

Bitcoin Basics

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1. Introduction to Bitcoin & Blockchain

2. Bitcoin Architecture

- Blockchain & Blocks
- Block Header & Contents
- Genesis Block

3. Transactions in Bitcoin

- Data Structure
- Transaction Validation

4. Bitcoin Network

- P2P Network
- Types of Nodes

5. Bitcoin Use Cases

- Micropayments
- Scaling Bitcoin

6. Storing Bitcoins

This chapter is heavily inspired by and uses examples from „Bitcoin and Cryptocurrency Technologies“ by Arvind Narayanan.

Bitcoin: A Peer-to-Peer Electronic Cash System

Satoshi Nakamoto

October 31, 2008

Abstract

A purely peer-to-peer version of electronic cash would allow online payments to be sent directly from one party to another without going through a financial institution. Digital signatures provide part of the solution, but the main benefits are lost if a trusted third party is still required to prevent double-spending. We propose a solution to the double-spending problem using a peer-to-peer network. The network timestamps transactions by hashing them into an ongoing chain of hash-based proof-of-work, forming a record that cannot be changed without redoing the proof-of-work. The longest chain not only serves as proof of the sequence of events witnessed, but proof that it came from the largest pool of CPU power. As long as a majority of CPU power is controlled by nodes that are not cooperating to attack the network, they'll generate the longest chain and outpace attackers. The network itself requires minimal structure. Messages are broadcast on a best effort basis, and nodes can leave and rejoin the network at will, accepting the longest proof-of-work chain as proof of what happened while they were gone.

1. Introduction

Commerce on the Internet has come to rely almost exclusively on financial institutions serving as trusted third parties to process electronic payments. While the system works well enough for most transactions, it still suffers from the inherent weaknesses of the trust based model. Completely non-reversible transactions are not really possible, since financial institutions cannot avoid mediating disputes. The cost of mediation increases transaction costs, limiting the minimum practical transaction size and cutting off the possibility for small casual transactions,

- This is a technical paper published online in the year of the financial crisis.
- **Satoshi Nakamoto** wrote a paper in 2008 about “*Bitcoin: A Peer-to-Peer Electronic Cash System*”
- The **real identity** of Satoshi Nakamoto remains **unknown**. We don't know whether it was a single person or a group.
- In **January 2009** the **first block** of the Bitcoin blockchain was **mined**.
- In contrast to public opinion, Bitcoin was **not invented because of the financial crisis**. Satoshi Nakamoto said he started working on Bitcoin in May 2007 (in contrast the financial crisis started in August 2007).

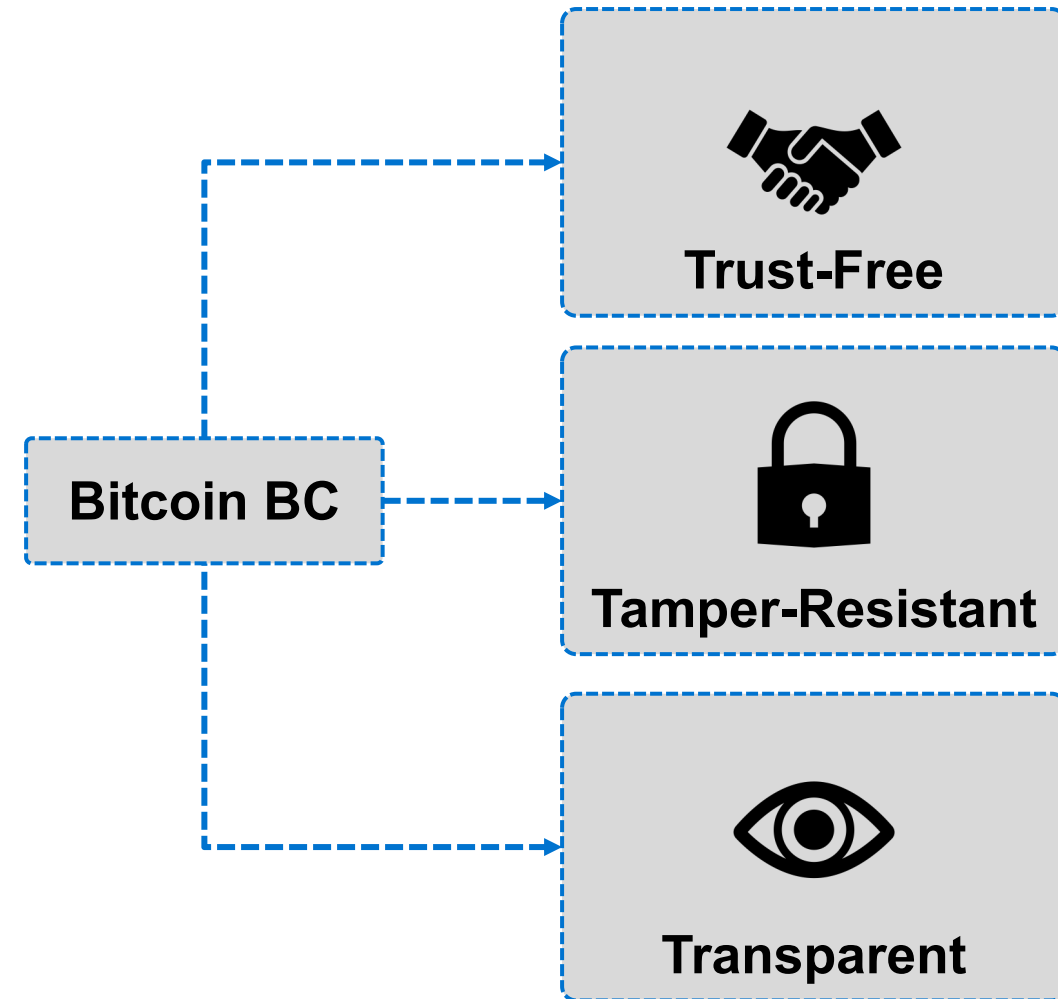
Bitcoin's History



Key Properties of the Bitcoin Blockchain

It has **three key properties**:

- **Trust-Free:** *The system does not require a third party which controls or maintains the system.*
- **Tamper-Resistant:** *The system is resistant to manipulation. The history of events cannot be changed.¹*
- **Transparent:** *Every participant of the system can read and validate all information and the current state.*



¹ We will see in the upcoming lectures that this is actually possible with blockchain history re-organization attacks.

