Please comment on slides with anything unclear, incorrect or suggestions for improvement
https://drive.google.com/file/d/16zVbDqjxpEgUEAweWTCrijpjvTsONW8h/view?usp=sharing

PV204 Security technologies

Bitcoin basics I.

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CROCS
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Cryptography and Security

WHY BITCOIN?

Especially if you are not interested in Bitcoin.

“Bitcoin fixes everything!”

https://twitter.com/DominicFrisby/status/1388448025970884609

Goals for the lecture

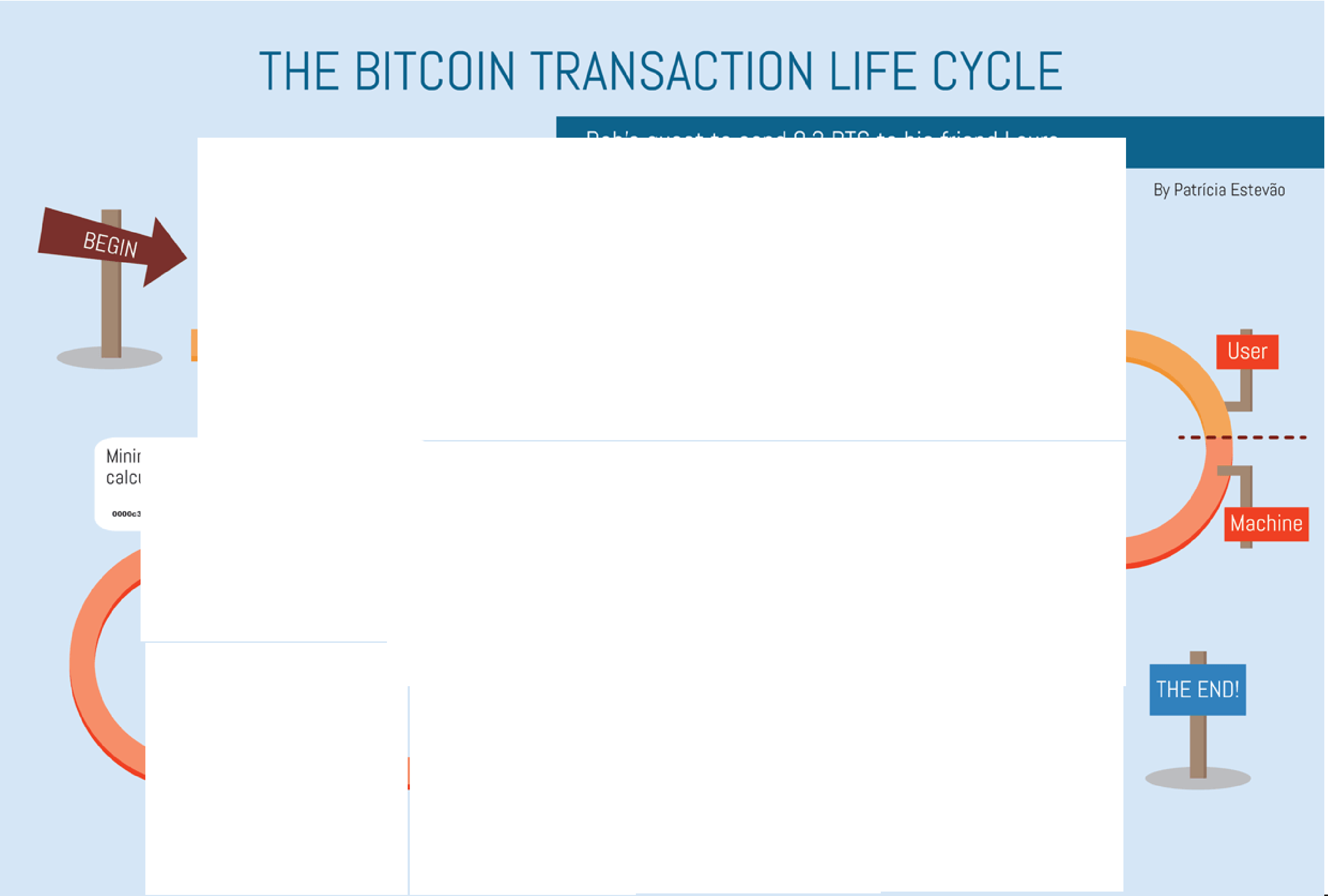
- Bitcoin does not fix everything, but is on a frontline
  - No safety net, no chargeback, attacker anonymous => security technique must really work, great for battle-testing security ideas, natural “bug bounty program”
- 6 main tech pieces we will cover (also usable outside Bitcoin world)
  1. How to backup key(s) (single seed, BIP39, Shamir)
  2. How to make always fresh keys (derivation via BIP32, also address privacy)
  3. How to protect signing key against malware
     - (multisig, hardware wallet, airgap pc + tx broadcast, mpc sig)
  4. How to introduce restricted signing policy (time, limit… lockscript/multisig)
  5. How to protect your financial privacy (CoinJoin, Tor)
  6. How to use hardware wallet with secure element

What is your previous exposure to the cryptocurrencies? Please check all items which applies to you.

ⓘ Start presenting to display the poll results on this slide.

BASICS

https://livebitnews.com/wp-content/uploads/2017/09/bitcoin-transaction-life-cycle-high-resolution-1.png



- Wallet
- Address
- Fee
- Transaction
- Signing
- Network nodes
- Block
- Mining
- Proof of Work
- Verification
- Block reward
- Tx confirmation
- And many more…

Main design goals of the Bitcoin

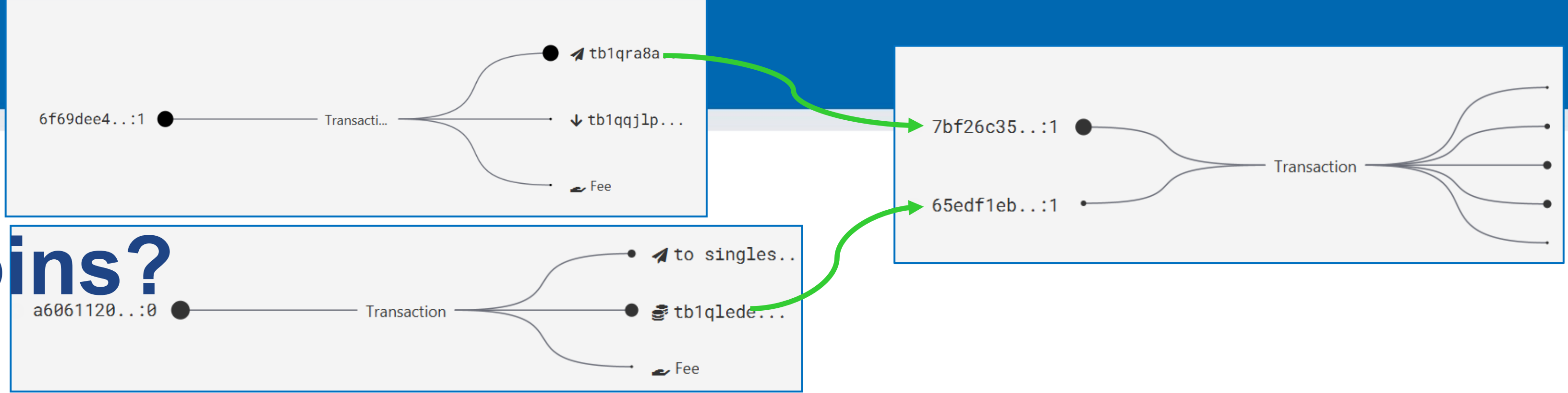
1. Decentralization
   - No central authority or intermediary (=> no single point of failure), possibility of self-custody
   - No limitation on network participants (no permission to join is required)
   - Applies to executing a transaction, but also development, infrastructure, mining…
2. Transparency
   - All transactions recorded on public ledger; validity of every “bitcoin” easy to verify
   - Total number of bitcoins in circulation easy to assess (monetary policy, fixed supply)
3. Security based on cryptography (mainly signature, hash functions)
   - Ownership of bitcoins proved only cryptographically (no “chargeback” based on human decision)
   - Protection of bitcoins reduced to protection of private key(s)
4. Pseudonymity of participants
   - bitcoins connected to public keys, not usernames (does not automatically mean anonymity!)

Problems to tackle

- How to prevent double spending?
- How to allow for permissionless participation?
- Who will store authoritative copy of public ledger?
- How to prevent modification of ledger history?
- Who will include next block in blockchain?
- How to maintain decentralization in distant future?
- …

Double-spending problem and Bitcoin's solution

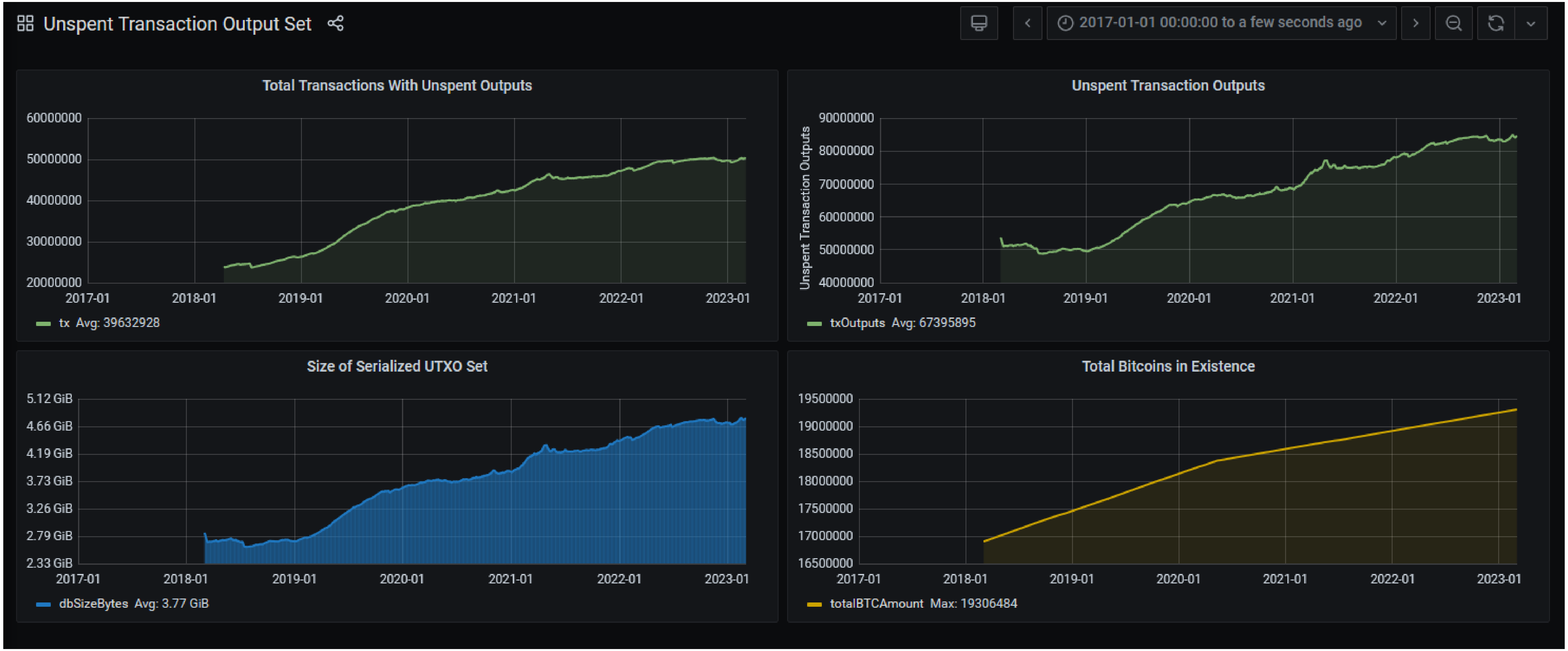
- Digital data are inherently easy to copy perfectly
  - If used as monetary coins, how to prevent double/triple… spending the same coin?
  - Previous proposals (eCash, B-money, Bit Gold..) required central party for prevention
- Digital coin X is "spent" by a transaction between users A and B
  - Double spend is another transaction from A to C using same coin X
- If all transactions are ordered strictly in time, double spend is not possible
  - Later transaction with same coin X is invalid
  - Decentralized ordering is costly as all participants need to agree on global state
- If ordered after every transaction => costly and slow
- Bitcoin orders in batches of transaction every 10 minutes on average
  - User needs to wait one (or more blocks) for ordering (longer => higher certainty)



Where are my bitcoins?

- Public ledger of all transactions (blockchain)
  - Replicated between all Bitcoin fullnodes (P2P network)
- “Bitcoin holdings” - sum of values of not-yet-spent transactions control
  - Unspent Transaction Output (UTXO)
- “Bitcoin receive” operation – generate variable part of lockscript (public) and share with sender + monitor blockchain for my transaction
- “Bitcoin send” operation – take “your” UTXO and use it as input to new one
  - Specify recipient by script specifying what must be done int future send (lockscript)
  - Typical lockscript is “prove that you can sign with private key corresponding to THIS public key”
- Protection and handling of private keys is paramount
  - “Not your keys, not your bitcoin!“

UTXO set = all currently valid “bitcoins”

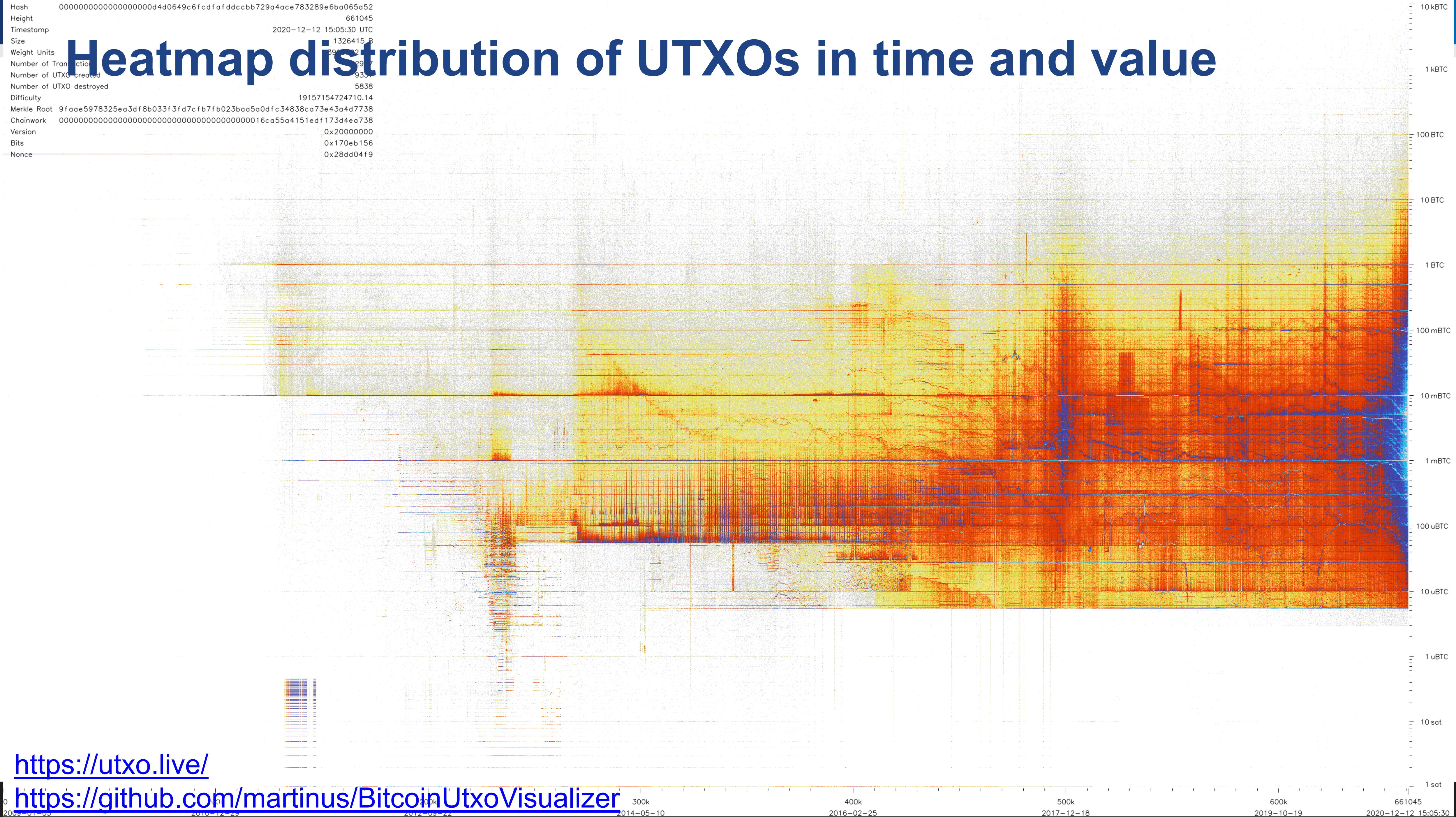


Unspent Transaction Output Set

2017-01-01 00:00:00 to a few seconds ago

https://statoshi.info/d/000000009/unspent-transaction-output-set?orgId=1&refresh=10m&from=1483225200000&to=now

