANYONECANPAY` modifier for a 2-input, 2-output transaction when signature is being calculated for top input. (in Antonopoulos, 2014)

Block

Structure

- Block Header (80 bytes)
  - version - different version, different Block validation rules[1]
  - previous_block_hash[2] - linking of chain of blocks!
  - Merkle Root - represents all transactions in Block
  - Timestamp - Unix creation time
  - Bits (4 bytes) - encoded difficulty *target* [3]
    - bits = [exponent (1 byte)][coefficient (3 bytes)]
    - target = C × 256^(E - 3)
    - mining: `valid block_hash ≤ target (Proof-of-work!)`
    - adjusts every 2016 blocks (~2 weeks)

--> *Fig next page*

1 examples: v1- Original Bitcoin rules; v2 - P2SH + coinbase height; v3 - Strict DER signatures; ...
2 `block_hash = SHA256(SHA256(block_header))`
3 sets how hard is mining - the smaller, the more difficult!

- Nonce - changed by miners to try different hashes for Proof-of-work
  - See Mining below
- Body
  - Transaction count
  - TX0 (coinbase), TX1, TX2...
  - hashes... in Merkle tree technique

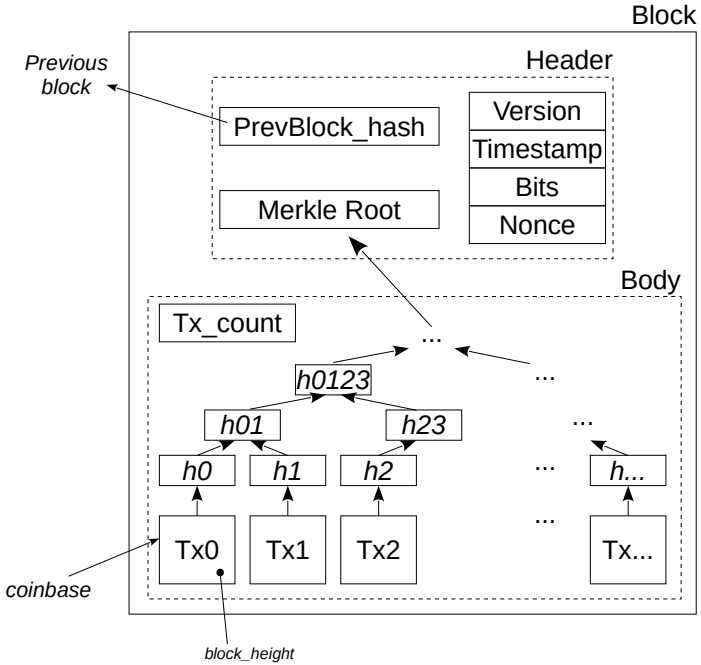

Fig. Basic block.
Tx0, first transaction of block, is called *coinbase* and is where new money appears, mined and owned by the builder of the block; *blockheight* is number of block in chain of blocks!.

Mining

- building a Block to be connected to the Chain of Blocks
  - ... and collect the *subsidy* (reward for mining)
- Process:
  - assemble a candidate block
    - set transactions
    - compute Merkle root
    - set version, previous block, timestamp, bits
  - Hash the header with the current nonce:
    - `block_hash = SHA256(SHA256(block_header))`
  - Check if `block_hash ≤ target(bits)`
    - Yes → block found
    - No → change nonce[1] → repeat Process

1 If necessary, miners can also adjust *coinbase's extra data* and *Timestamp*.

Chain (of Blocks)

Structure

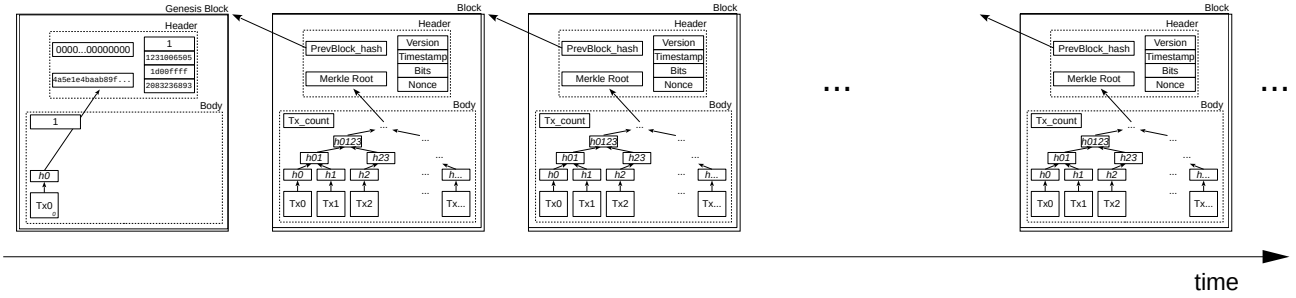

Fig. Bitcoin's Chain of Blocks.