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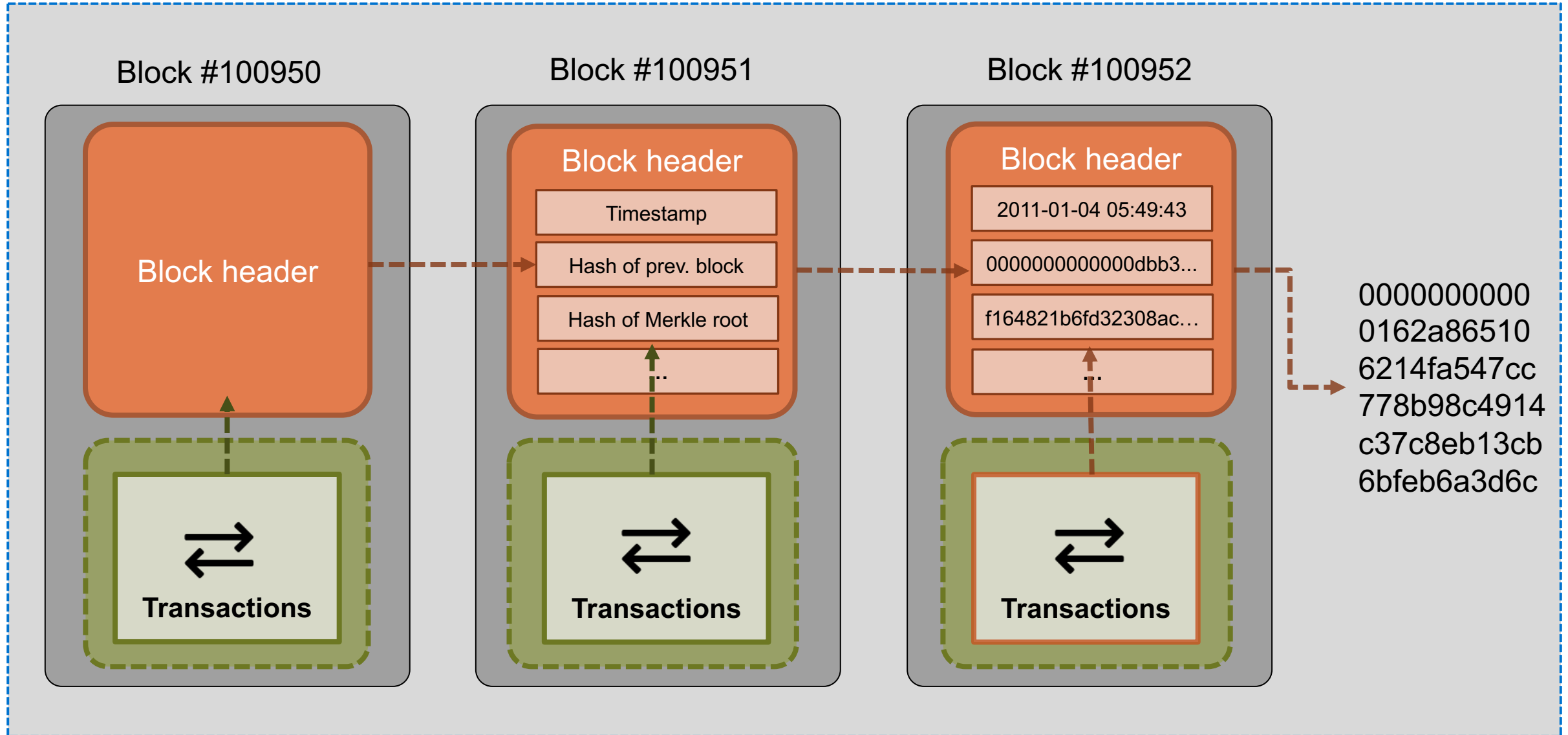
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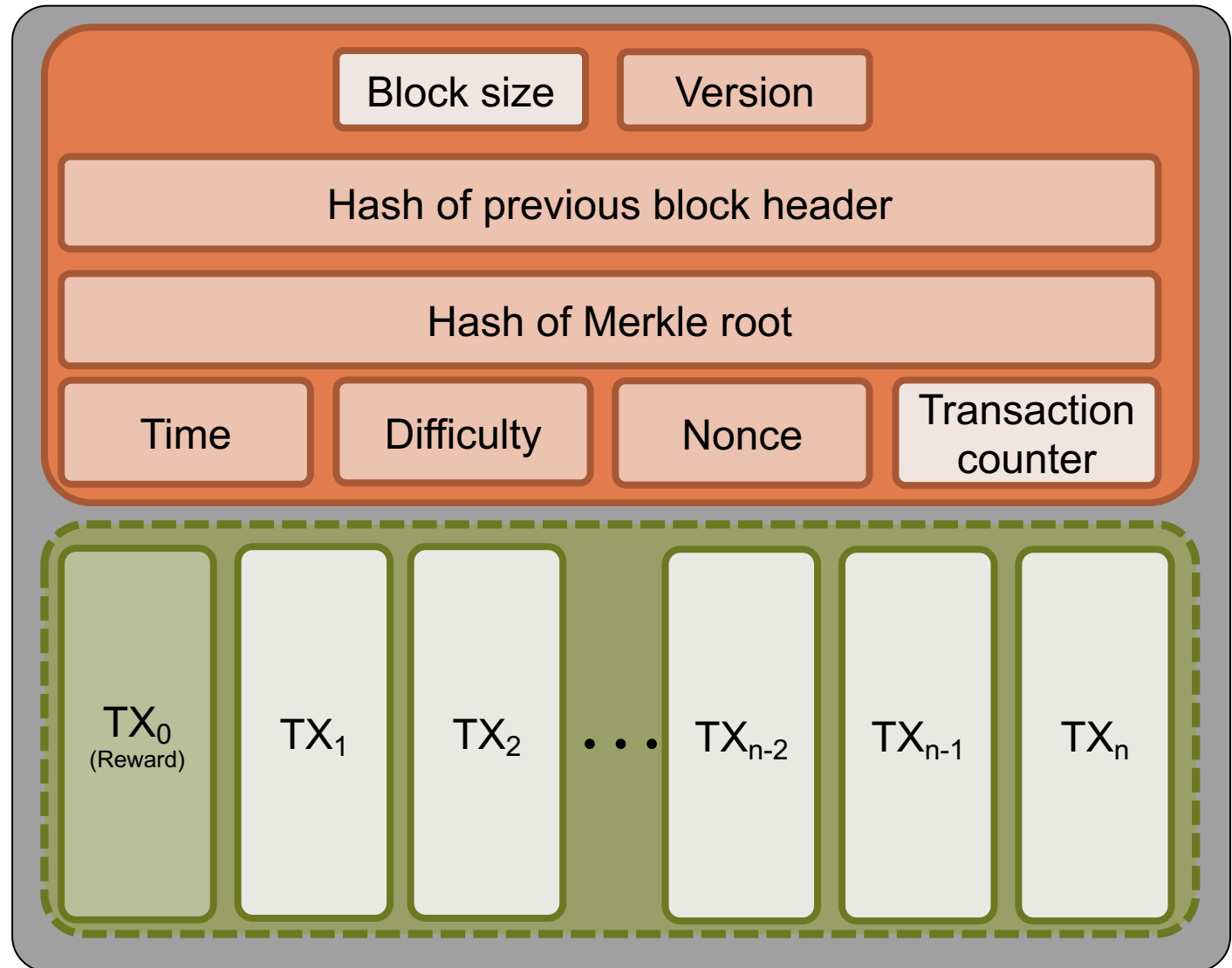
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Block Details

- The *hash of the previous* block creates the chaining.
- The hash of the Merkle root node of a Merkle tree structure with all transactions (as explained in Chapter 2).
- The *nonce* is required for the consensus mechanism in the network (used while solving the search puzzle).
- The block's hash used for chaining is calculated from the *version* until the *nonce* field.
- The height of the block is stored in the coinbase transaction.¹ (TX₀)



¹ The coinbase transaction is the first transaction included in each block where the block miner receives the block reward. It will be further explained in the upcoming lectures.

Blocks have to reference their predecessor → **How does a blockchain start?**

Bitcoin's genesis block¹:

- mined at 2009-01-03 18:15:05
- references a previous block with hash 0
- contains only the mining reward transaction → first 50 BTC which can never be spent

The fact that it cannot be spent is based on the source code of the current bitcoin-core client². The client searches through all blocks in `ConnectBlock` and processes all transactions but skips the genesis block.

¹ <https://blockchain.info/block/000000000019d6689c085ae165831e934ff763ae46a2a6c172b3f1b60a8ce26f> (accessed 24.10.2017)

² <https://github.com/bitcoin/bitcoin/blob/9546a977d354b2ec6cd8455538e68fe4ba343a44/src/main.cpp#L1668> (accessed 24.10.2017)

Data Contained in the Genesis Block



00000000	01 00 00 00 00 00 00 00	00 00 00 00 00 00 00 00
00000010	00 00 00 00 00 00 00 00	00 00 00 00 00 00 00 00
00000020	00 00 00 00 3B A3 ED FD	7A 7B 12 B2 7A C7 2C 3E;éíýz{.²zÇ,>
00000030	67 76 8F 61 7F C8 1B C3	88 8A 51 32 3A 9F B8 AA	gv.a.È.Ã^ŠQ2:Ÿ,ª
00000040	4B 1E 5E 4A 29 AB 5F 49	FF FF 00 1D 1D AC 2B 7C	K.^J)«_Iÿÿ...¬+
00000050	01 01 00 00 00 01 00 00	00 00 00 00 00 00 00 00
00000060	00 00 00 00 00 00 00 00	00 00 00 00 00 00 00 00
00000070	00 00 00 00 00 00 FF FF	FF FF 4D 04 FF FF 00 1DÿÿÿÿM.ÿÿ..
00000080	01 04 45 54 68 65 20 54	69 6D 65 73 20 30 33 2F	..EThe Times 03/
00000090	4A 61 6E 2F 32 30 30 39	20 43 68 61 6E 63 65 6C	Jan/2009 Chancel
000000A0	6C 6F 72 20 6F 6E 20 62	72 69 6E 6B 20 6F 66 20	lor on brink of
000000B0	73 65 63 6F 6E 64 20 62	61 69 6C 6F 75 74 20 66	second bailout f
000000C0	6F 72 20 62 61 6E 6B 73	FF FF FF FF 01 00 F2 05	or banksÿÿÿÿ..ò.
000000D0	2A 01 00 00 00 43 41 04	67 8A FD B0 FE 55 48 27	*....CA.gŠÿ*pUH*
000000E0	19 67 F1 A6 71 30 B7 10	5C D6 A8 28 E0 39 09 A6	.gñ!q0-. \Ö" (à9.!
000000F0	79 62 E0 EA 1F 61 DE B6	49 F6 BC 3F 4C EF 38 C4	ybaê.aF¶Iö4?Li8Ä
00000100	F3 55 04 E5 1E C1 12 DE	5C 38 4D F7 BA 0B 8D 57	óU.Á.Ä.Æ\8M÷°..W
00000110	8A 4C 70 2B 6B F1 1D 5F	AC 00 00 00 00	ŠLp+kñ._¬....