Heatmap distribution of UTXOs in time and value



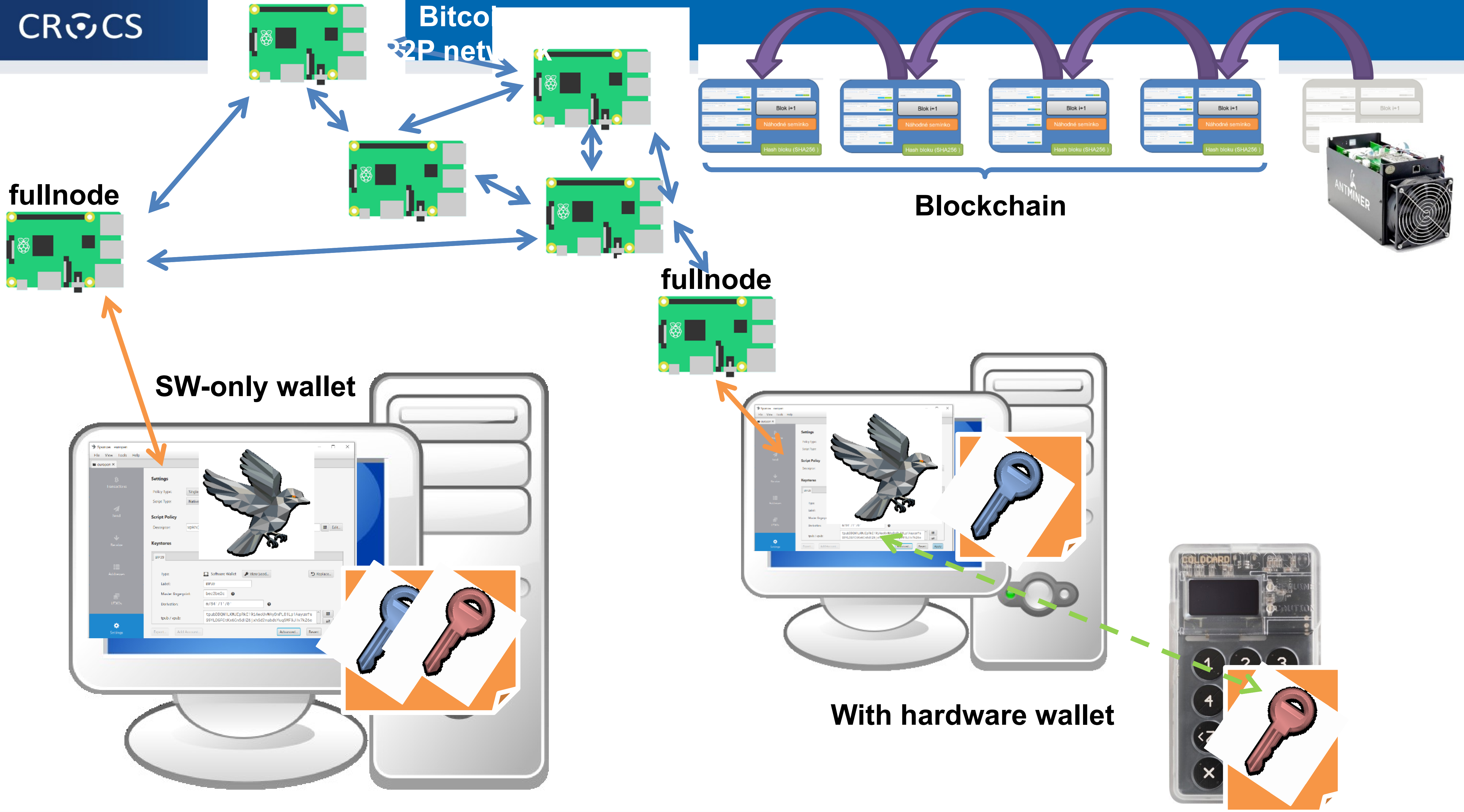
```
Hash       0000000000000000000d4d0649c6fcdfafddccbb729a4ace783289e6ba065a52
Height                                                            661045
Timestamp                                        2020-12-12 15:05:30 UTC
Size                                                           1326415 B
Weight Units                                                  39[illegible]
Number of Trans[illegible]ctio[illegible]                       29[illegible]7
Number of UTXO created                                           933[illegible]
Number of UTXO destroyed                                            5838
Difficulty                                             19157154724710.14
Merkle Root 9faae5978325ea3df8b033f3fd7cfb7fb023baa5a0dfc34838ca73e43a4d7738
Chainwork  000000000000000000000000000000000000000016ca55a4151edf173d4ea738
Version                                                       0x20000000
Bits                                                          0x170eb156
Nonce                                                         0x28dd04f9
```

https://utxo.live/

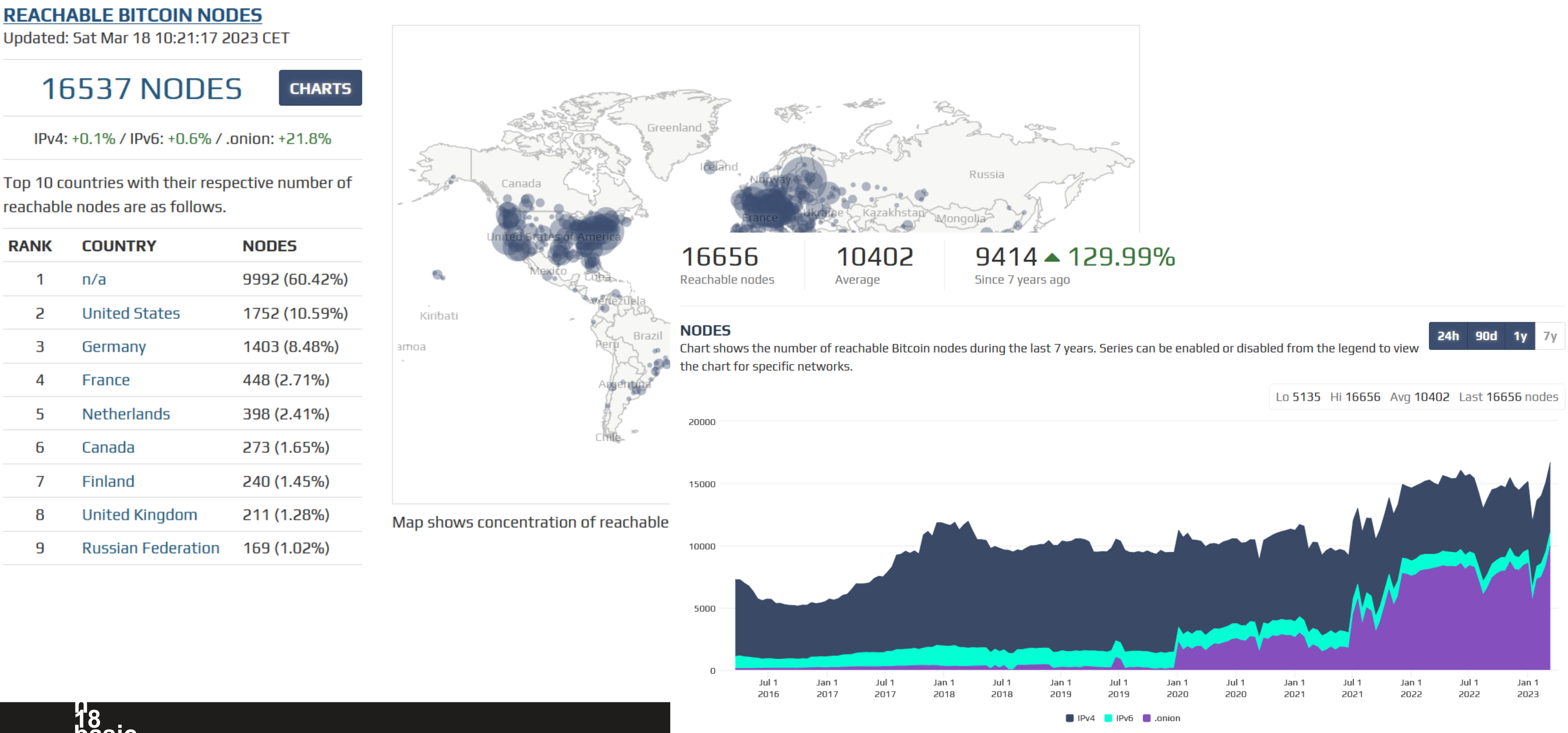
https://github.com/martinus/BitcoinUtxoVisualizer

Problem: How to allow for permissionless participation?

BITCOIN NETWORK


Bitco
P2P netw
fullnode
fullnode
Blok i+1
Náhodné seminko
Hash bloku (SHA256)
Blockchain
ANTMINER
SW-only wallet
With hardware wallet
COLDCARD

P2P Bitcoin network map https://bitnodes.io/



REACHABLE BITCOIN NODES

Updated: Sat Mar 18 10:21:17 2023 CET

16537 NODES

IPv4: +0.1% / IPv6: +0.6% / .onion: +21.8%

Top 10 countries with their respective number of reachable nodes are as follows.

RANK	COUNTRY	NODES
1	n/a	9992 (60.42%)
2	United States	1752 (10.59%)
3	Germany	1403 (8.48%)
4	France	448 (2.71%)
5	Netherlands	398 (2.41%)
6	Canada	273 (1.65%)
7	Finland	240 (1.45%)
8	United Kingdom	211 (1.28%)
9	Russian Federation	169 (1.02%)

Map shows concentration of reachable

16656 Reachable nodes

10402 Average

9414 ▲ 129.99% Since 7 years ago

NODES

Chart shows the number of reachable Bitcoin nodes during the last 7 years. Series can be enabled or disabled from the legend to view the chart for specific networks.

What is Bitcoin “fullnode”

- Software capable to connect and interact with P2P network
- Downloads whole blockchain, fully verifies all blocks (PoW) and transactions starting from the Genesis block (or trusted checkpoint)
  - Dynamically builds own UTXO set (unspent txs) and Mempool (unconfirmed txs)
- Propagates new incoming blocks and transactions
- No formal specification of Bitcoin consensus exists
  - Bitcoin Core software is defacto specification (https://github.com/bitcoin/bitcoin)
  - Other implementations also exists (but large majority of nodes are Bitcoin Core)
- Currently several days to fully synchronize (CPU/bandwith), ~465GB
- Can be run over Tor to protect user privacy
- Bitcoin wallet needs to connect to some fullnode (your = better privacy)

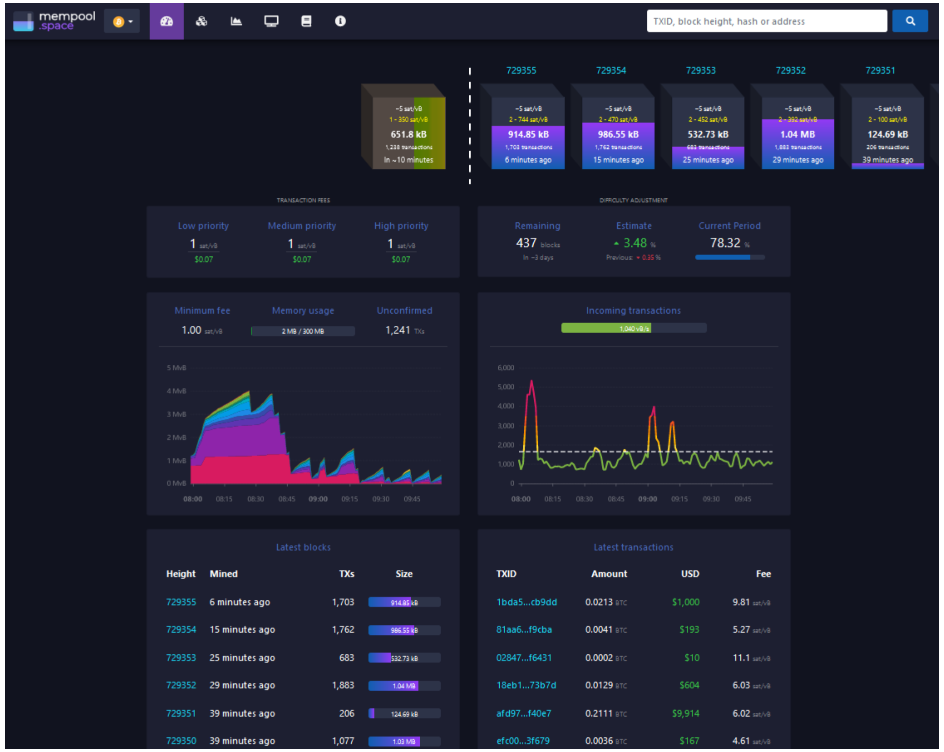
Networks in Bitcoin (Mainnet, Testnet, Regtest, Signet)

- Mainnet – main, global production network ("real" bitcoins)
- Testnet – testing network (global, some mining happens…)
  - Restarted from time to time, contains many different types and versions of TXs
- Regtest – local instance of Bitcoin network
  - Used for local testing (integration, regression,debugging)
  - Blockchain started from block 0, you are the only miner
  - (mined bitcoins unusable on Mainnet)
  - You can insert own transactions, decide on mining new blocks, debug…
- Signet – testing network like Testnet, but with features not yet active on Mainnet
  - Initially for testing Taproot, now for future possible softforks
- (Lighting – second layer network of payment channels atop of mainnet)
  - Practically instant and very low fees independently from mainnet

Mempool – unconfirmed transactions

- Every fullnode maintains own list of unconfirmed transactions (mempool)
  - – No single global mempool! But local mempools tend to synchronize quickly
- Miners construct next block from transactions maximizing profit (mostly)
- What if tx is in a mempool, but with too low fee (not getting confirmed)?
  1. Child pays for parent –additional transaction spending output of previous (high fee)
  2. Replace By Fee (RBF) flag – new tx, but with higher fee, replaced by nodes
  3. (Wait for purge, pay miner out of band…)
- If too many unconfirmed txs present, some existing are purged (removed)
  - – Default size of mempool (for Bitcoin Core) is ~300MB
  - – Selection depends on configuration (low-fee tx, large tx, old tx)
  - – If discarded, it can be re-inserted later from other nodes or resubmitted (by owner)

Popular mempool explorer – https://mempool.space



mempool .space

TXID, block height, hash or address

~5 sat/vB
1 - 350 sat/vB
651.8 kB
1,238 transactions
In ~10 minutes

729355	729354	729353	729352	729351
~5 sat/vB	~5 sat/vB	~5 sat/vB	~5 sat/vB	~5 sat/vB
2 - 744 sat/vB	2 - 470 sat/vB	2 - 452 sat/vB	2 - 392 sat/vB	2 - 100 sat/vB
914.85 kB	986.55 kB	532.73 kB	1.04 MB	124.69 kB
1,703 transactions	1,762 transactions	683 transactions	1,883 transactions	206 transactions
6 minutes ago	15 minutes ago	25 minutes ago	29 minutes ago	39 minutes ago

TRANSACTION FEES

Low priority	Medium priority	High priority
1 sat/vB	1 sat/vB	1 sat/vB
$0.07	$0.07	$0.07

DIFFICULTY ADJUSTMENT

Remaining	Estimate	Current Period
437 blocks In ~3 days	▲ 3.48 % Previous: ▼ 0.35 %	78.32 %