Consensus Rules

- *The laws of the Bitcoin system!*
- enforced by every node: determine validity of blocks and transactions
- define the decentralized shared agreement
- Types:
  - Transaction rules
  - Block rules
  - Monetary rules
  - Chain rules

Consensus rules' types:

- Transaction rules
  - inputs must exist in the UTXO set (previous TX)
  - signatures must be valid
  - no double spending
  - scripts must evaluate to true
  - total outputs ≤ total inputs
- Block rules
  - block hash must satisfy difficulty
    - difficulty (Bits-target) must be same as value related to the calculated times of previous 2,016 blocks!
  - block size / weight limits respected
  - Merkle root must match transactions
  - first transaction must be Coinbase
  - block reward must be correct

Consensus rules' types (cont.):

- Monetary rules
  - block subsidy follows halving schedule
  - total supply capped (~21 million BTC)
  - no creation of coins outside Coinbase
- Chain rules
  - each block must reference a valid previous block
  - nodes follow the chain with the most *cumulative work*

Chain (temporary) fork

- Bitcoin is decentralized:
  - multiple miners can mine blocks at nearly the same time
  - occasionally, two blocks compete (might give rise to fork of chain) [FIG]

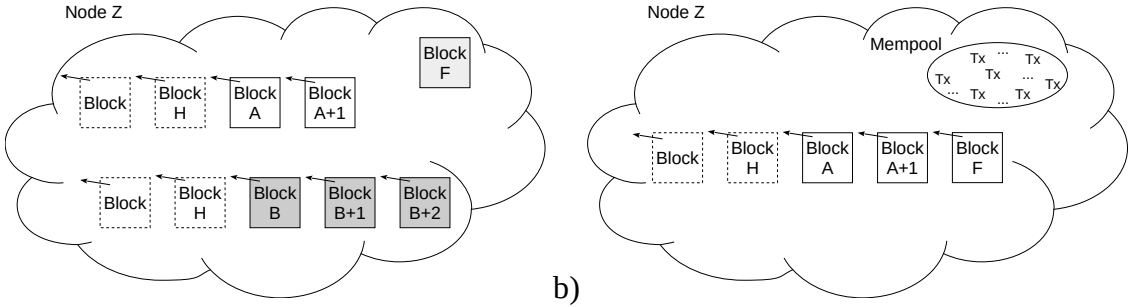

Fig. Bitcoin's Chain temporary fork at Node Z: a) conflict situation; b) final tie-breaker chain, e.g. as cumulative work of chain with A-series blocks is greater than chain's with B-series blocks. Transactions from B-series blocks are kept in Mempool to be added to future block.

Major details

Cumulative work defines chain choosing

- node calculates cumulative work of competing chains
  - work - expected number of hash computations required to find a *valid* block
    - valid block: `block_hash ≤ target` [1]
  - for each block of a chain:
    - `work (block) = 2^256 / (target+1)`
  - for all *i* blocks in chain:
    - `cumulative work (chain) = ∑i 2^256 / (target(i)+1)`
- efficient computation:
  - node keeps local database of info on known blocks; one field is "total_work"
    - `new_block.total_work = prev_block.total_work + new_block_work`
  - so, need just look at total_work of the (block) tip of each chain**!**

1 *target* is related to field "bits" in block structure

...Chain (of Blocks): Major details...