The data highlighted is stored in the *scriptSig* field of the first transaction (=coinbase transaction).

A possible motivation to put this headline into the genesis block is to prove that no “pre-mining” has happened.

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Create 25 coins and credit to Alice	signed by miners
Transfer 17 coins from Alice to Bob	signed by Alice
Transfer 8 coins from Bob to Carol	signed by Bob
Transfer 5 coins from Carol to Alice	signed by Carol
Transfer 15 coins from Alice to Bob	signed by Alice

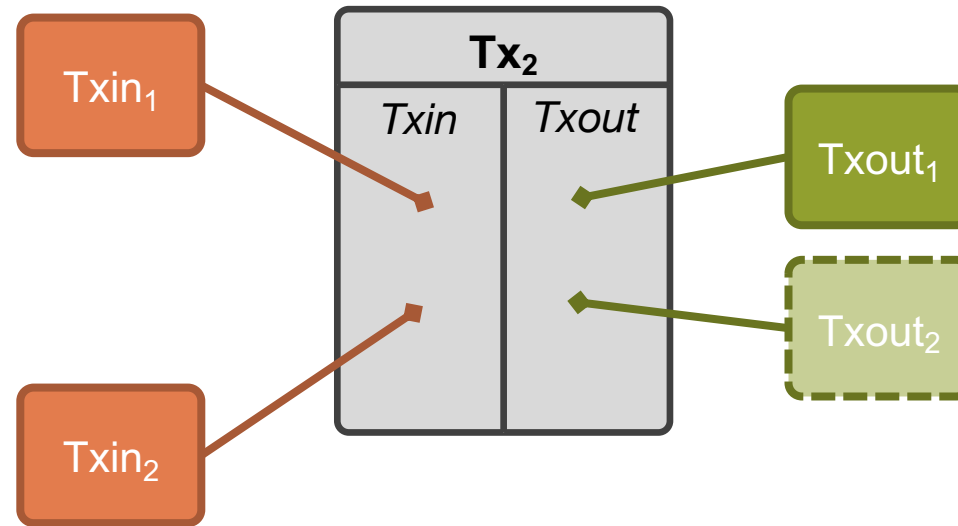
Transactions

Alice	Bob	Carol
25	0	0
8	17	0
8	9	8
13	9	3
-2	24	3

World State

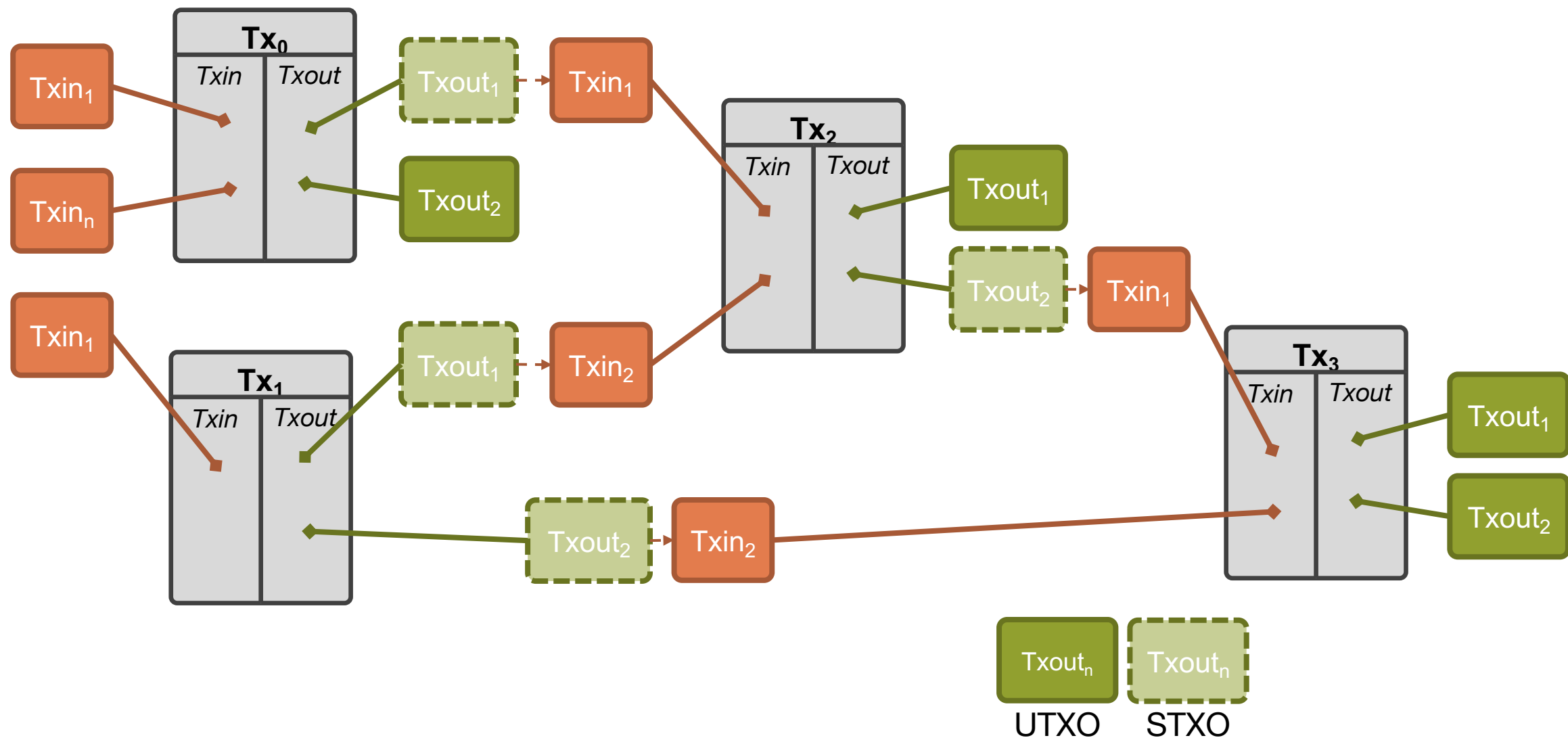
- *Intuitively:* We consider Bitcoin to use an account-based ledger. However, an account-based approach takes a lot of effort to track the balances of every account.
- In reality, Bitcoin keeps track of the transactions an account has received and does not add up account balances (on the chain).
- Transactions lead to a “world-state” of accounts and allow to calculate account balances off-chain (e.g., in a wallet).
- By using a transaction-based ledger, Bitcoin enables wallet owners to define conditional transactions using Bitcoin Script¹.

¹Bitcoin Script is a stack-based scripting language used in Bitcoin transactions. It will be covered further in the upcoming exercises..



- Transactions (**Tx**) have a number of inputs and a number of outputs.
 - **Inputs (Txin)**: Former outputs, that are being consumed
 - **Outputs (Txout)**: Creation of new coins and transfer of coin ownership
- In transactions where **new coins** are created, **no Txin** is used (no coins are consumed)
- Each transaction has a unique identifier (**Txid**). Each output has a unique identifier within a transaction. We refer to them (in this example) as $\#TX[\#txout]$, e.g., 1[1], which is the second Txout of the second transaction.

Transactions Connected by Inputs and Outputs



0	Txin: \emptyset Txout: 25.0 → Alice
1	Txin: 0[0] Txout: 17.0 → Bob, 8.0 → Alice signed by Alice
2	Txin: 1[0] Txout: 8.0 → Carol, 9.0 → Bob signed by Bob
3	Txin: 1[1] Txout: 6.0 → David, 2.0 → Alice signed by Alice

Example:

0. No input required, as coins are created.
1. The Tx is used as an Txin. Two Txout are created, one to Bob and one to Alice. (1[0] and 1[1]) The Tx is signed by Alice.
2. Uses first Txout of Tx1. Creates two Txout to Carol and Bob, signed by Bob.
3. Uses second Txout of Tx1. Creates two Txout to David and Alice, signed by Alice.