Minimum fee	Memory usage	Unconfirmed
1.00 sat/vB	2 MB / 300 MB	1,241 TXs

Incoming transactions

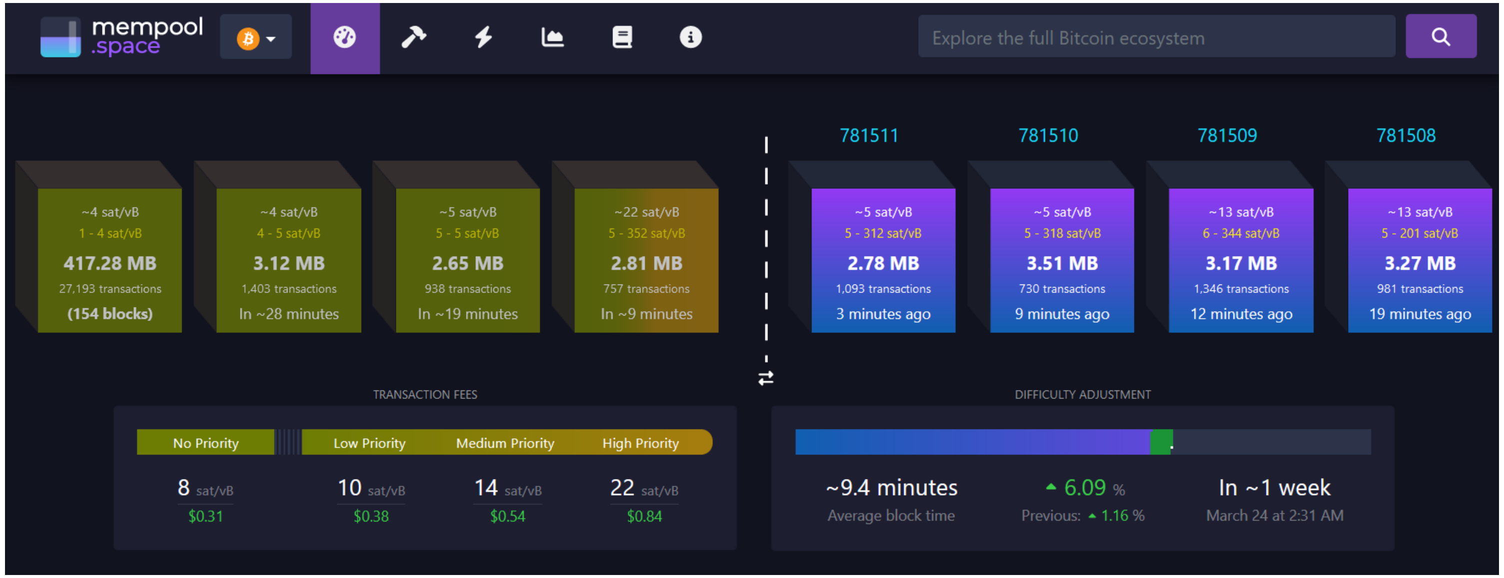
1,040 vB/s

Latest blocks

Height	Mined	TXs	Size
729355	6 minutes ago	1,703	914.85 kB
729354	15 minutes ago	1,762	986.55 kB
729353	25 minutes ago	683	532.73 kB
729352	29 minutes ago	1,883	1.04 MB
729351	39 minutes ago	206	124.69 kB
729350	39 minutes ago	1,077	1.03 MB

Latest transactions

TXID	Amount	USD	Fee
1bda5...cb9dd	0.0213 BTC	$1,000	9.81 sat/vB
81aa6...f9cba	0.0041 BTC	$193	5.27 sat/vB
02847...f6431	0.0002 BTC	$10	11.1 sat/vB
18eb1...73b7d	0.0129 BTC	$604	6.03 sat/vB
afd97...f40e7	0.2111 BTC	$9,914	6.02 sat/vB
efc00...3f679	0.0036 BTC	$167	4.61 sat/vB



mempool .space

Explore the full Bitcoin ecosystem

				781511	781510	781509	781508
~4 sat/vB	~4 sat/vB	~5 sat/vB	~22 sat/vB	~5 sat/vB	~5 sat/vB	~13 sat/vB	~13 sat/vB
1 - 4 sat/vB	4 - 5 sat/vB	5 - 5 sat/vB	5 - 352 sat/vB	5 - 312 sat/vB	5 - 318 sat/vB	6 - 344 sat/vB	5 - 201 sat/vB
417.28 MB	3.12 MB	2.65 MB	2.81 MB	2.78 MB	3.51 MB	3.17 MB	3.27 MB
27,193 transactions	1,403 transactions	938 transactions	757 transactions	1,093 transactions	730 transactions	1,346 transactions	981 transactions
(154 blocks)	In ~28 minutes	In ~19 minutes	In ~9 minutes	3 minutes ago	9 minutes ago	12 minutes ago	19 minutes ago

TRANSACTION FEES

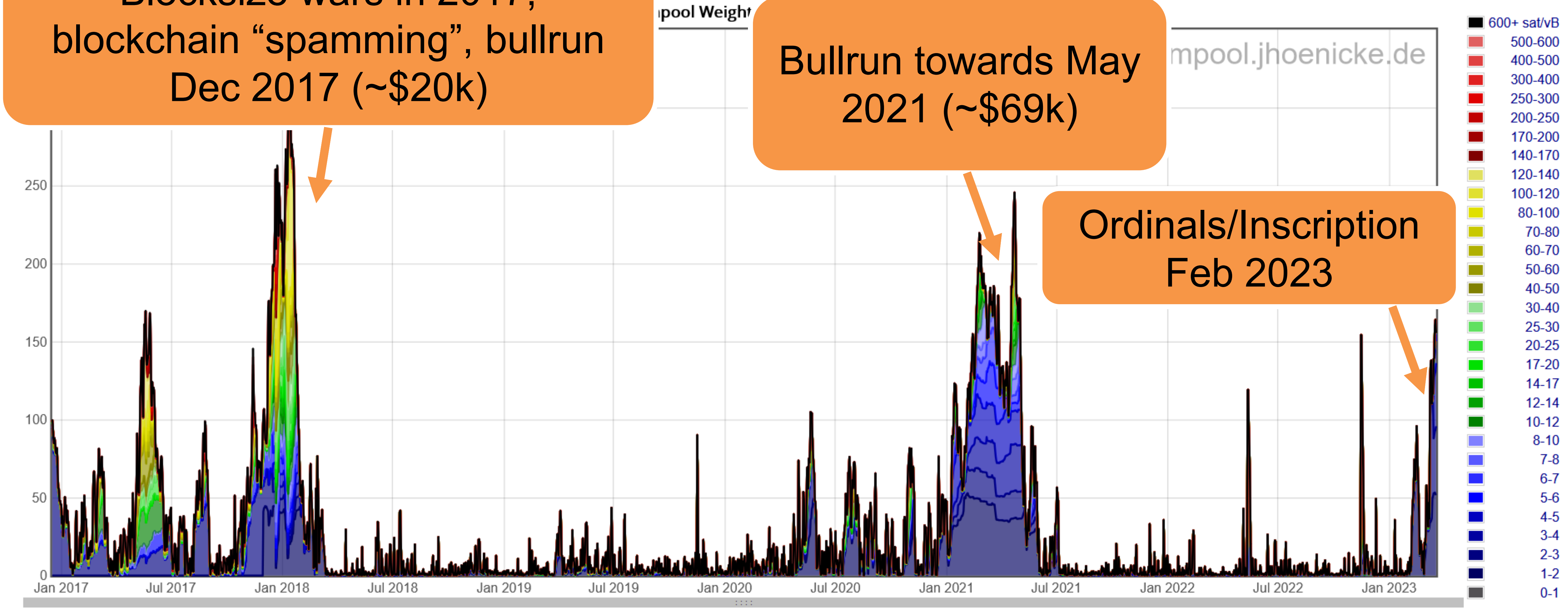
No Priority	Low Priority	Medium Priority	High Priority
8 sat/vB	10 sat/vB	14 sat/vB	22 sat/vB
$0.31	$0.38	$0.54	$0.84

DIFFICULTY ADJUSTMENT

~9.4 minutes	▲ 6.09 %	In ~1 week
Average block time	Previous: ▲ 1.16 %	March 24 at 2:31 AM

- Can be run on your own fullnode (privacy improvement)
- Testnet version https://mempool.space/testnet

Mempool size in time



Blocksize wars in 2017, blockchain “spamming”, bullrun Dec 2017 (~$20k)

Bullrun towards May 2021 (~$69k)

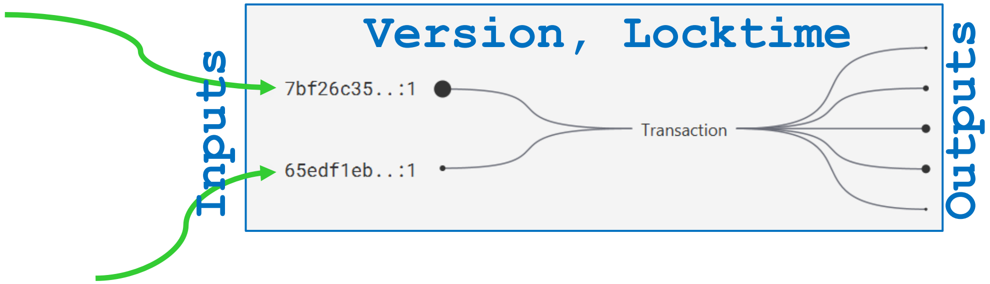
Ordinals/Inscription Feb 2023

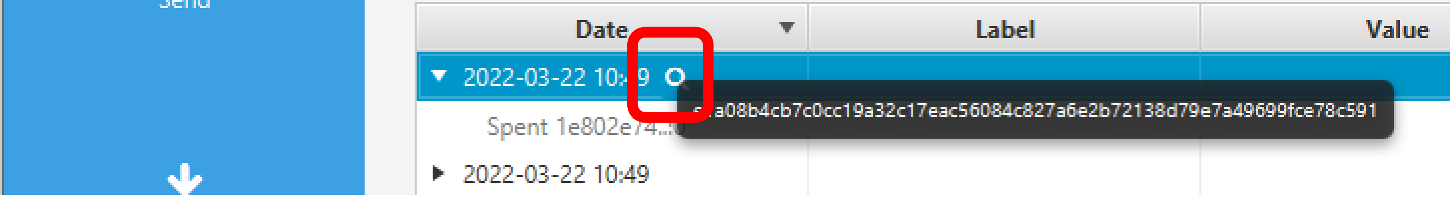
DEMO: LOOK AND COMMENT THE CURRENT MEMPOOL STATE

TRANSACTION

Transaction components

- Binary structure optimized for small size (further decreased over time)
  - Version
  - Inputs (bitcoins spent, points to some previous tx outpt + unlock script)
  - Outputs (bitcoins received, description of lock script)
  - Locktime (when starts to be valid, absolute or relative, time or block height)
- Can be created offline, broadcasted immediately or later (Lighting)



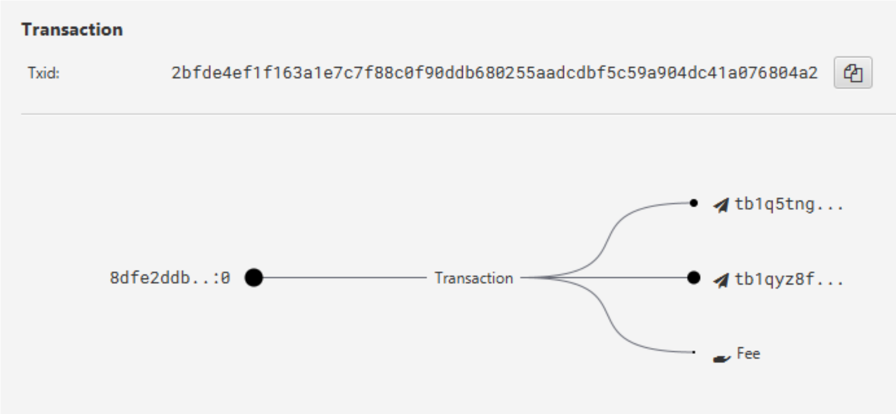


Date	Label	Value
▼ 2022-03-22 10:49		
Spent 1e802e74...		
▶ 2022-03-22 10:49		

a08b4cb7c0cc19a32c17eac56084c827a6e2b72138d79e7a49699fce78c591

Various transactions can be created

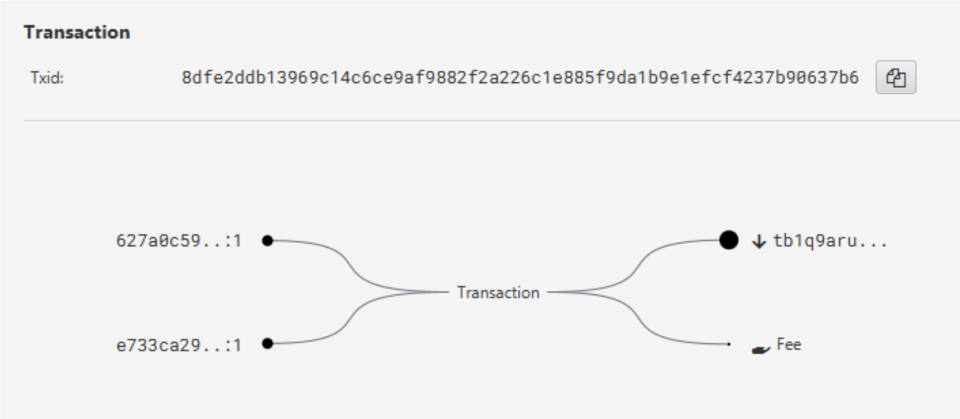
One input, two outputs + fee (possibly classic pay)



Transaction

Txid: 2bfde4ef1f163a1e7c7f88c0f90ddb680255aadcdbf5c59a904dc41a076804a2

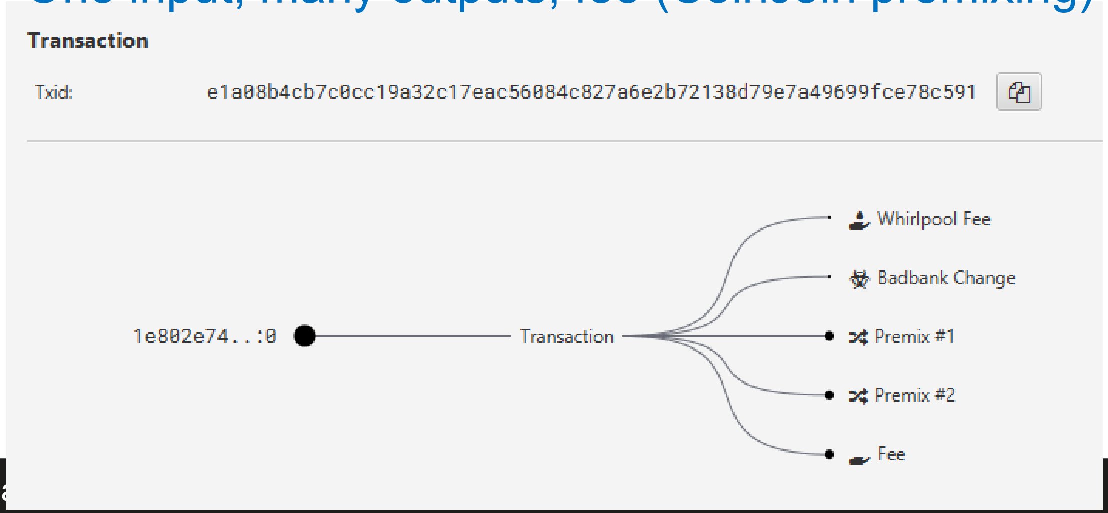
Two inputs, one output + fee (possibly consolidation)