10-minute block interval between new block formation

- design choice of Satoshi Nakamoto: critical safety margin
  - prevent excessive number of forks that waste computing work
  - give reasonable latency for new block prapagation through network

Hard limit on Bitcoin's total amount of money

- enforced by "monetary rule":
  - scarcity of money to eliminate inflation (fabrication of money at will)
  - predictability of money supply to ensure confidence (avoiding "surprises")
- limit: ~21 million BTC
  - as new bitcoins are created only via the block subsidy
  - as initial subsidy was 50 BTC per block
  - as subsidy halves every 210,000 blocks
    ---> Total amount = $210{,}000 * \sum_n 50 * (1/2)^n = \approx 20{,}999{,}999.9769$ BTC
- year of last mined bitcoin: ~ 2140 ; after that, miners earn only transaction fees

...Chain (of Blocks): Major details...

Addresses & encoding

- Bitcoin address: the recipient of a money transfer!
  - recipient: entity (represented by a public key) or script (set of rules)
  - convolved fingerprint of recipient's public key or (redeem) script
    - written in a *Base58Check* format that is human-readable [FIG]
    - Base58 encode ():
      - interpret data as number
      - apply radix-58 algorithm
      - translate numbers to position chars of alphabet:
        - `123456789ABCDEFGHJKLMNPQRSTUVWXYZabcdefghijkmnopqrstuvwxyz`[1]
      - for every leading `0x00` in original data --> prepend a `1`
      - Example: `0x00010966778899` --> `1WwgmrFz` [2]

1 Note: no 0 (zero) , O (capital o) , I (capital i), l (lowercase L) -- avoids visual confusion
2 use: https://learnmeabitcoin.com/technical/keys/base58/

...Chain (of Blocks): address encoding...

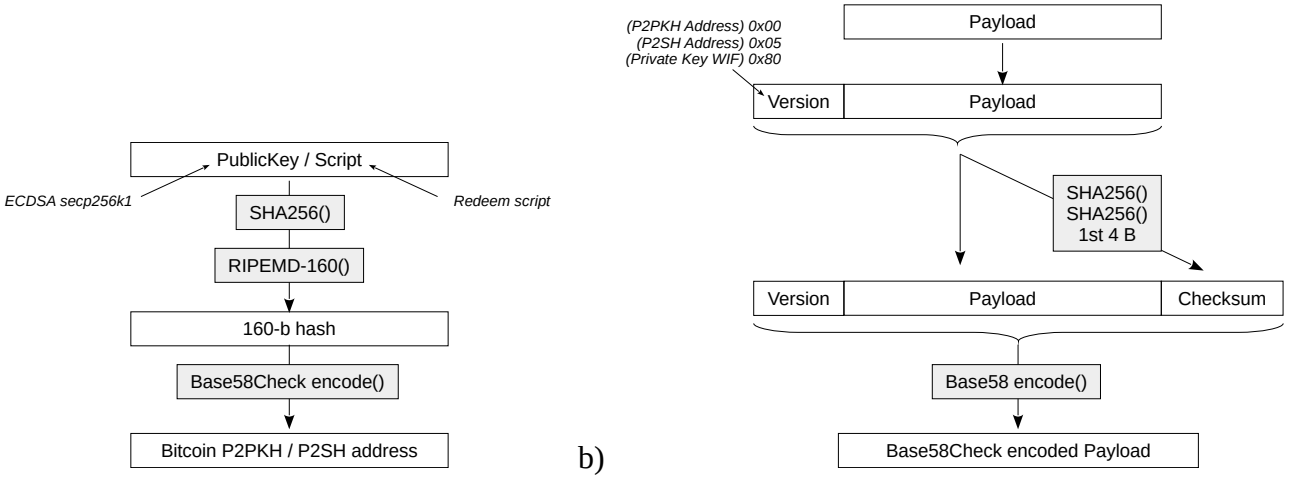

Fig. Bitcoin address building: a) general construction; b) Base58Check encoding (payload can be a hash, such as the shown in a) or something else.

Pointers...

- "**Bitcoin: A Peer-to-Peer Electronic Cash System**", 2008 – S. Nakamoto
  - https://bitcoin.org/bitcoin.pdf
- "**Bitcoin**", 2026 – Wikipedia
  - https://en.wikipedia.org/wiki/Bitcoin
- The "**Bitcoin Developer's Glossary**", 2020, Bitcoin Project
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  - https://developer.bitcoin.org/reference/
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  - https://github.com/bitcoinbook/bitcoinbook
- The *amazing* "**learn me a bitcoin**" site, 2026, Greg Walker
  - https://learnmeabitcoin.com/technical/