Further remarks

Change Address:

Why does Alice have to send money back to herself?
In Bitcoin, either all or none of the coins have to be consumed by another transaction. The address the money is sent back to is called a *change address*. This enables an efficient verification, as one only has to keep a list of **unspent transaction outputs (UTXO)**.

Consolidating funds:

Instead of having many unspent transaction outputs, a user can create a transaction that uses all UTXO she has and creates a single UTXO with all the coins in it.

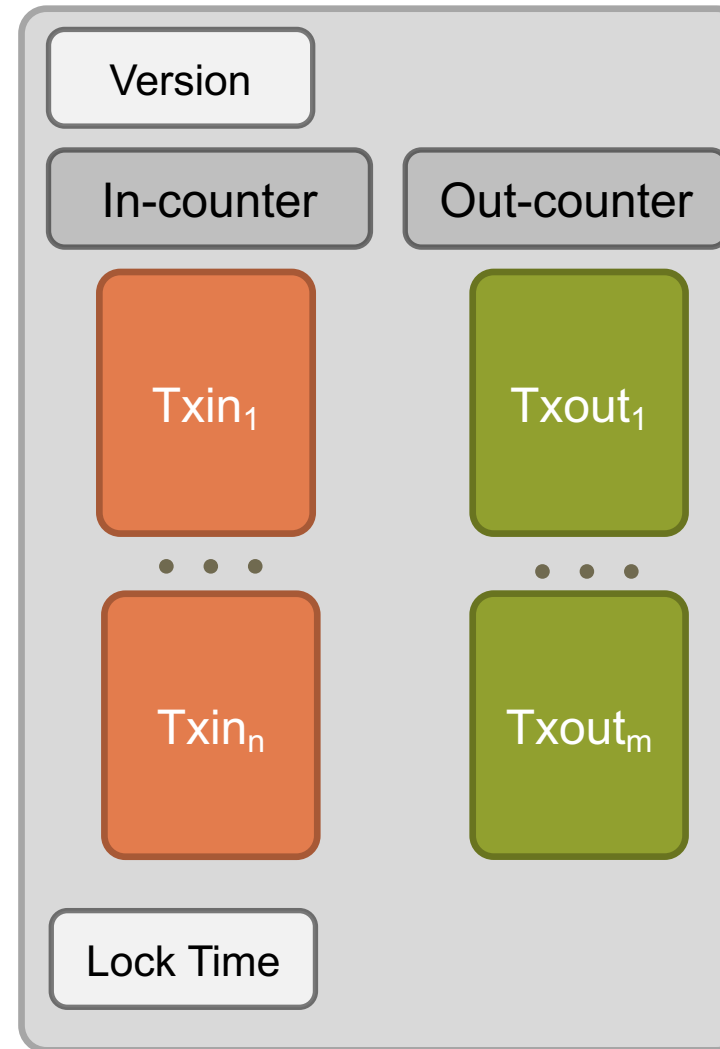
Joint payments:

Two or more parties can combine their inputs and create one output. Of course, it requires signatures from all involved parties.

An Advanced Look at Transactions

As previously stated, transactions consist of inputs and outputs following these principles:

- All inputs reference an existing unspent output or a coinbase transaction.
- Inputs and outputs contain scripts (**scriptSig**, **scriptPubKey**) for verification.
- Output scripts (scriptPubKey) **specify the conditions to redeem their value**.
 - *Locking script*
- Input scripts (scriptSig) **provide a signature** to redeem the referenced output.
 - *Unlocking script*
- Only **outputs store the BTC value** and the **receiver's address**.
- **All coins have a history (inputs/outputs) up to the original coinbase transaction that created them.**



Input format

Txin

- previous transaction hash
- previous Txout-index
- script length
- *scriptSig*

Output format

Txout

- value in *Satoshi* ($=10^{-8}$ BTC)
- script length
- *scriptPubKey*

Logical Data Structure of Transactions

```
"hash": "5a42590fbe0a90ee8e8747244d6c84f0db1a3a24e8f1b95b10c9e050990b8b6b",
"ver": 1,
"vin_sz": 2,
"vout_sz": 1,
"lock_time": 0,
"size": 404,
"in": [
  {
    "prev_out": {
      "hash": "3be4ac9728a0823cf5e2deb2e86fc0bd2aa503a91d307b42ba76117d79280260",
      "n": 0
    },
    "scriptSig": "30440..."
  },
  {
    "prev_out": {
      "hash": "7508e6ab259b4df0fd5147bab0c949d81473db4518f81afc5c3f52f91ff6b34e",
      "n": 0
    },
    "scriptSig": "3f3a4ce81...."
  }
],
"out": [
  {
    "value": "10.12287097",
    "scriptPubKey": "OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG"
  }
]
```

Metadata

It contains the **size of the transaction**, the **number of inputs** and **outputs**, the version and a lock-time. The hash is also contained, which can be referenced.

Inputs

An **array of all inputs**. Each input contains the previous transaction and the index of Txout. Also, a signature *script* is provided.

Outputs

An **array of all outputs**. One output has two fields: the amount of the transferred coins¹ and the *scriptPubKey*.

An example transaction with two Txin and one Txout.

¹Note, that the sum of all output amounts has to be the same or smaller than the sum of all inputs. The difference is the transaction fee, which is covered in the chapter “Bitcoin Consensus”.

Example taken from „Bitcoin and Cryptocurrency Technologies“ by Arvind Narayanan

Whenever a transaction is validated, it **must pass a long list of checks**. Simplified, they look like this:

1. Check syntactic correctness
2. Make sure neither in or out lists are empty
3. Check that size in bytes \leq MAX_BLOCK_SIZE
4. Each output value, as well as the total, must be in legal money range
5. No input may be a coinbase transaction input
6. Check that each input ...
 - a) references an old output
 - b) references an old output not yet referenced in another transaction (in block or in memory pool)
 - c) contains the correct authorization to spend that old output
 - d) ... satisfies the conditions defined by the script
7. Check that the sum of output values \leq sum of input values
8. Add to transaction pool
9. Relay transaction to peers

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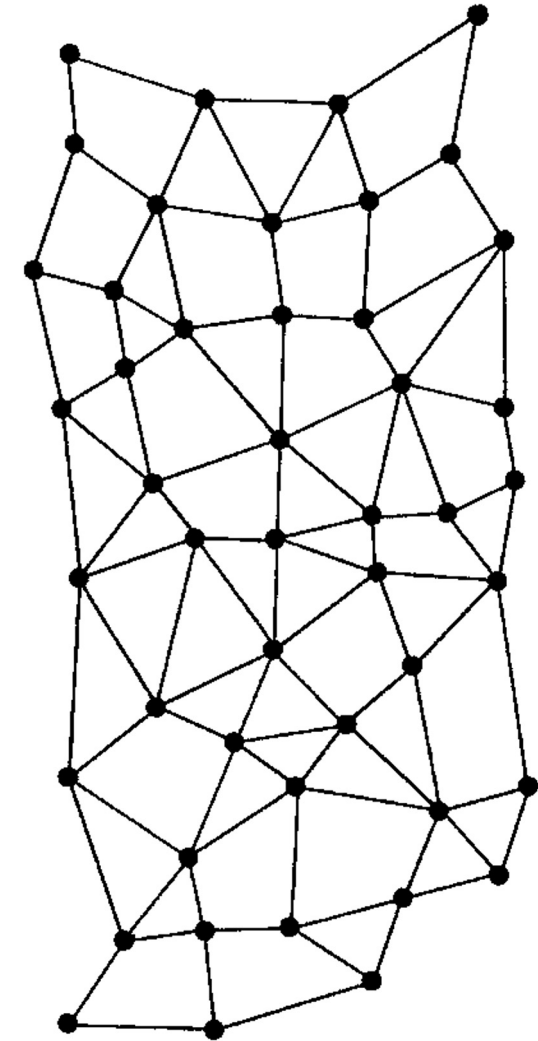
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- Bitcoin itself consists of different users and nodes. We distinguish between **wallet owners**, **light nodes**, **full nodes** and **miners**. (More on that topic later)
- They communicate in a **decentralized** fashion, meaning that no single entity or node is superior.
- To communicate, they need to have clear rules
 - How to **find** other nodes (bootstrapping)
 - How the **sync** the blockchain
 - How to **send** and **receive** transactions
 - How to **send** and **receive** blocks
- The basic network uses a peer-to-peer (P2P) **gossip** protocol. Messages about new blocks or transactions are **validated** and then **broadcasted**. To prevent a second broadcast, the node keeps track of the transactions and blocks sent by itself.