Transaction

Txid: 8dfe2ddb13969c14c6ce9af9882f2a226c1e885f9da1b9e1efcf4237b90637b6

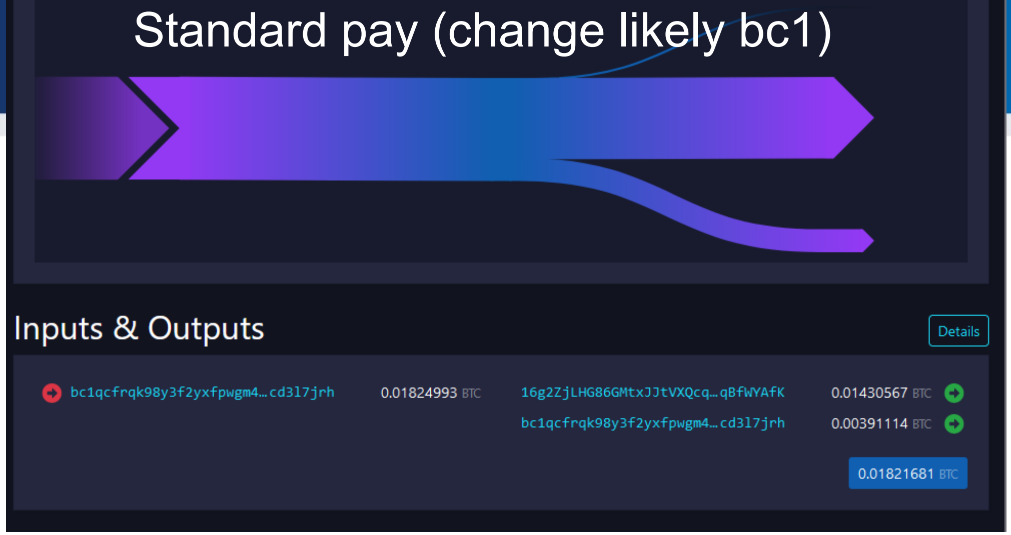
One input, many outputs, fee (CoinJoin premixing)



Transaction

Txid: e1a08b4cb7c0cc19a32c17eac56084c827a6e2b72138d79e7a49699fce78c591

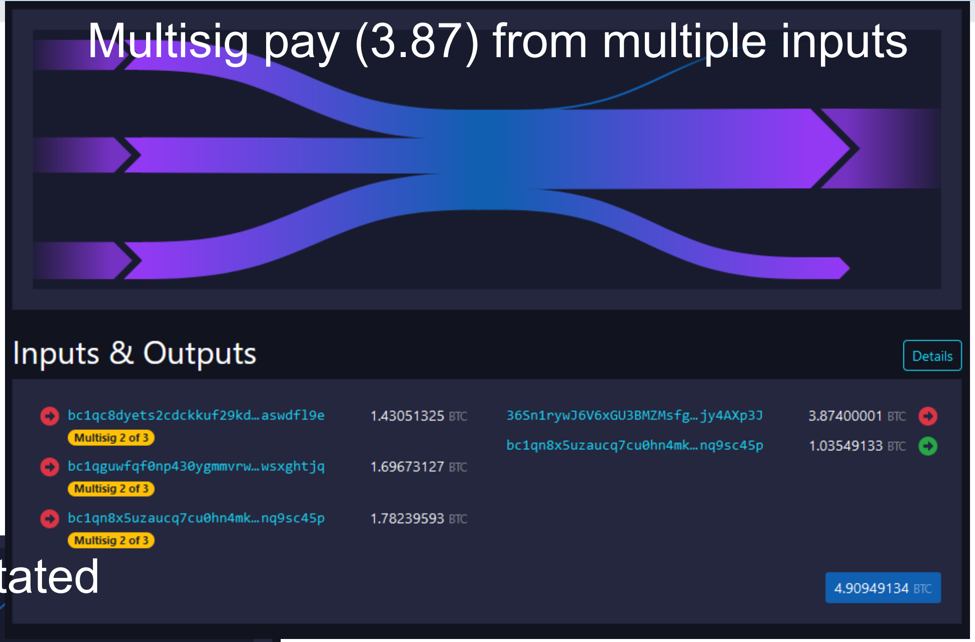
Many inputs, many outputs, fee…



Standard pay (change likely bc1)

Inputs & Outputs

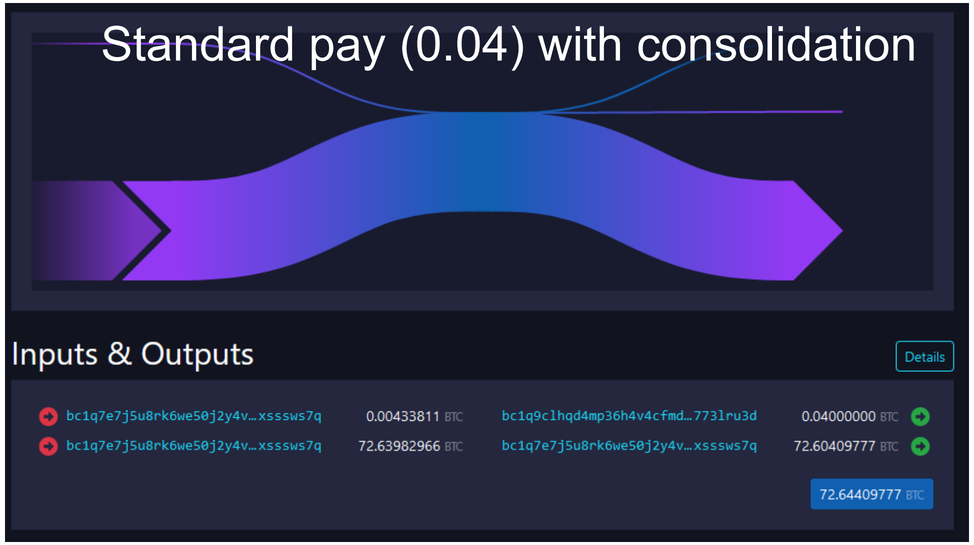
bc1qcfrqk98y3f2yxfpwgm4…cd3l7jrh	0.01824993 BTC	16g2ZjLHG86GMtxJJtVXQcq…qBfWYAfK	0.01430567 BTC
		bc1qcfrqk98y3f2yxfpwgm4…cd3l7jrh	0.00391114 BTC
			0.01821681 BTC



Multisig pay (3.87) from multiple inputs

Inputs & Outputs

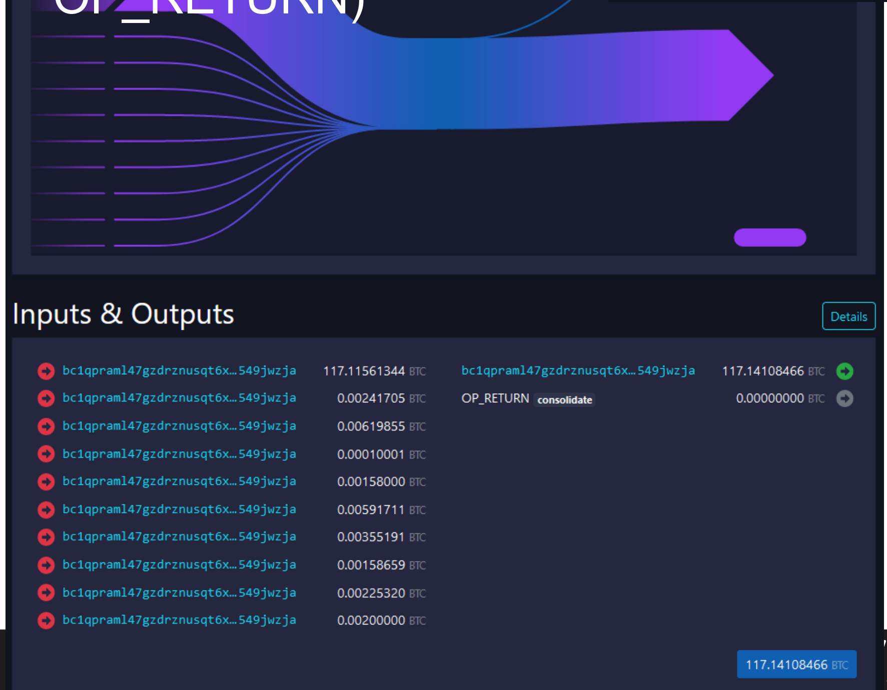
bc1qc8dyets2cdckkuf29kd…aswdfl9e Multisig 2 of 3	1.43051325 BTC	36Sn1rywJ6V6xGU3BMZMsfg…jy4AXp3J	3.87400001 BTC
bc1qguwfqf0np430ygmmvrw…wsxghtjq Multisig 2 of 3	1.69673127 BTC	bc1qn8x5uzaucq7cu0hn4mk…nq9sc45p	1.03549133 BTC
bc1qn8x5uzaucq7cu0hn4mk…nq9sc45p Multisig 2 of 3	1.78239593 BTC		
			4.90949134 BTC



Standard pay (0.04) with consolidation

Inputs & Outputs

bc1q7e7j5u8rk6we50j2y4v…xssws7q	0.00433811 BTC	bc1q9clhqd4mp36h4v4cfmd…773lru3d	0.04000000 BTC
bc1q7e7j5u8rk6we50j2y4v…xssws7q	72.63982966 BTC	bc1q7e7j5u8rk6we50j2y4v…xssws7q	72.60409777 BTC
			72.64409777 BTC

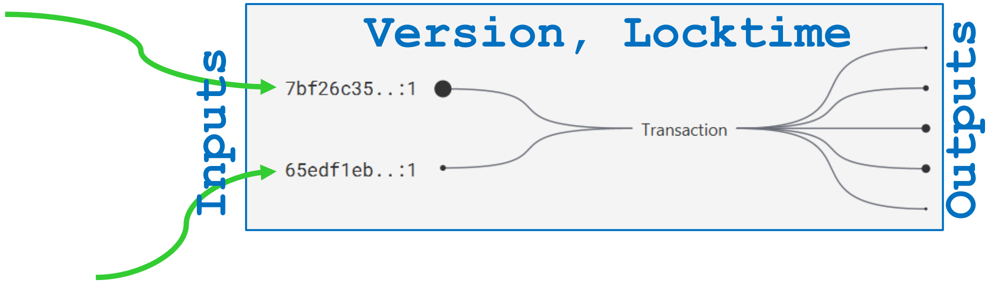


Consolidation (even annotated OP_RETURN)

Inputs & Outputs

bc1qpraml47gzdrznusqt6x…549jwzja	117.11561344 BTC	bc1qpraml47gzdrznusqt6x…549jwzja	117.14108466 BTC
bc1qpraml47gzdrznusqt6x…549jwzja	0.00241705 BTC	OP_RETURN consolidate	0.00000000 BTC
bc1qpraml47gzdrznusqt6x…549jwzja	0.00619855 BTC		
bc1qpraml47gzdrznusqt6x…549jwzja	0.00010001 BTC		
bc1qpraml47gzdrznusqt6x…549jwzja	0.00158000 BTC		
bc1qpraml47gzdrznusqt6x…549jwzja	0.00591711 BTC		
bc1qpraml47gzdrznusqt6x…549jwzja	0.00355191 BTC		
bc1qpraml47gzdrznusqt6x…549jwzja	0.00158659 BTC		
bc1qpraml47gzdrznusqt6x…549jwzja	0.00225320 BTC		
bc1qpraml47gzdrznusqt6x…549jwzja	0.00200000 BTC		
			117.14108466 BTC

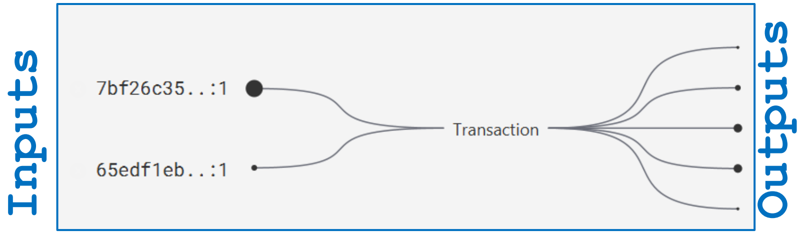
DEMO: LOOK AT CURRENT MEMPOOL TRANSACTIONS (CONFIRMED, UNCORFIRMED)



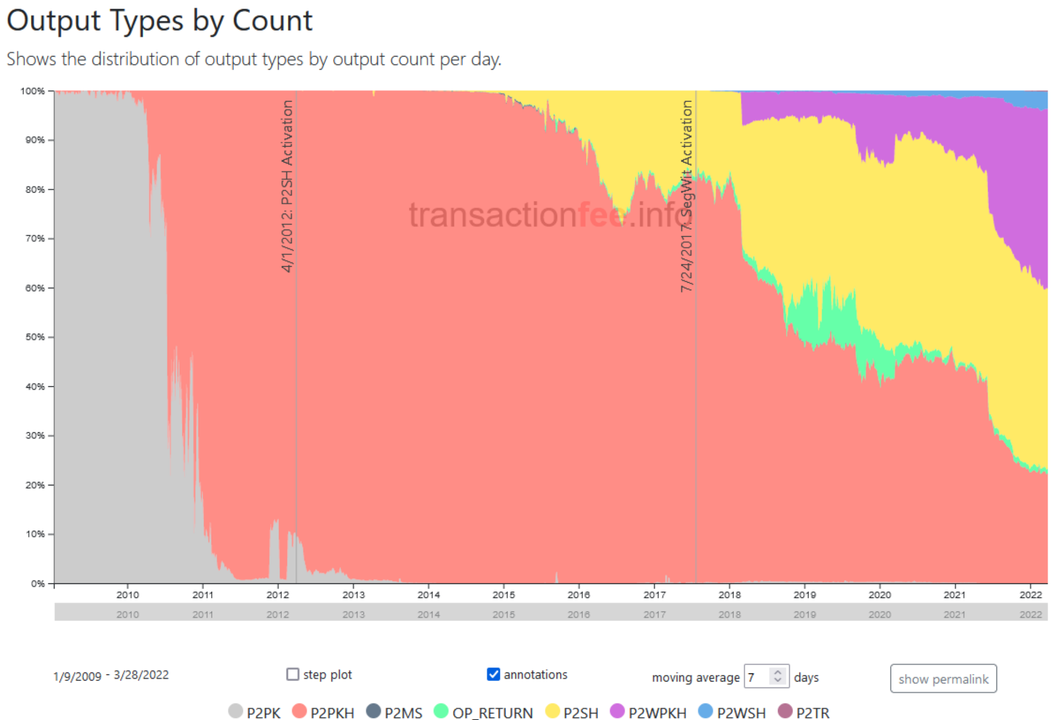
LOCK AND UNLOCK SCRIPTS

https://transactionfee.info/charts/output-type-distribution-count/

Types of receiving “addresses”



- There is no ”address” defined in Bitcoin network
- Standard patterns how to construct lock script emerged over the time
  - e.g., unlock if signature is verifiable with the public key stored in lock script (P2PK)
  - “Address” is the variable part of the lock script differing between (different receivers / transactions)
- *Notation warning: scriptSig (script + signature), scriptPubKey (initial meaning script + public key == P2PK)*
- Well-known standard types of lock scripts
  - Pay-to-public-key (P2PK)
  - Pay-to-public-key-hash (P2PKH, starts with 1)
  - Pay-to-script-hash (P2SH, BIP16)
  - OP_RETURN (any data 40B)
  - Native Pay-to-witness-script-hash (P2WSH, starts with 3)
  - P2WSH-nested-in-P2SH
  - P2SH-P2WPKH, P2SH-P2WSH
  - Native P2WPK, P2WSH (Bech32, starts with bc1)
  - Pay-to-Taproot (P2TR, Schnorr signature, starts bc1p)


Output Types by Count

Shows the distribution of output types by output count per day.

1/9/2009 - 3/28/2022 ☐ step plot ☑ annotations moving average 7 days show permalink

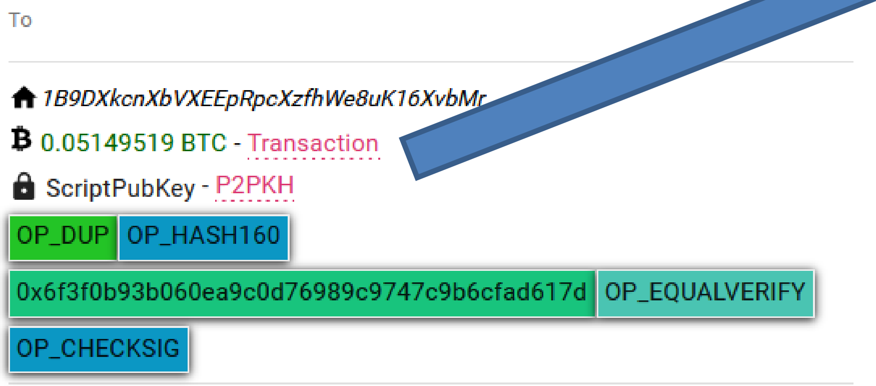
100%
90%
80%
70%
60%
50%
40%
30%
20%
10%
0%
4/1/2012: P2SH Activation
7/24/2017: SegWit Activation
transactionfee.info
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
● P2PK ● P2PKH ● P2MS ● OP_RETURN ● P2SH ● P2WPKH ● P2WSH ● P2TR

Pay-to-public-key (P2PK), Pay-to-public-key-hash (P2PKH)

- Pay-to-public-key (P2PK)
  - Lock script contains direct value of public key and instructions to push signature and verify with the public key
  - Used initially by Satoshi and others, now infrequent
  - Disadvantage: if practical dlog attack against secp256k1 is found, private key can be computed
- Pay-to-public-key-hash (P2PKH), starts with ‘1’
  - Lock script contains hash of public key later used for signature verification
  - Advantage: smaller lockscript, attacker does not know public key until spent

https://nioctib.tech/#/transaction/f2f398dace996dab12e0cfb02fb0b59de0ef0398be393d90ebc8ab397550370b
https://nioctib.tech/#/transaction/feff813f13340060f641c11ab1307bb1b8cabcdcc3af1aed8a089e38c8407aef

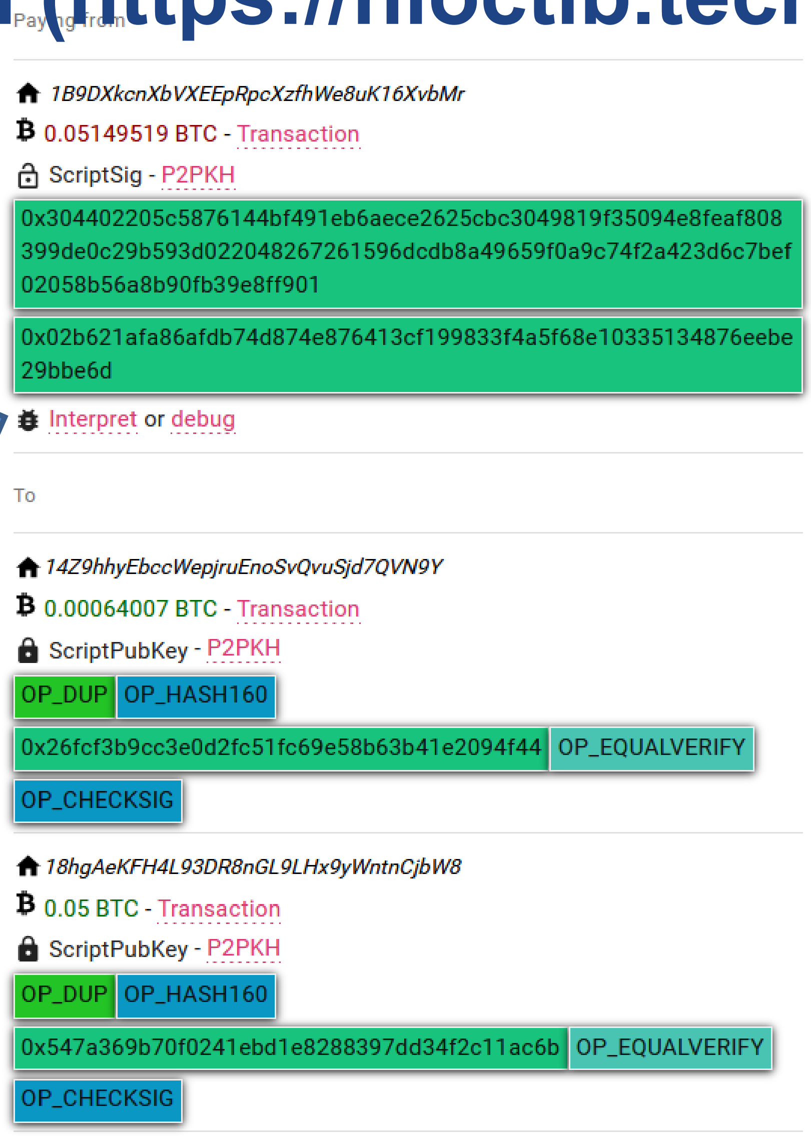
P2PKH - script execution (https://nioctib.tech/)



To

1B9DXkcnXbVXEEpRpcXzfhWe8uK16XvbMr
฿ 0.05149519 BTC - Transaction
ScriptPubKey - P2PKH

```
OP_DUP OP_HASH160
0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d OP_EQUALVERIFY
OP_CHECKSIG
```



Paying from

1B9DXkcnXbVXEEpRpcXzfhWe8uK16XvbMr
฿ 0.05149519 BTC - Transaction
ScriptSig - P2PKH

```
0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef02058b56a8b90fb39e8ff901
0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe29bbe6d
```

Interpret or debug

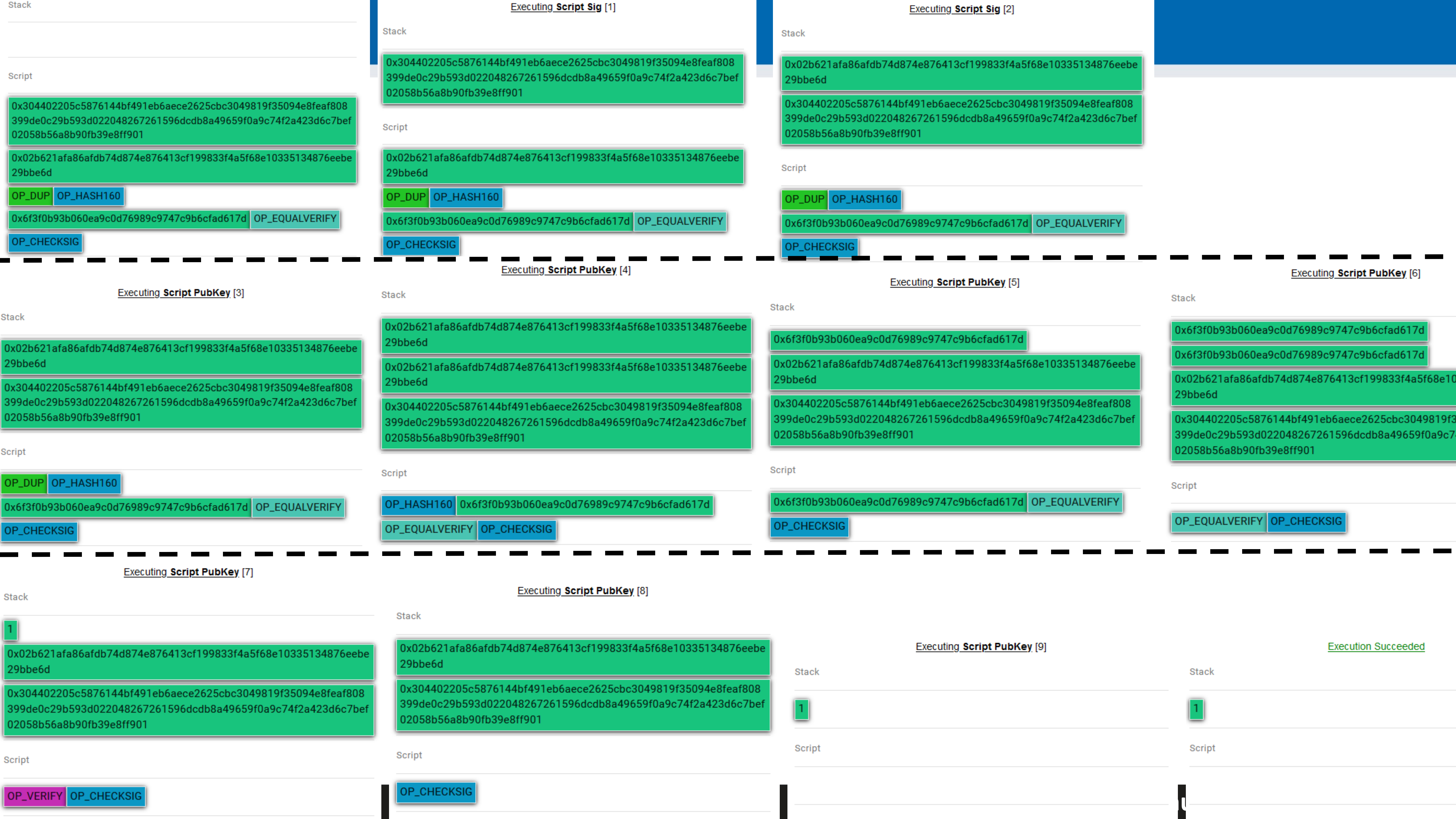
To

14Z9hhyEbccWepjruEnoSvQvuSjd7QVN9Y
฿ 0.00064007 BTC - Transaction
ScriptPubKey - P2PKH

```
OP_DUP OP_HASH160
0x26fcf3b9cc3e0d2fc51fc69e58b63b41e2094f44 OP_EQUALVERIFY
OP_CHECKSIG
```

18hgAeKFH4L93DR8nGL9LHx9yWntnCjbW8
฿ 0.05 BTC - Transaction
ScriptPubKey - P2PKH

```
OP_DUP OP_HASH160
0x547a369b70f0241ebd1e8288397dd34f2c11ac6b OP_EQUALVERIFY
OP_CHECKSIG
```



Stack

Script

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

OP_DUP OP_HASH160

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d OP_EQUALVERIFY

OP_CHECKSIG

Executing **Script Sig** [1]

Stack

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

Script

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

OP_DUP OP_HASH160

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d OP_EQUALVERIFY

OP_CHECKSIG

Executing **Script Sig** [2]

Stack

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

Script

OP_DUP OP_HASH160

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d OP_EQUALVERIFY

OP_CHECKSIG

Executing **Script PubKey** [3]

Stack

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

Script

OP_DUP OP_HASH160

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d OP_EQUALVERIFY

OP_CHECKSIG

Executing **Script PubKey** [4]

Stack

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

Script

OP_HASH160 0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d

OP_EQUALVERIFY OP_CHECKSIG

Executing **Script PubKey** [5]

Stack

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

Script

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d OP_EQUALVERIFY

OP_CHECKSIG

Executing **Script PubKey** [6]

Stack

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d

0x6f3f0b93b060ea9c0d76989c9747c9b6cfad617d

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10
29bbe6d

0x304402205c5876144bf491eb6aece2625cbc3049819f3
399de0c29b593d022048267261596dcdb8a49659f0a9c7
02058b56a8b90fb39e8ff901

Script

OP_EQUALVERIFY OP_CHECKSIG

Executing **Script PubKey** [7]

Stack

1

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

Script

OP_VERIFY OP_CHECKSIG

Executing **Script PubKey** [8]

Stack

0x02b621afa86afdb74d874e876413cf199833f4a5f68e10335134876eebe
29bbe6d

0x304402205c5876144bf491eb6aece2625cbc3049819f35094e8feaf808
399de0c29b593d022048267261596dcdb8a49659f0a9c74f2a423d6c7bef
02058b56a8b90fb39e8ff901

Script

OP_CHECKSIG

Executing **Script PubKey** [9]

Stack

1

Script

Execution Succeeded

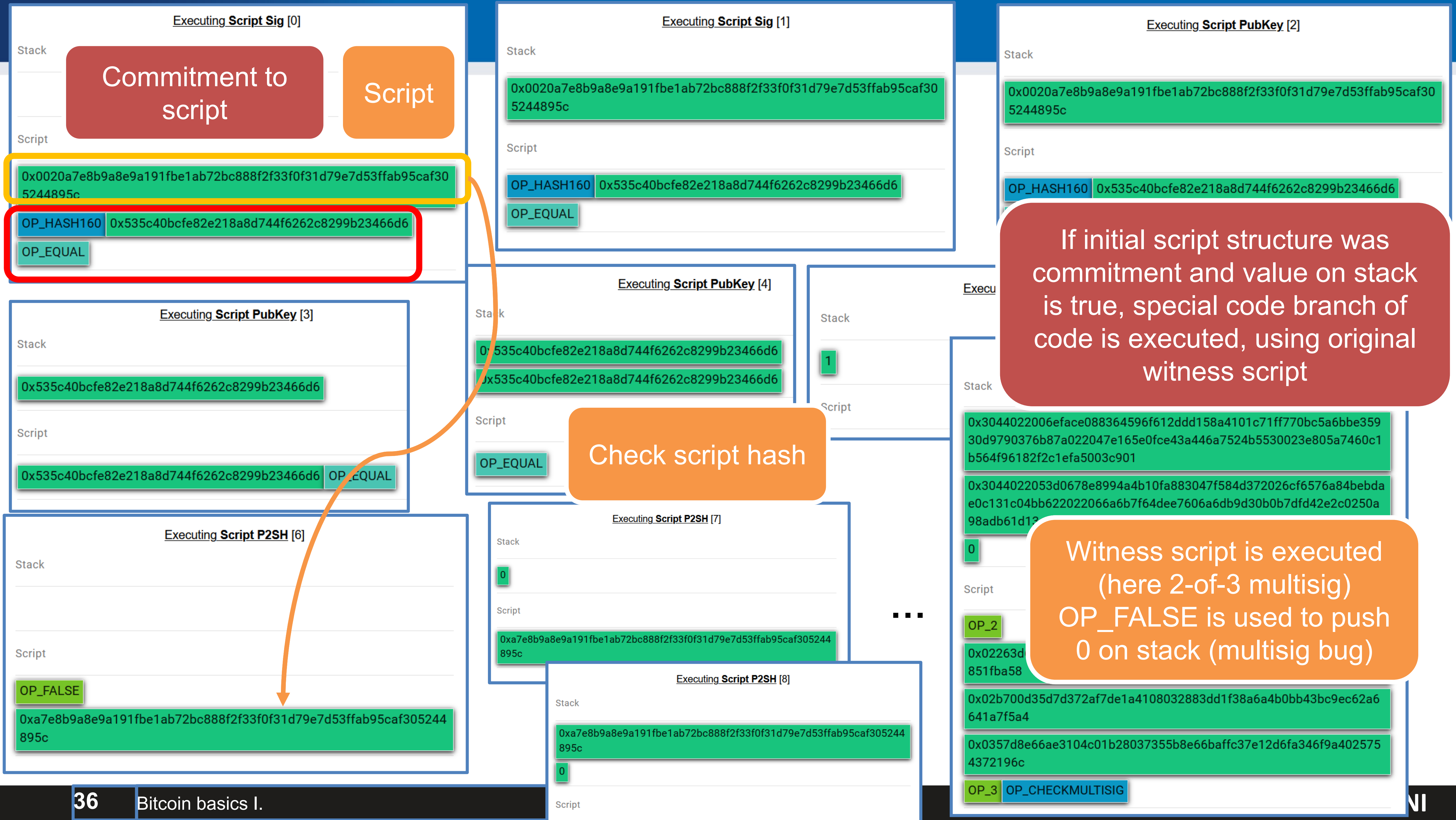
Stack

1

Script

Pay to script hash (P2SH), BIP16, starts with ‘3’

- Lock script separated into two parts
  - 1) commitment to the script (hash value, checked later)
  - 2) actual lock script (hash value must match the commitment)
- Sending tx sets output’s ScriptPub to the commitment
  - Shorter as only hash is posted, not whole lock script
  - Lock script is provided only later when spending (privacy, fee to be paid)
  - Lock script can have multiple spending paths (Merkle tree) and only the one used is posted (better for privacy)
- Redeeming tx provides actual lock script + unlock script



Executing **Script Sig** [0]

Stack

Script

```
0x0020a7e8b9a8e9a191fbe1ab72bc888f2f33f0f31d79e7d53ffab95caf30
5244895c
OP_HASH160 0x535c40bcfe82e218a8d744f6262c8299b23466d6
OP_EQUAL
```

Commitment to script

Script

Executing **Script Sig** [1]

Stack

```
0x0020a7e8b9a8e9a191fbe1ab72bc888f2f33f0f31d79e7d53ffab95caf30
5244895c
```

Script

```
OP_HASH160 0x535c40bcfe82e218a8d744f6262c8299b23466d6
OP_EQUAL
```

Executing **Script PubKey** [2]

Stack

```
0x0020a7e8b9a8e9a191fbe1ab72bc888f2f33f0f31d79e7d53ffab95caf30
5244895c
```

Script

```
OP_HASH160 0x535c40bcfe82e218a8d744f6262c8299b23466d6
```

Executing **Script PubKey** [3]

Stack

```
0x535c40bcfe82e218a8d744f6262c8299b23466d6
```

Script

```
0x535c40bcfe82e218a8d744f6262c8299b23466d6 OP_EQUAL
```

Executing **Script PubKey** [4]

Sta k

```
0 535c40bcfe82e218a8d744f6262c8299b23466d6
x535c40bcfe82e218a8d744f6262c8299b23466d6
```

Script

```
OP_EQUAL
```

Check script hash

Execu

Stack

```
1
```

Script

If initial script structure was commitment and value on stack is true, special code branch of code is executed, using original witness script

Executing **Script P2SH** [6]

Stack

Script

```
OP_FALSE
0xa7e8b9a8e9a191fbe1ab72bc888f2f33f0f31d79e7d53ffab95caf305244
895c
```

Executing **Script P2SH** [7]

Stack

```
0
```

Script

```
0xa7e8b9a8e9a191fbe1ab72bc888f2f33f0f31d79e7d53ffab95caf305244
895c
```

Executing **Script P2SH** [8]

Stack

```
0xa7e8b9a8e9a191fbe1ab72bc888f2f33f0f31d79e7d53ffab95caf305244
895c
0
```

Script

...