An advanced look into the verification of messages containing transactions or blocks provides [The Bitcoin Wiki: Protocol Rules](#).

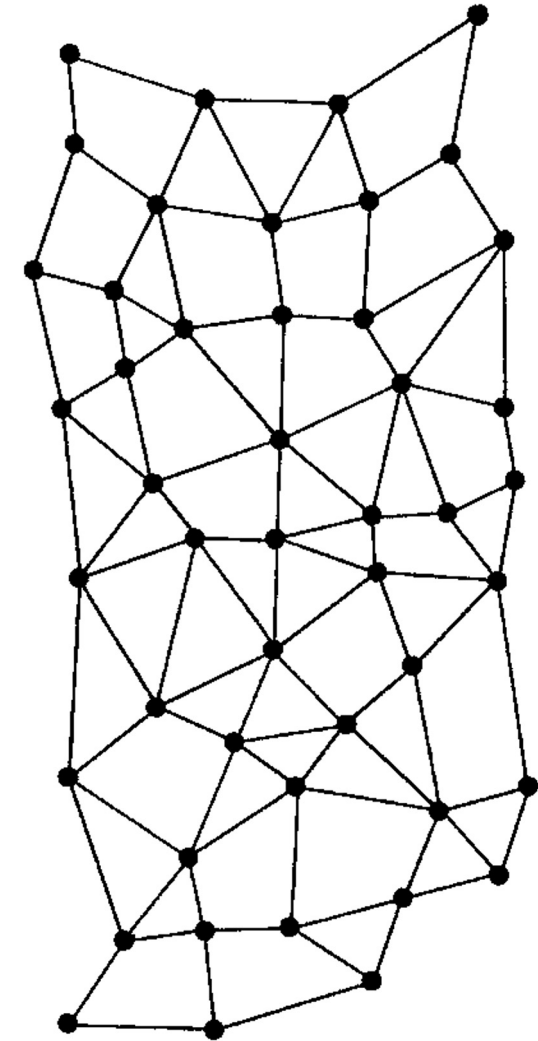
Bootstrapping of Nodes

Client Node Discovery

How are new nodes introduced into the Bitcoin network?

There are several ways:

- (deprecated) Get to know new clients via **IRC-channels**
- Hard-coded **DNS-services** which offer IP-addresses of nodes
- Hard-coded **seed addresses** (last resort)
- Addresses stored in a **database** maintained locally (to be loaded after a restart)
- **Command-line** provided addresses
- **Text-file** provided addresses



Wallet Owner (User)

- The wallet owner owns different **private keys** to unspent transaction outputs (UTXOs).
- He is the **owner** of all stored currencies on these addresses.
- He sends money by **signing** and **publishing** new transactions to a connected light node, full node or miner.

Full Node (Software)

- The full node **maintains** the **complete blockchain**. Its record of the chain is complete, it contains every single transaction and block until the genesis block.
- Is **connected to** other **full nodes** and exchanges information. Namely:
 - **Validates** every transaction and block it receives
 - **Relays** all new transactions and blocks

Miner (Software)

- The miner **needs** the **same record** as a **full node** in order to work properly. He also is connected to other nodes and maintains the network.
- Additionally, the miner is **responsible** for **creating** new **blocks** by trying to solve the **mining puzzle**.
- The miner gets rewarded by creating new blocks.

Light Node (Software)

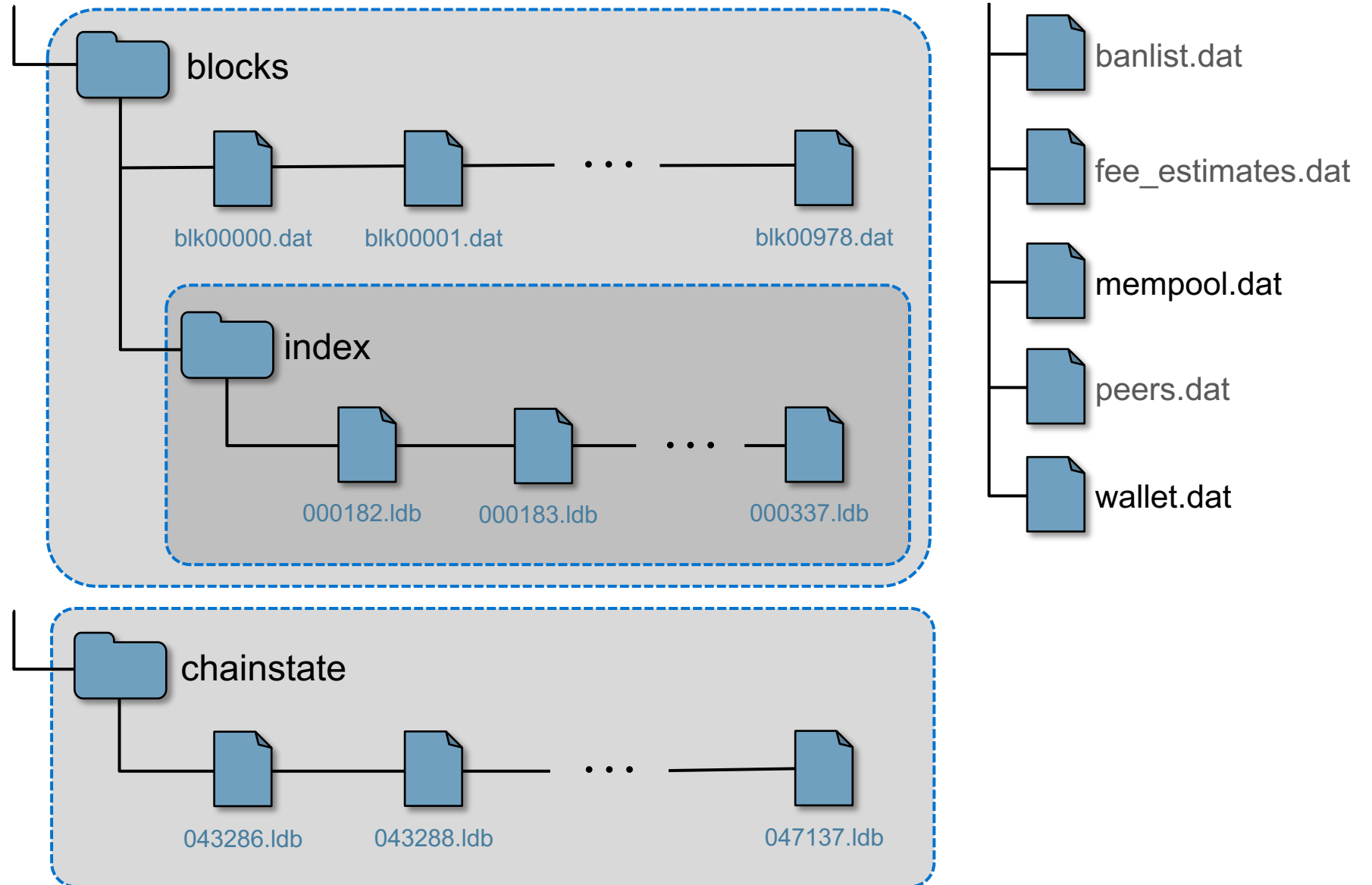
- The light node can **act** as a **relay** for transactions of one **wallet owner**.
- It **validates** whether a **single transaction** of the wallet owner was executed correctly.
- The light node also **requires a full node** to connect to the network.
- **Almost no relevance** in practice today. Today, centralized services are used to create transactions.

Anatomy of the Bitcoin Blockchain

Raw data is on a disk.

Miners and full nodes organize their data in a certain way. (Bitcoin core)

As of March 2024, the total data size of the Bitcoin blockchain is 560 GB.



blocks and **blocks/index**

Contains .blk files that contain the actual blockchain in raw network format; **index** contains a database which stores the location of each block on the disk keyed with its hash.

chainstate

A LevelDB (leveldb.org) database with all currently unspent transaction outputs in the system (UTXO). This is used when operating a Bitcoin node in favor of the raw blockchain data.