Stack

```
0x3044022006eface088364596f612ddd158a4101c71ff770bc5a6bbe359
30d9790376b87a022047e165e0fce43a446a7524b5530023e805a7460c1
b564f96182f2c1efa5003c901
0x3044022053d0678e8994a4b10fa883047f584d372026cf6576a84bebda
e0c131c04bb622022066a6b7f64dee7606a6db9d30b0b7dfd42e2c0250a
98adb61d13
0
```

Script

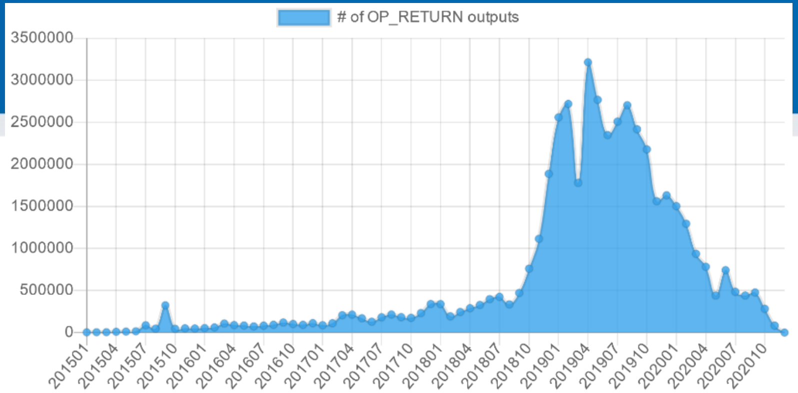
```
OP_2
0x02263d
851fba58
0x02b700d35d7d372af7de1a4108032883dd1f38a6a4b0bb43bc9ec62a6
641a7f5a4
0x0357d8e66ae3104c01b28037355b8e66baffc37e12d6fa346f9a402575
4372196c
OP_3 OP_CHECKMULTISIG
```

Witness script is executed (here 2-of-3 multisig) OP_FALSE is used to push 0 on stack (multisig bug)

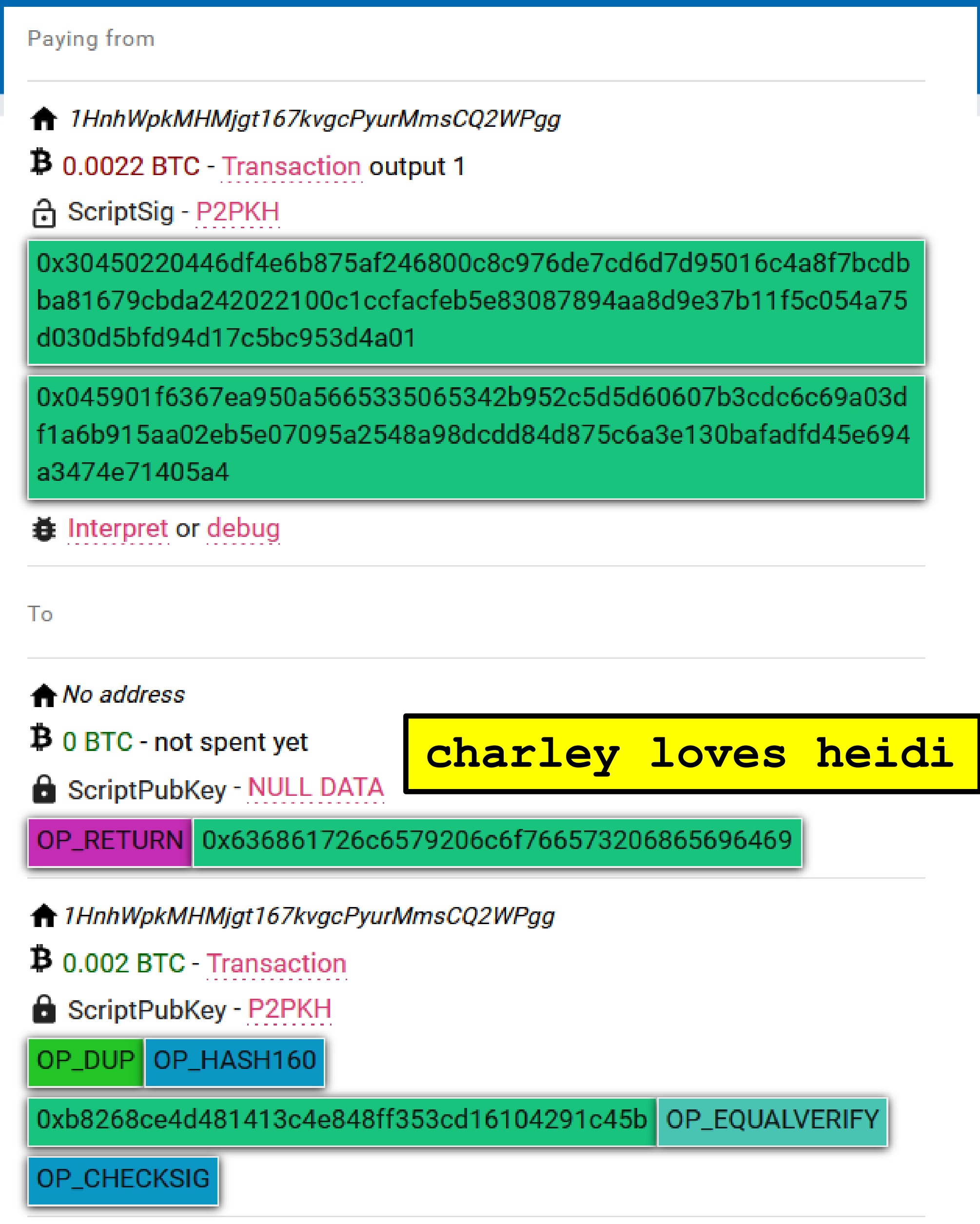
Interesting, non-standard scripts

- SHA1 collision bounty
  - Bitcoins locked to script requiring two different inputs hashed to same SHA1 hash
  - Redeemed shortly after Google published SHA1 collision blocks
    - https://blockstream.info/tx/8d31992805518fd62daa3bdd2a5c4fd2cd3054c9b3dca1d78055e9528cff6adc
    - https://nioctib.tech/#/transaction/f2f398dace996dab12e0cfb02fb0b59de0ef0398be393d90ebc8ab397550370b
  - More details: https://bitcoinjs-guide.bitcoin-studio.com/bitcoinjs-guide/v5/part-three-pay-to-script-hash/puzzles/computational_puzzle_sha1_collision_p2sh.html
  - Similar bounties for

OP_RETURN



- If OP_RETURN is encountered during execution of unlock+lock script, it is FALSE
  - Such output is provably unspendable
- Somewhat controversial instruction
  - Some feels, that blockchain shall not be used for non-financial data (USDT was initially on Bitcoin via OP_RETURN)
  - But there were already ways how to store arbitrary data into blockchain anyway (e.g., bytes of value, invalid address)
- Analysis of OP_RETURN data
  - https://www.blockchainresearchlab.org/2020/03/13/how-do-op-return-transactions-impact-bitcoin/
  - https://opreturn.org/



Paying from

1HnhWpkMHMjgt167kvgcPyurMmsCQ2WPgg

0.0022 BTC - Transaction output 1

ScriptSig - P2PKH

0x30450220446df4e6b875af246800c8c976de7cd6d7d95016c4a8f7bcdbba81679cbda242022100c1ccfacfeb5e83087894aa8d9e37b11f5c054a75d030d5bfd94d17c5bc953d4a01

0x045901f6367ea950a5665335065342b952c5d5d60607b3cdc6c69a03df1a6b915aa02eb5e07095a2548a98dcdd84d875c6a3e130bafadfd45e694a3474e71405a4

Interpret or debug

To

No address

0 BTC - not spent yet

ScriptPubKey - NULL DATA

charley loves heidi

OP_RETURN 0x636861726c6579206c6f766573206865696469

1HnhWpkMHMjgt167kvgcPyurMmsCQ2WPgg

0.002 BTC - Transaction

ScriptPubKey - P2PKH

OP_DUP OP_HASH160

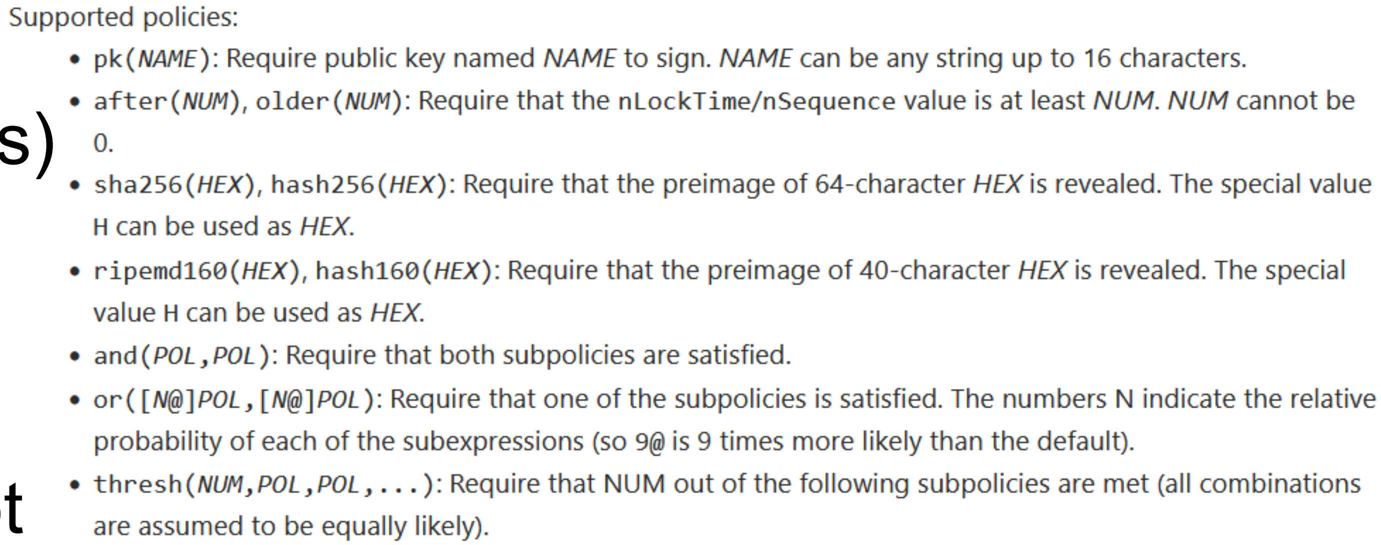
0xb8268ce4d481413c4e848ff353cd16104291c45b OP_EQUALVERIFY

OP_CHECKSIG

https://nioctib.tech/#/transaction/f2f398dace996dab12e0cfb02fb0b59de0ef0398be393d90ebc8ab397550370b

Miniscript (A. Poelstra, P. Wuille, S. Kanjalkar, 2019)

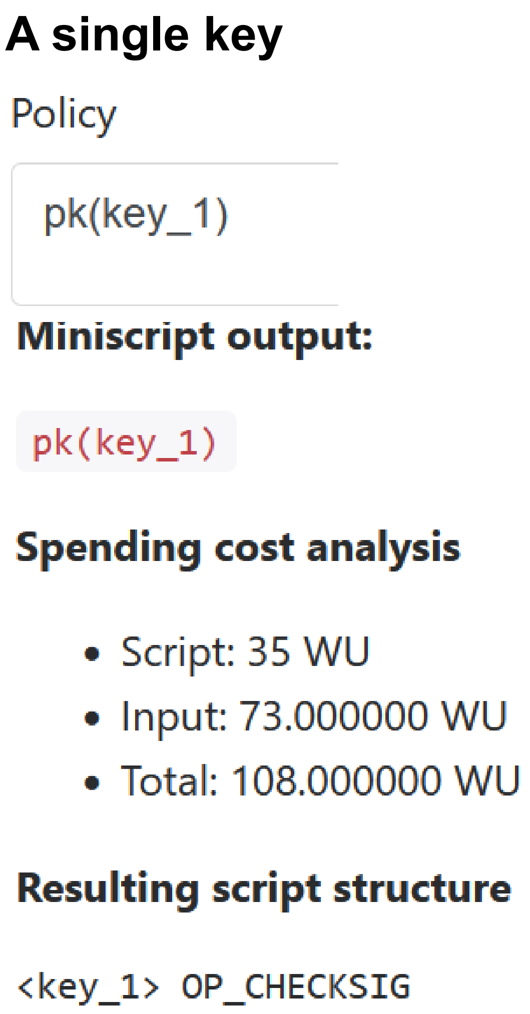
- Language for easier and error-prone creation of Bitcoin scripts
  - Subset of Bitcoin script language
  - Human-readable, easy to express complex locking conditions
  - https://bitcoin.sipa.be/miniscript/
- Simple building blocks (policies)
  - Single-key, Multi-key,
  - Time-locks, Check-sequence,
  - Hash-lock…
- Compiler creates optimal script
  - And cost analysis



Supported policies:

- `pk(`*NAME*`)`: Require public key named *NAME* to sign. *NAME* can be any string up to 16 characters.
- `after(`*NUM*`)`, `older(`*NUM*`)`: Require that the `nLockTime/nSequence` value is at least *NUM*. *NUM* cannot be 0.
- `sha256(`*HEX*`)`, `hash256(`*HEX*`)`: Require that the preimage of 64-character *HEX* is revealed. The special value `H` can be used as *HEX*.
- `ripemd160(`*HEX*`)`, `hash160(`*HEX*`)`: Require that the preimage of 40-character *HEX* is revealed. The special value `H` can be used as *HEX*.
- `and(`*POL*`,`*POL*`)`: Require that both subpolicies are satisfied.
- `or([`*N*`@]`*POL*`,[`*N*`@]`*POL*`)`: Require that one of the subpolicies is satisfied. The numbers N indicate the relative probability of each of the subexpressions (so `9@` is 9 times more likely than the default).
- `thresh(`*NUM*`,`*POL*`,`*POL*`,...)`: Require that NUM out of the following subpolicies are met (all combinations are assumed to be equally likely).

Miniscript examples



A single key

Policy

pk(key_1)

Miniscript output:

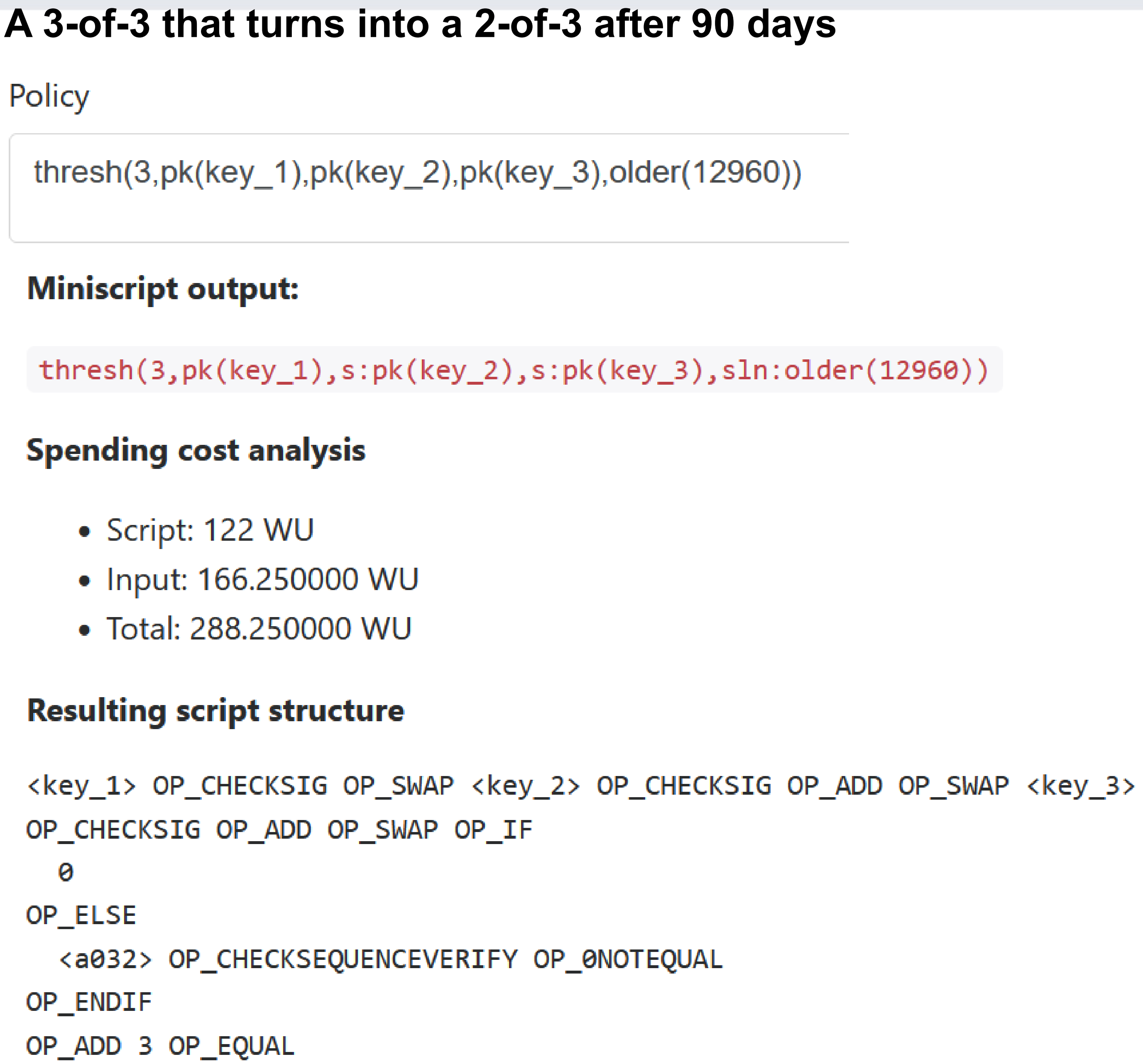
`pk(key_1)`

Spending cost analysis

- Script: 35 WU
- Input: 73.000000 WU
- Total: 108.000000 WU

Resulting script structure

```
<key_1> OP_CHECKSIG
```



A 3-of-3 that turns into a 2-of-3 after 90 days

Policy

thresh(3,pk(key_1),pk(key_2),pk(key_3),older(12960))

Miniscript output:

`thresh(3,pk(key_1),s:pk(key_2),s:pk(key_3),sln:older(12960))`

Spending cost analysis

- Script: 122 WU
- Input: 166.250000 WU
- Total: 288.250000 WU

Resulting script structure

```
<key_1> OP_CHECKSIG OP_SWAP <key_2> OP_CHECKSIG OP_ADD OP_SWAP <key_3>
OP_CHECKSIG OP_ADD OP_SWAP OP_IF
  0
OP_ELSE
  <a032> OP_CHECKSEQUENCEVERIFY OP_0NOTEQUAL
OP_ENDIF
OP_ADD 3 OP_EQUAL
```

BLOCKS AND MINING

Problem: Who will include next block in blockchain?

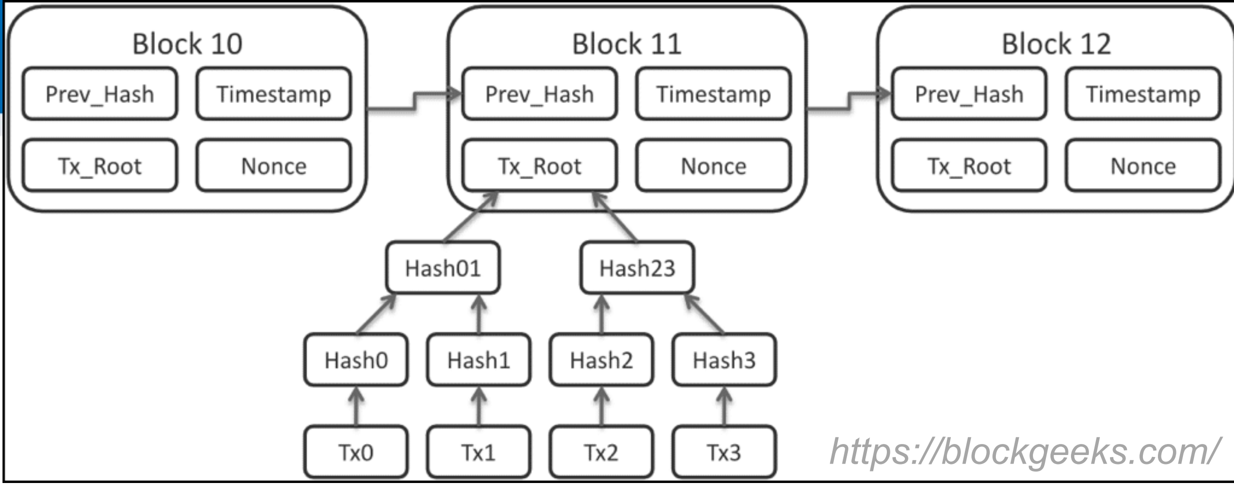
- Transactions (state updates) has to be included somehow into block to be "permanently" valid
- Entity including new block has special position and power
  - Can decide which transactions (state updates) will be included
    - May lead to censorship of certain transactions
    - May lead to transactions reordering impacting the financial value (e.g. MEV)
  - Can decide where new block is appended
    - Shall be last previous block, but can cause malicious forks abandoning part of previously extended blockchain (e.g., 51% attack to rewrite history)
  - Typically receive some reward (motivation for participation)
    - May cause long-term centralized accumulation of underlying token

Who can include next block to blockchain?

We will focus mainly on Proof Of Work used in Bitcoin

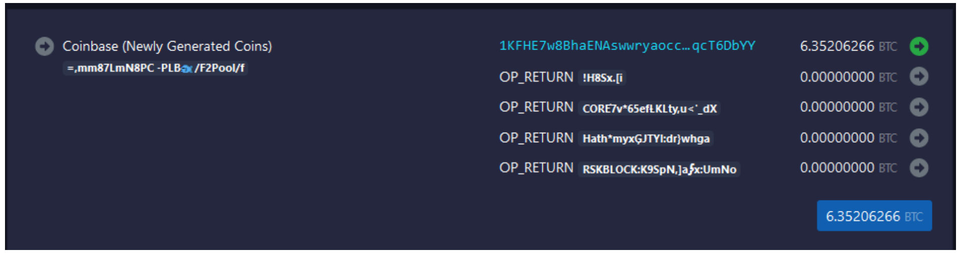
- Proof of Work (PoW, Bitcoin, Ethereum 1.0, Zcash…)
  - Solver of computationally hard puzzle can include new block
- Proof of Stake (PoS, Zcoin, Cardano, BNB, Ethereum 2.0…)
  - More coins you own, higher the probability you will be selected to include next block
  - Various variants, Stake pools…
- Merged Mining (Namecoin…)
  - Hash of block from the chain is included in coinbase tx of other chain (typically Bitcoin)
  - The chain is not performing own mining, Bitcoin miners are getting reward for inclusion of other chains
- Proof of Proof (PoP)
  - Hash of block from other chain is included in Bitcoin transaction (typically OP_RETURN)
  - Security of other chain is improved by security of Bitcoin blockchain
- Proof of Authority (PoA)
  - Small number of trusted actors create new blocks

Bitcoin block



https://blockgeeks.com/

- Header (80 B) + data (up to ~4MB)
  - Version
  - Previous block hash (linking to past blockchain)
  - Merkle root of all included transactions (Coinbase tx + others)
  - Timestamp (unix time)
  - Bits (specification of required mining difficulty)
  - Nonce (variable part to mine , now insufficient)



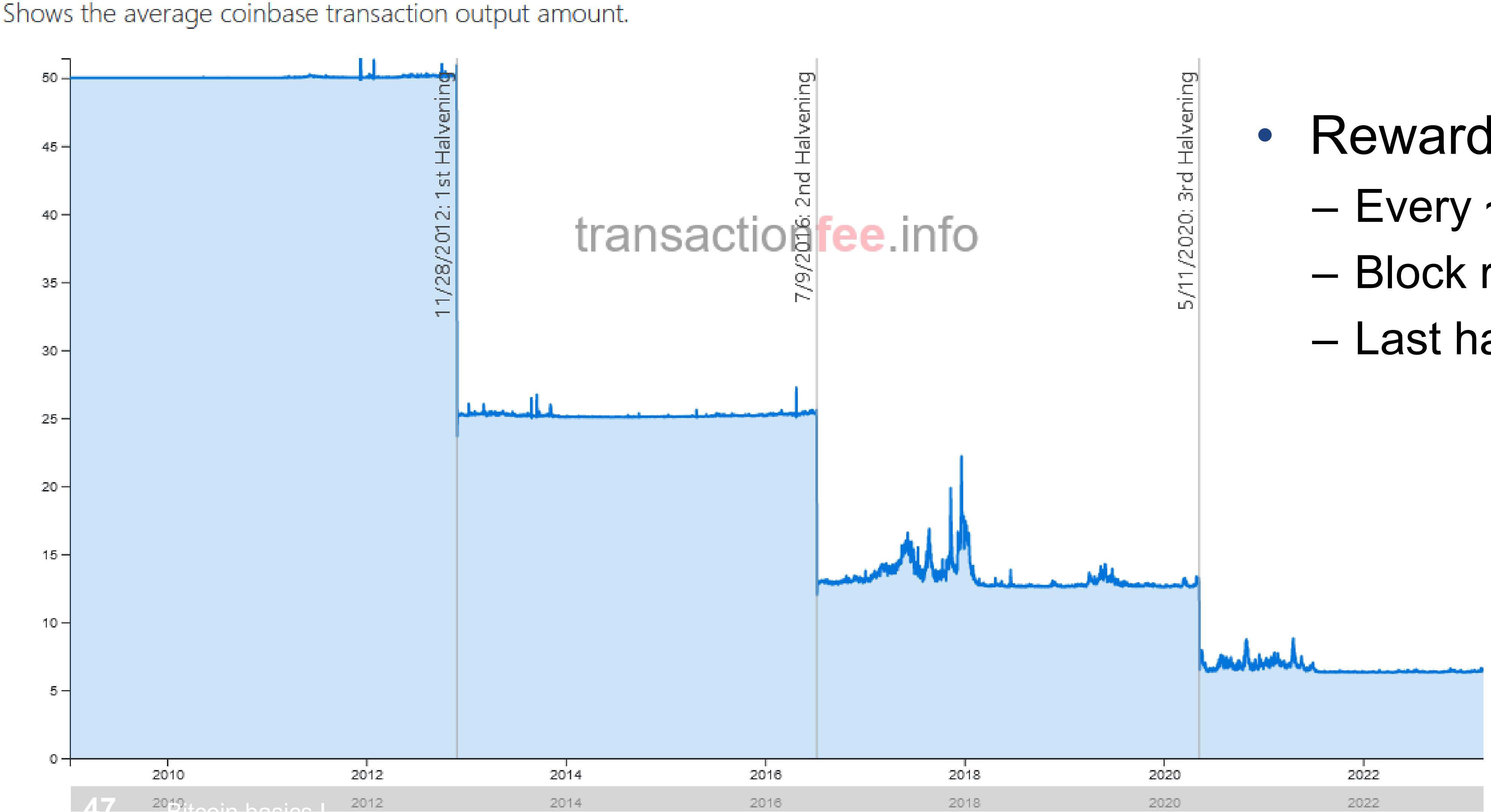
```
Coinbase (Newly Generated Coins)       1KFHE7w8BhaENAswwryaocc…qcT6DbYY        6.35206266 BTC
=,mm87LmN8PC -PLB /F2Pool/f            OP_RETURN !H8Sx.[i                      0.00000000 BTC
                                       OP_RETURN CORE7v*65efŁKLty,u<'_dX       0.00000000 BTC
                                       OP_RETURN Hath*myxGJTYI:dr}whga         0.00000000 BTC
                                       OP_RETURN RSKBLOCK:K9SpN,]aʆx:UmNo      0.00000000 BTC
                                                                               6.35206266 BTC
```

- Coinbase transaction (reward for miners, emission of new bitcoins)
  - First transaction in every block (only one)
  - Only one input, previous TX ID = 0x0000..00, prev. TX index = 0xffffffff
  - (Typically) equal to block reward + all fees from included transactions

Mining in Proof of Work chains

- Crucial for security of blockchain (no rewrite of history)
- Initially on CPU (Satoshi: everyone can participate 1 CPU 1 vote)
- CPU→GPU →FPGA →ASIC
- Initially solo mining, later collaborative mining (too little chance alone)
- First mining pool: SlushPool in Prague (now Braiins Pool)
  - Miners join their hashrate, fraction of reward based on number of partial solutions
- Cambridge university centre for alternative finance (CBECI)
  - Where are the miners? https://cbeci.org/mining_map/
  - More mining details: https://cbeci.org/cbeci/methodology

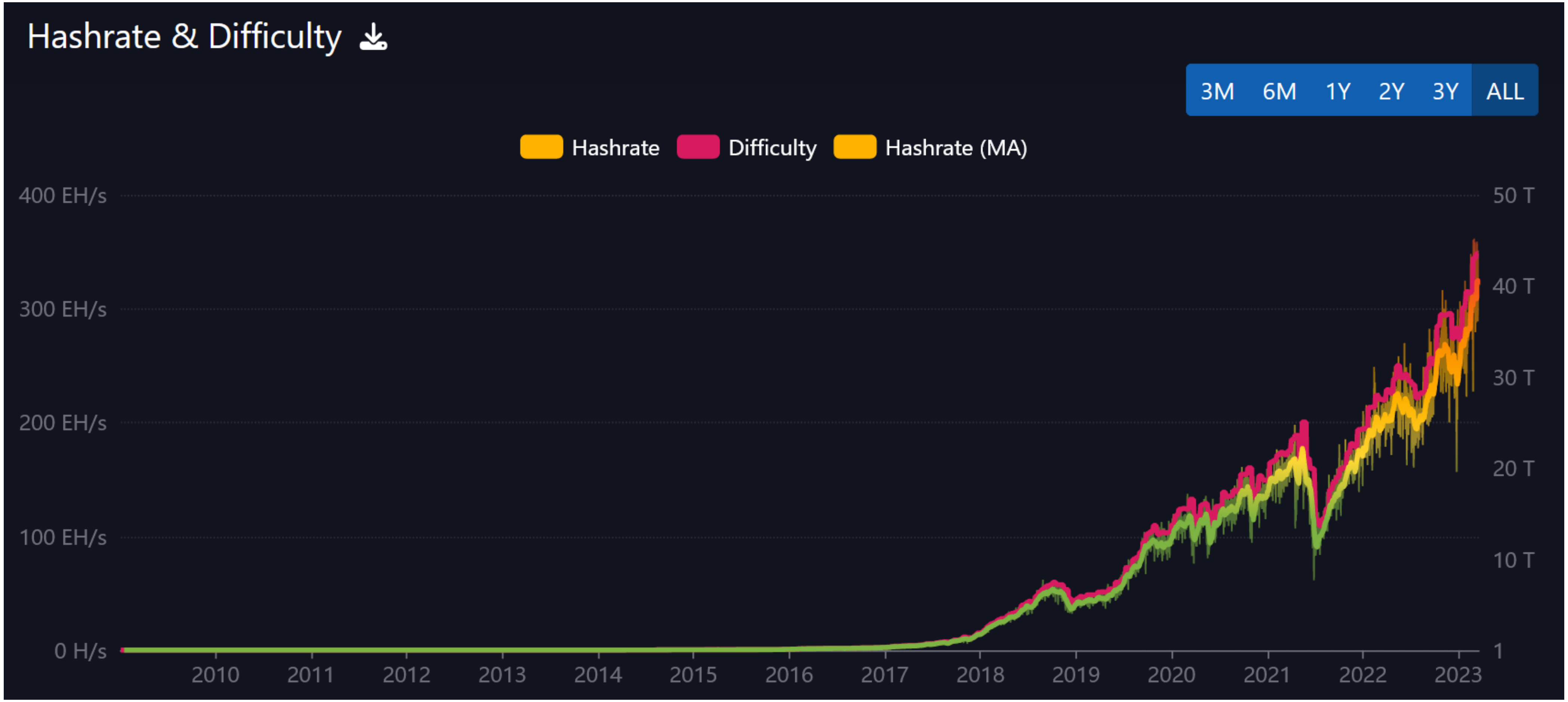
Miner reward – coinbase output: block + fees



Shows the average coinbase transaction output amount.