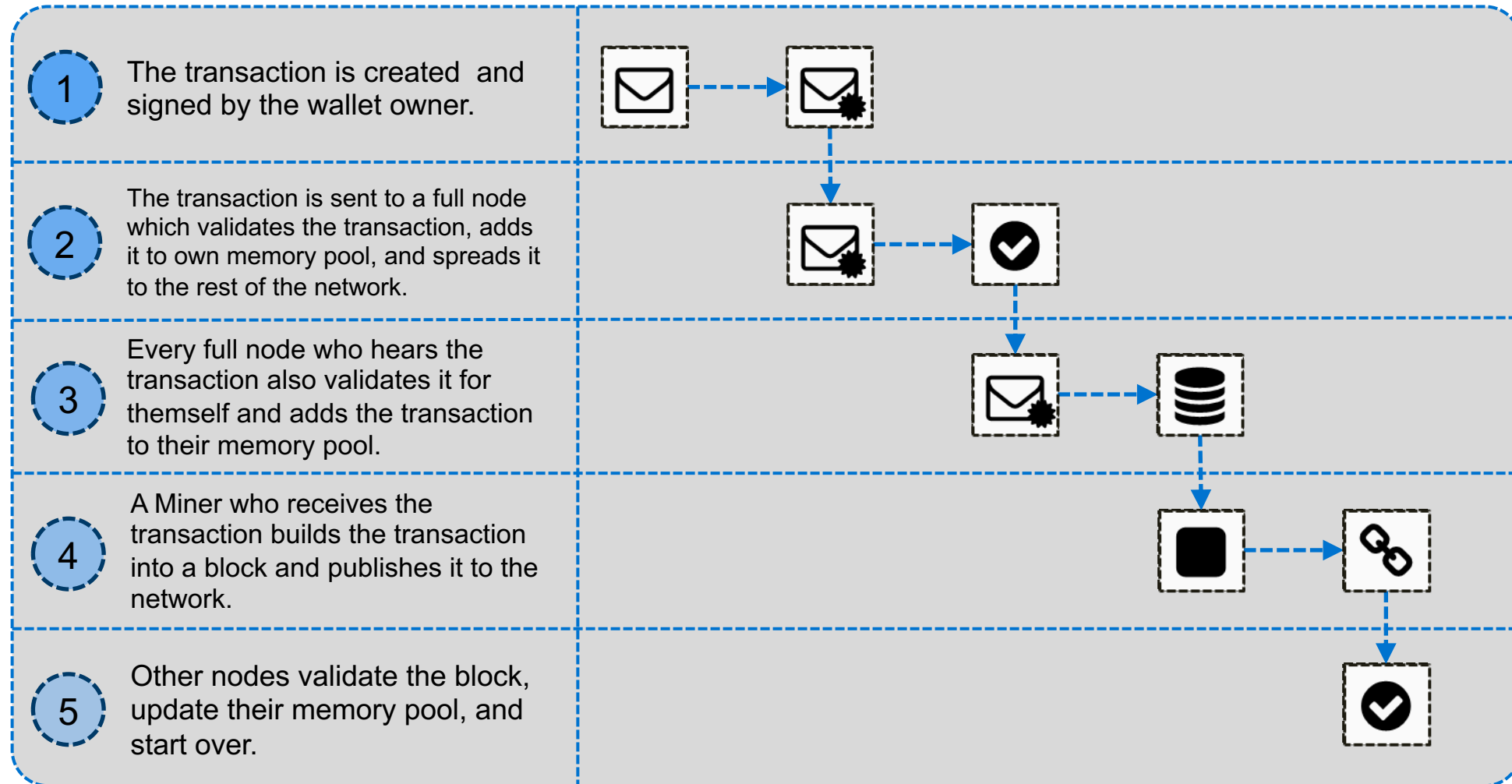
mempool.dat

A list of unconfirmed transactions to be part of a future block.

wallet.dat

Data regarding the user's (owner of the node) personal wallet.

A Newly Created Transaction's Way into a Block



A high-level representation of how transactions are included in blocks.

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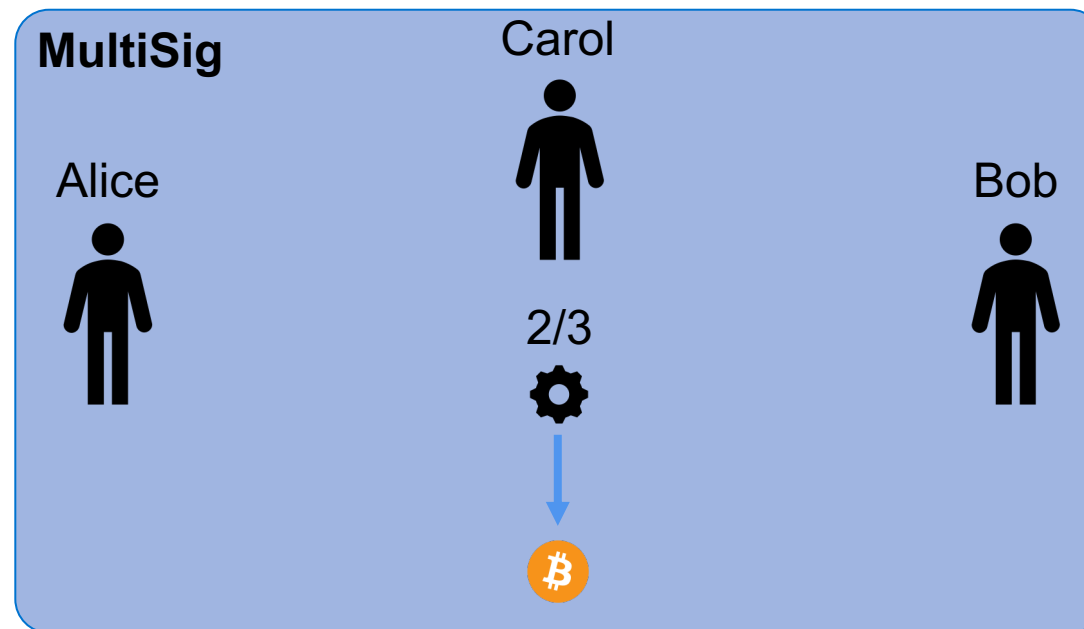
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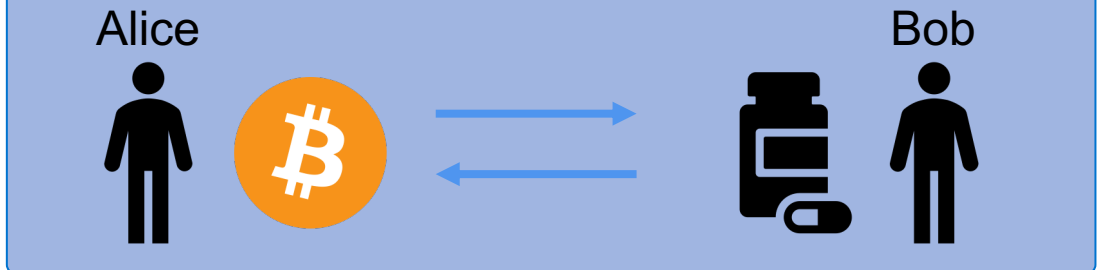
- A N/M multisig address is an address which has following properties
 - It requires more than one signature
 - N defines the number of required signatures
 - M defines the number of maximum signatures
- A $2/3$ multisig address requires two arbitrary signatures from a pool of three predefined signatures.



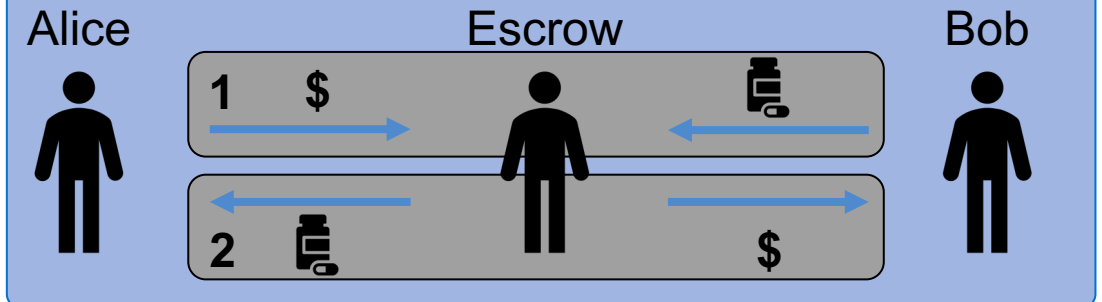
Escrow

- Alice and Bob want to do business together. Alice wants to buy some real-world product from Bob with Bitcoin. However, Alice does not want to send the Bitcoin before having the physical good, but Bob does not want to send the physical good before having the Bitcoin in his wallet.
- What to do? In traditional systems, an escrow would enable the transaction. The escrow would receive both the good and the money and exchange them.
- With Bitcoin (or other cryptocurrencies), this process can be enhanced. Alice creates a 2/3 multisig-address and transfers the money to it. Bob can now safely send his good.
- When the good arrives, both Alice and Bob can sign the transaction and Bob receives his money.
→ If the exchange is correctly executed, the escrow is not involved.