- Reward halving
  - Every ~4 years
  - Block reward drops to ½
  - Last halving in year 2140

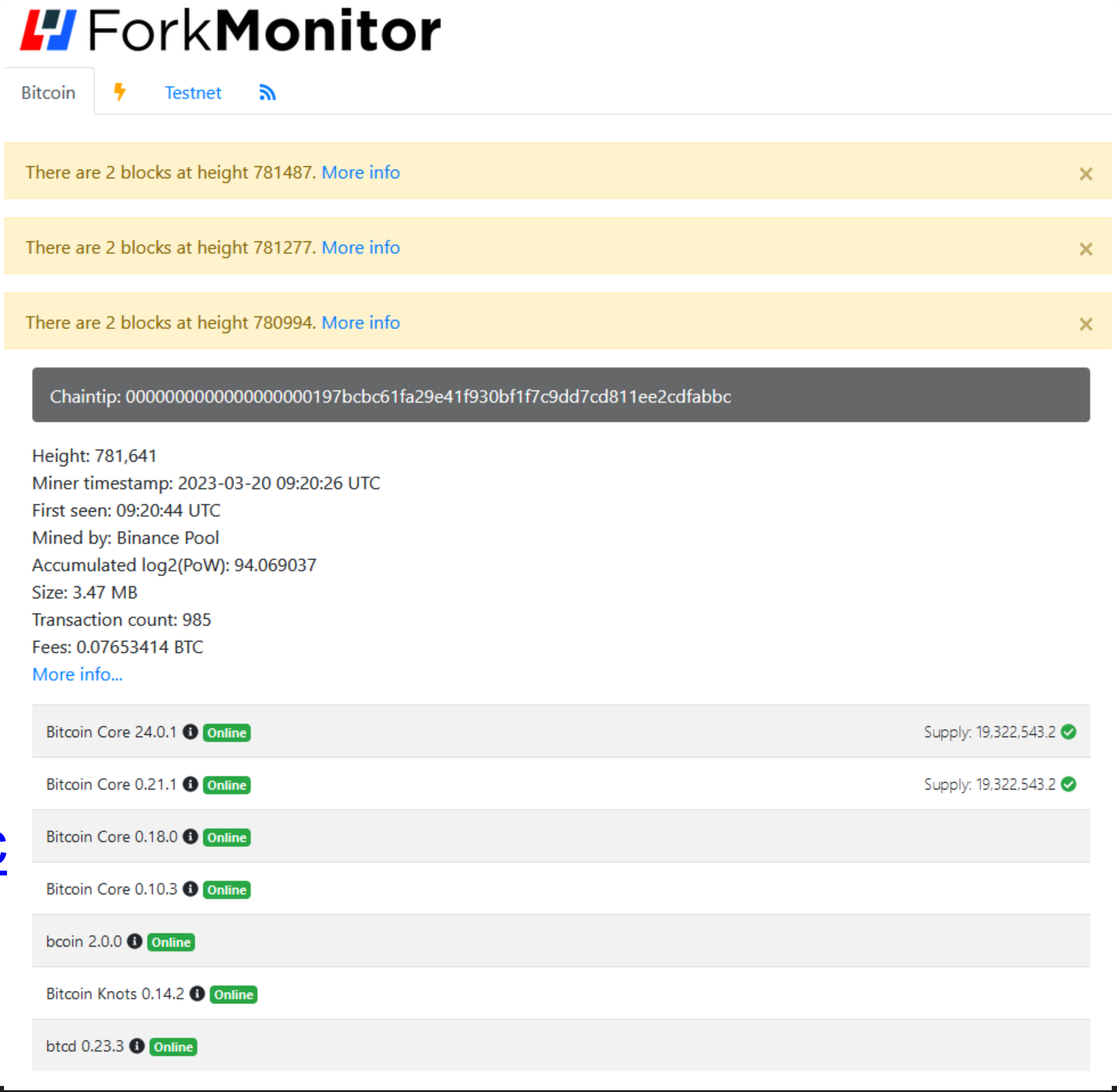
Hashrate in time (~320EH/s = $3.2*10^{20}$ hash/sec = 2^{66} /sec)



https://mempool.space/graphs/mining/hashrate-difficulty#all

Blockchain forks

- Occasional natural forks happen
  - (not to be confused with softforks)
- Quickly resolved
  - usually, next block
- Sometimes temporary double-spent can occur
  - Same input used in different txs
- https://forkmonitor.info/nodes/btc



ForkMonitor

Bitcoin | Testnet

There are 2 blocks at height 781487. More info ×

There are 2 blocks at height 781277. More info ×

There are 2 blocks at height 780994. More info ×

Chaintip: 0000000000000000000197bcbc61fa29e41f930bf1f7c9dd7cd811ee2cdfabbc

Height: 781,641
Miner timestamp: 2023-03-20 09:20:26 UTC
First seen: 09:20:44 UTC
Mined by: Binance Pool
Accumulated log2(PoW): 94.069037
Size: 3.47 MB
Transaction count: 985
Fees: 0.07653414 BTC
More info...

Bitcoin Core 24.0.1 Online	Supply: 19,322,543.2 ✓
Bitcoin Core 0.21.1 Online	Supply: 19,322,543.2 ✓
Bitcoin Core 0.18.0 Online	
Bitcoin Core 0.10.3 Online	
bcoin 2.0.0 Online	
Bitcoin Knots 0.14.2 Online	
btcd 0.23.3 Online	

DEMO: SHOW DIFFICULTY ADJUSTMENT

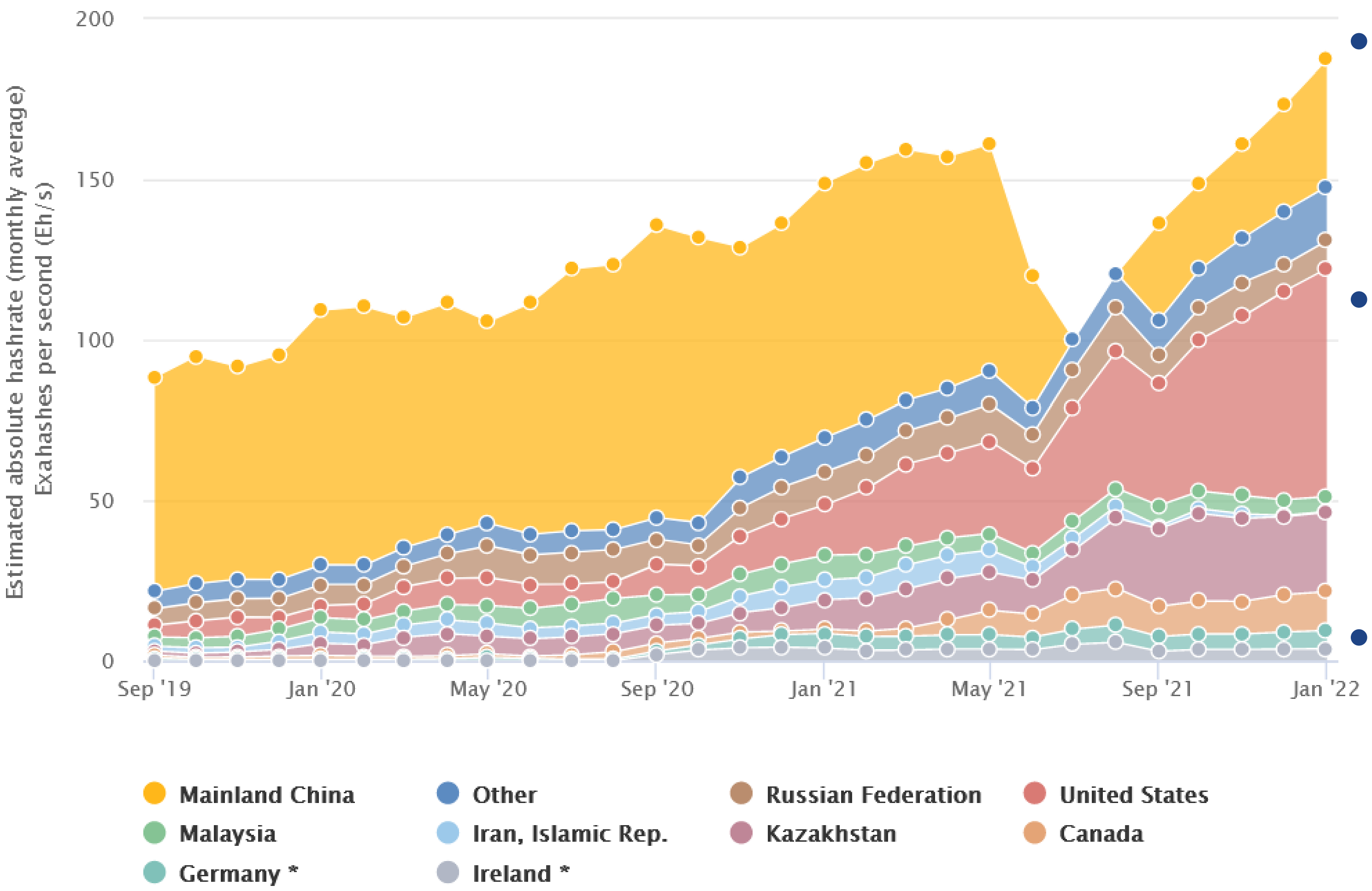
Difficulty adjustment

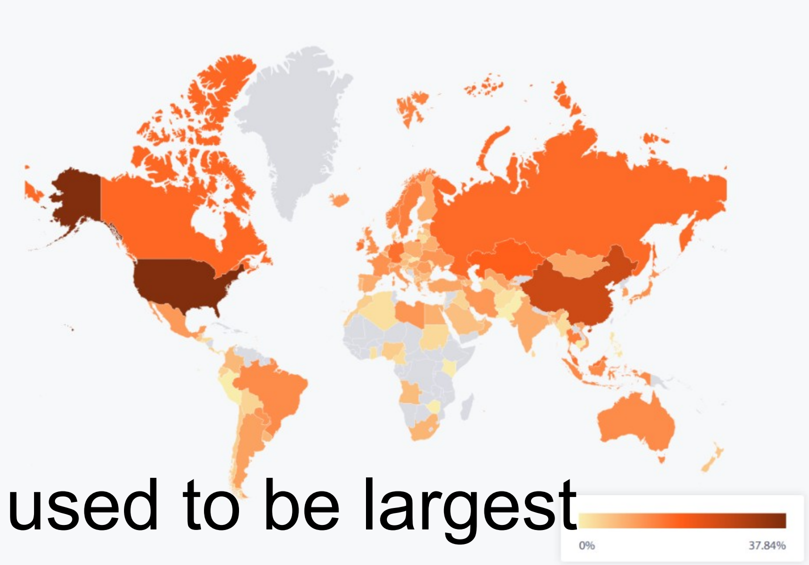
- Bitcoin shall have one block every ten minutes (on average)
- Block must have overall hash with specific number of leading zeroes (March 2023 ~75 binary 0)
  - Miners change part of block header to try different hashes until required found
- How to specify the number of leading zeroes for decades in future?
  - Speed of new blocks found depends on the overall speed of hashing
  - Overall speed of hashing depends on technology advancements (single chip) and number of chips deployed
  - Impossible to predict technology and interest into distant future
  - If # zeroes is too low => blocks are found too fast (and vice versa)
- Idea of difficulty adjustment (part of consensus protocol), https://en.bitcoin.it/wiki/Difficulty
  - Check number of actually mined blocks every 2016 blocks (shall be ~14 days)
    - Increase/decrease difficulty for next period based on actual number of mined blocks
  - Every full node can deterministically compute expected difficulty (lower # zeroes rejected)
- Block hash must be below the “Target” number (computed to avg keep 1 block / ~10 min)
  - “Target” is transformed to “Bits” (condensed 4 bytes number – coefficient (3B) + exponent (1B))
  - Current difficulty is relative number of current Target with respect to Target of Genesis block

https://cbeci.org/mining_map/

Bitcoin mining map (January 2022)

Evolution of network hashrate





- China used to be largest
  - >80% (till 2018, slow decrease)
  - Mining ASICS made in China
- China evicted “all” miners in May 2021
  - Officially 0% (unofficially still active)
  - Now coming back 21.11%
- Resulted in strong increase in:
  - US 37.84%, Kazakhstan 13.22%
  - Canada 6.48%, other 9% …

Is Bitcoin mining wasteful?

- Heavily discussed topic (“Bitcoin will boil the oceans by 2020”)
- Some questions to ask (**Do your own research!**)
  - What value you are getting for the energy expended? (neutral decentralized monetary system)
  - Miners want the cheapest energy available to maximize profits => energy nobody wants => waste energy
  - What is the source of the energy used? (btc mining 60-70% “green” energy due to its low cost)
  - Can mining help to stabilize electrical grid with intermittent (solar, wind) sources? (instant turn on/off of mining ASICs, consumption of only cheap (= not demanded) energy)
  - How long is mining hardware profitable before dismantling? (depends on energy price, 5+ years)
  - Can miners finance construction of energy sources (hydro…) at places otherwise not viable financially (stranded energy)?
  - Can miners incentivize higher portion of intermittent (solar, wind) sources? (bigger source even when low sun/wind?)

Warning: Why not put “blockchain” everywhere?

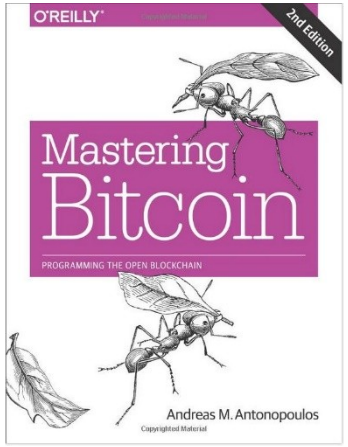
- ~~“Blockchain not Bitcoin”, “Blockchainize everything”~~… claims
- Permissionless distributed consensus on global state is very expensive
  - Confirmation time, storage space, energy expenditure (PoW)…
  - Most applications does not need it!
  - Especially when other components of application are centralized (development, governance decisions, data storage…)

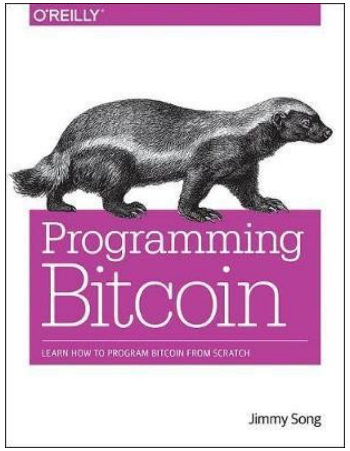
Study materials

- Mandatory reading
  - Bitcoin's academic pedigree (Arvind Narayanan, Jeremy Clark)
    - https://dl.acm.org/doi/10.1145/3132259 (copy in IS)
    - Explanation of roots of Bitcoin key components
- If you were not familiar with basics of Bitcoin before
  - Watch ‘But how does bitcoin actually work?’ by 3Blue1Brown (26min)
    - https://www.youtube.com/watch?v=bBC-nXj3Ng4
  - Read slides Hello Bitcoin (including notes under every slide)
    - From https://www.hellobitco.in/, copy of slides in IS

Further reading

- Mastering Bitcoin (Andreas M. Antonopoulos and others)
  - https://github.com/bitcoinbook/bitcoinbook
- Programming Bitcoin (Jimmy Song)
  - https://github.com/jimmysong/programmingbitcoin
- List of interesting resources
  - https://blockonomi.com/bitcoin-educational-resources/
  - https://learnmeabitcoin.com/, https://learnmeabitcoin.com/technical/





THANK YOU FOR COMING, SEE YOU NEXT WEEK