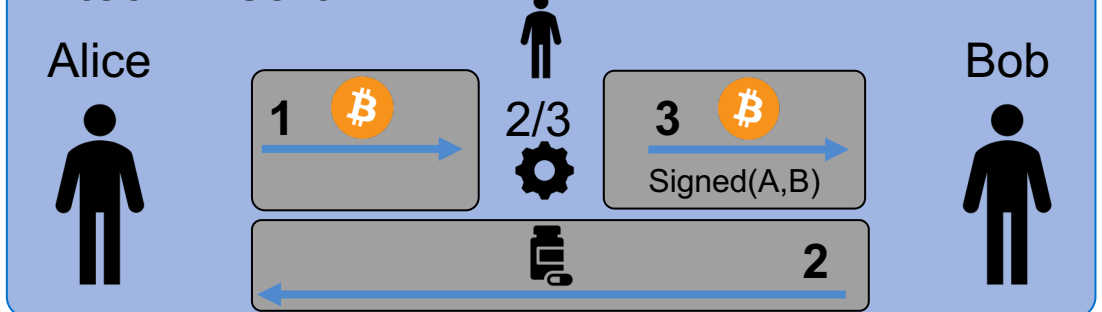
Situation



Traditional Escrow



Bitcoin Escrow



Micropayments

Alice wants to continuously use a service from Bob and pay a certain small amount of Bitcoin for each usage.

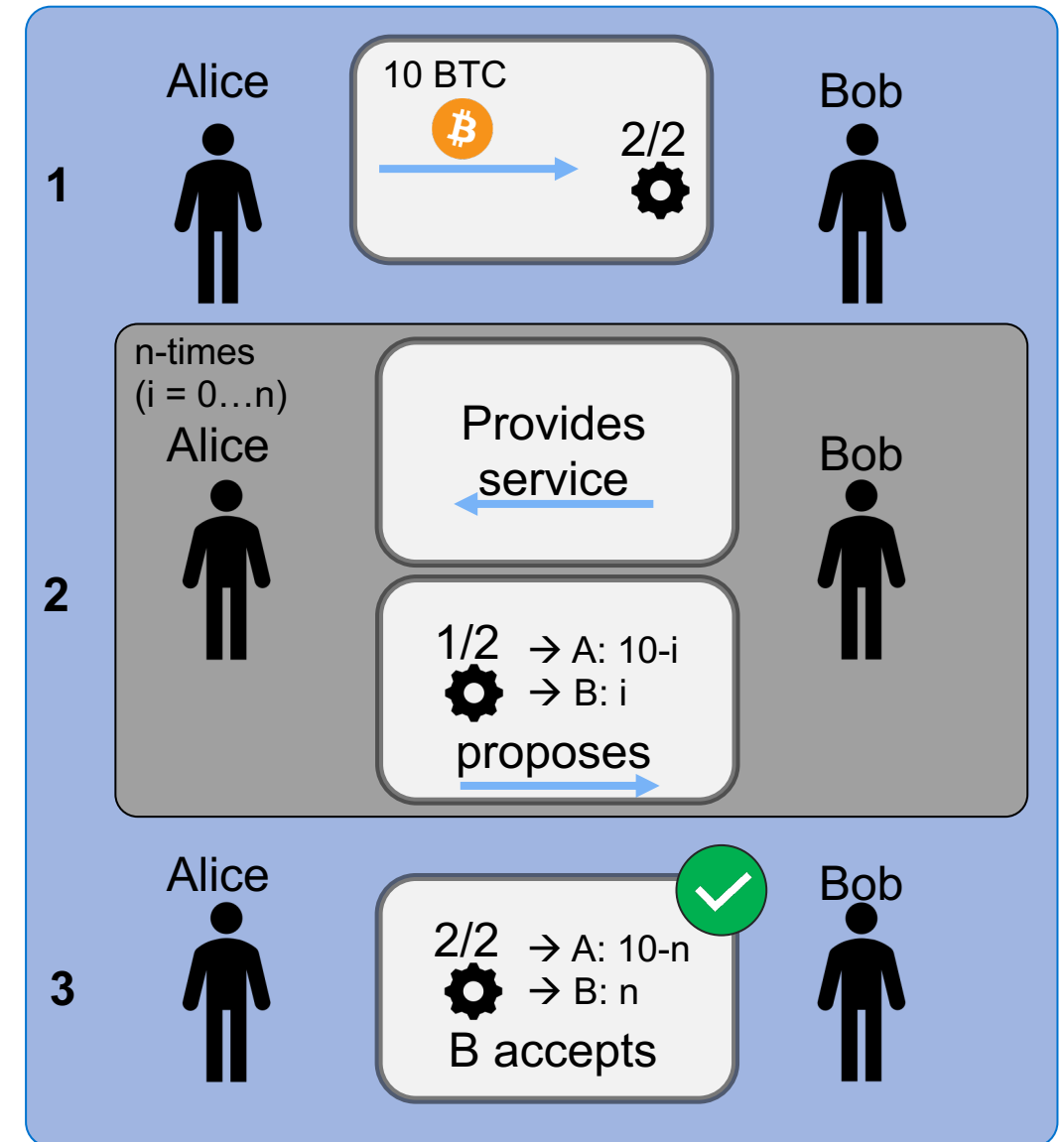
Creating new transactions every time won't work as:

- Too many transactions get created
- The fees for the transactions would be too high

An approach would be following:

- At the beginning, Alice send her maximum spendable amount to a 2/2 multisig address.
- Every time she consumes the service by Bob she signs a transaction locally for the multisig address, sending the accumulated amount to Bob and the change to herself. A message containing this incomplete transaction is sent to Bob.¹
- If she is done using the service, Bob will sign the last transaction he received and publish it on the network.

→ What is the problem?



¹ The transaction at this moment is rejected by the network as the second signature is missing.

Lock Time

The problem is that Bob could decide **not to sign** the last transaction (or any transaction at all), leaving Alice's money stuck inside the multisig address.

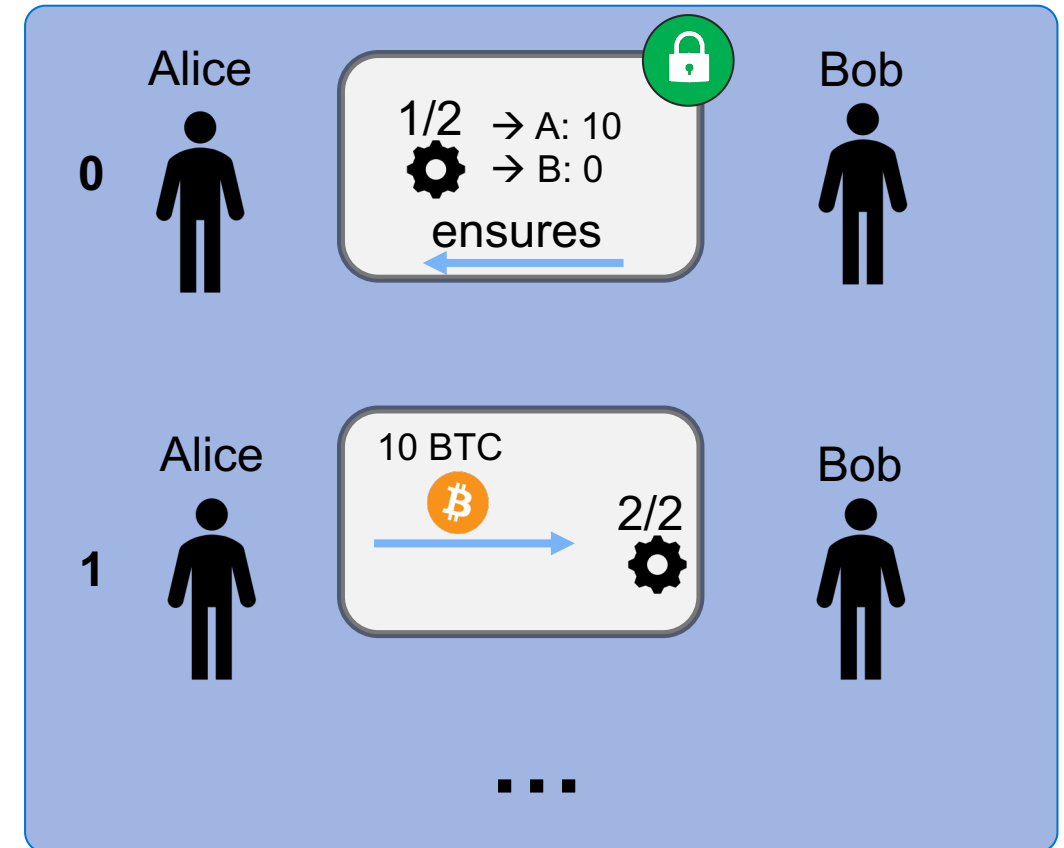
- Could also be the case that Alice decides to not work with Bob after sending the money to the multisig wallet but before using any service from him. If Bob does not cooperate, Alice's money is **stuck**.

However, there is a way around it:

In order to ensure that Alice receives her money back, she can demand from Bob to create a transaction from the multisig address, transferring the complete amount to Alice before she sends money to the multisig wallet.

This transaction contains a *lock time*¹ as the transaction output (i.e., Alice receiving 10 BTC) should only be spendable after a certain amount of time t and if the original transaction output (i.e., Alice sends 10 BTC to multisig) is not spent otherwise.

With this, it is safe to create a multisig address without having to worry if one receives the money back.



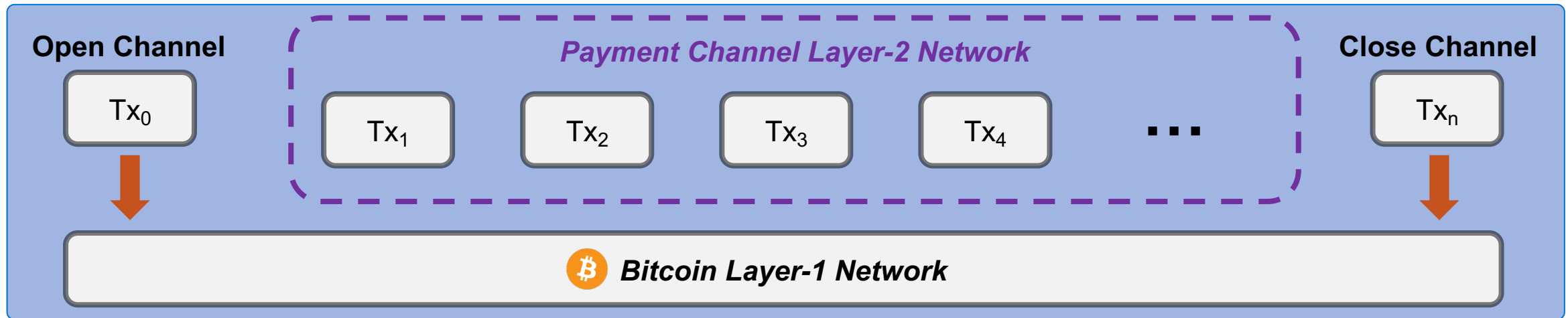
Time locked


¹ As there is no notion of time in Bitcoin, the lock time is given as the block height. Until this block height is reached, the transaction is invalid.

Micropayments is a concept used by **payment channels** allowing users to make Bitcoin transactions without committing every transaction to the main network.

Payment channels operate outside the chain and only require the initial transaction that **opens the channel** and the final transaction that **closes it** to be **recorded on-chain**. Any transaction in between these operations is executed outside the chain.

- Payment channels enable exchanging Bitcoins in a more efficient and cost-saving way, **scaling the network**.



- Solutions such as payment channels that help to scale the underlying network by handling some part of the workload on a **separate network** are also known as **Layer-2 solutions**.
 - Currently, the most well-known Layer-2 solution on Bitcoin is *Lightning Network*.¹ 

¹ Lightning Network: <https://lightning.network/>



Geographic distribution of nodes and channels on **Lightning Network**.

Screenshot taken from: <https://mempool.space/graphs/lightning/nodes-channels-map>

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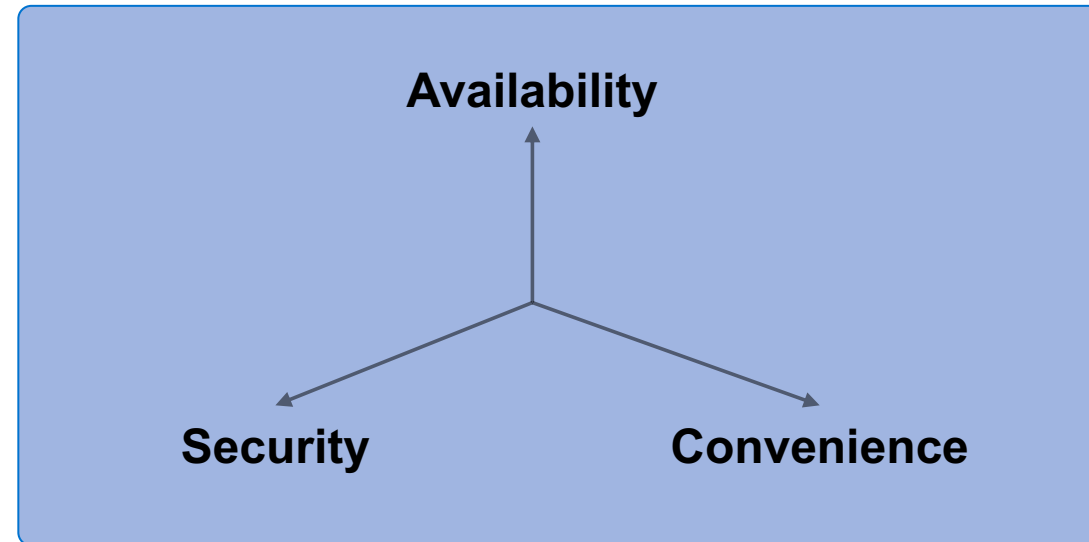
Storing Bitcoins is all about storing and managing secret keys.¹

Different approaches for storing and managing secret keys lead to different trade-offs between **availability**, **security** and **convenience**.

Availability: being able to access the keys when one wants to

Security: restricting access to the keys

Convenience: easy use



Of course: The simplest approach is to store the secret key on one's hard drive. What could *possibly* happen?

Cold Storage

- Takes some time to “activate”
- **Enhances security** at the cost of convenience and availability
- Advantage: Cold Storage does not have to be online to receive coins

Hot Storage

- Is **immediately available**
- Enables **convenience** and **availability** at the cost of security
- Example: Storage on your pc / mobile

Brain Wallet

- A brain wallet stores Bitcoins with nothing but a secret passphrase.
- There is no need for hard drives, paper or else to store information.
- Idea: a deterministic function to generate a private key out of a passphrase.
- However:
 - Source of randomness determines the security → offline guessing / password cracking
 - If passphrase is forgotten, bitcoins are lost forever
- Example:
*„witch collapse practice feed shame open despair
creek road again ice least“*

Paper Wallet

- **Key material is printed** to paper. Paper can be placed in secure places like safes or vaults.
- However, keep in mind:
 - **Source of randomness**
 - Side-Channel attacks
 - Infected computer / malware
 - Malicious paper-wallet generator
 - Monitored printer
 - Durability of paper
 - Durability of ink
 - Secure place: dark, 16-19°C, low humidity



Bitcoin Paper Wallet

Wallet Types (cont.)

Hardware Wallet

- **Key material** is stored on the **hardware device**.
- Additional: Generation of a 24-word passphrase. If device gets destroyed, the passphrase allows for a recovery.
- Device is designed to keep your private key private. Key is **securely stored** within the device.
- **The display shows the amount and target of a transaction.** The **keys** on the device allow for a **confirmation or rejection** of the transactions.
- Requires trust in manufacturer and intermediaries. (Never buy used hardware wallets!)



Hardware Wallet - Ledger Nano S

Online Wallet

- Let other people/ companies store your Bitcoins/ cryptocurrencies for you (custodial wallet).
- No access to the private key, coins can only be used through a certain interface / website.
- Very common within most exchanges. The money is sent to the exchange, the account on the platform has now a new balance which can be traded or paid out.
- However: **Very dangerous! Many exchanges got hacked, users lost their funds. Be careful!**

