BITCOIN MECHANICS AND OPTIMIZATIONS: A TECHNICAL OVERVIEW

Nadir Akhtar
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BLOCKCHAIN
AT BERKELEY

LECTURE OVERVIEW

1 CRYPTOGRAPHIC HASH FUNCTIONS

2 A TAMPER-EVIDENT DATABASE

3 SIGS, ECDSA, AND ADDRESSES

4 BITCOIN SCRIPT

5 P2PKH & P2SH

1 CRYPTOGRAPHIC HASH FUNCTIONS

CRYPTOGRAPHIC HASH FUNCTIONS

INTEGRITY OF INFORMATION

How do we ensure trust in communication in a trustless environment?

⇒ With **cryptographic hash functions**

CRYPTOGRAPHIC HASH FUNCTIONS

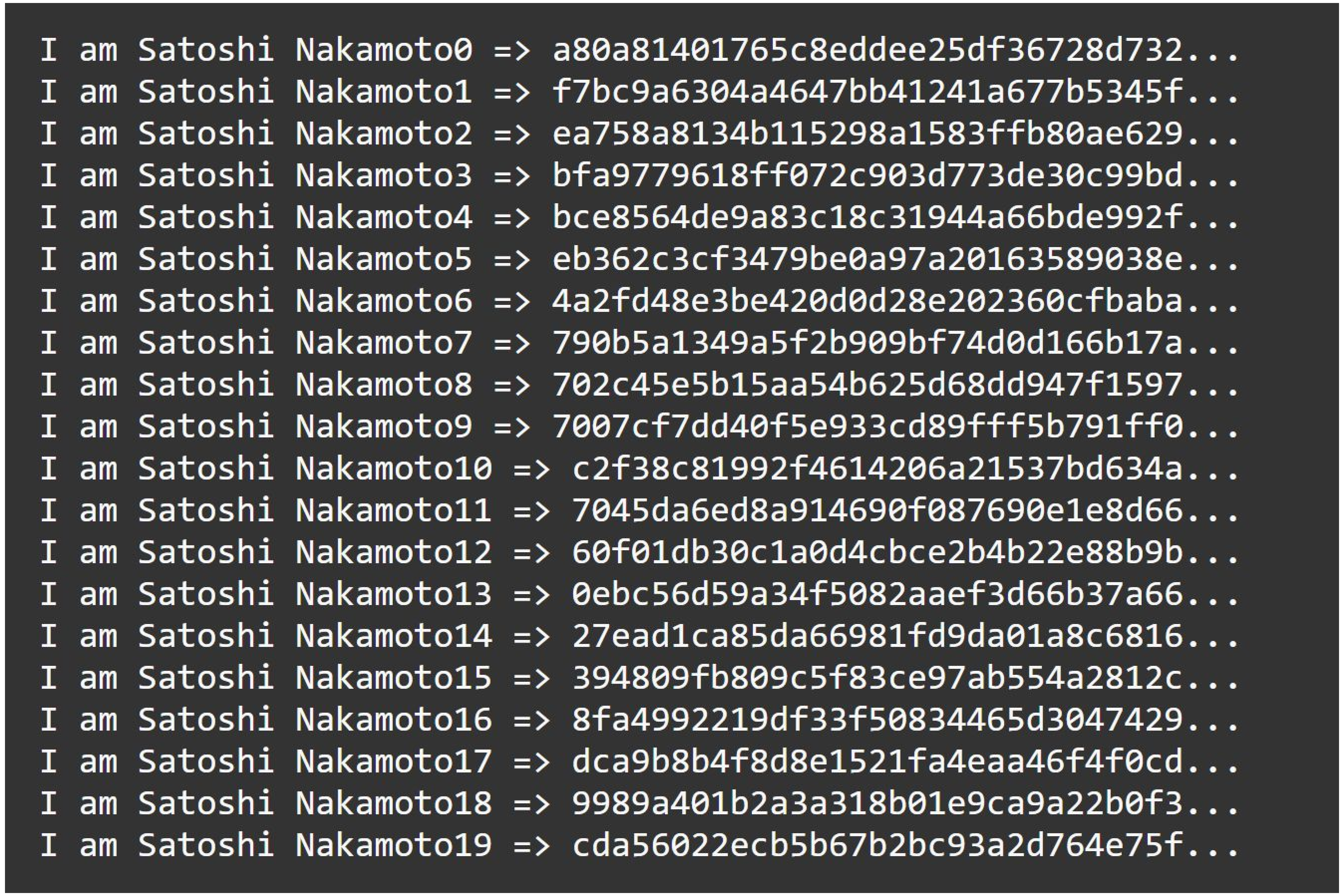
#CRYPTOGRAPHY

Cryptographic hash function:

A hash function with three special properties:

- Preimage resistance
- Second preimage resistance
- Collision resistance

The equivalent of **mathematical fingerprints/identifiers**



```
I am Satoshi Nakamoto0 => a80a81401765c8eddee25df36728d732...
I am Satoshi Nakamoto1 => f7bc9a6304a4647bb41241a677b5345f...
I am Satoshi Nakamoto2 => ea758a8134b115298a1583ffb80ae629...
I am Satoshi Nakamoto3 => bfa9779618ff072c903d773de30c99bd...
I am Satoshi Nakamoto4 => bce8564de9a83c18c31944a66bde992f...
I am Satoshi Nakamoto5 => eb362c3cf3479be0a97a20163589038e...
I am Satoshi Nakamoto6 => 4a2fd48e3be420d0d28e202360cfbaba...
I am Satoshi Nakamoto7 => 790b5a1349a5f2b909bf74d0d166b17a...
I am Satoshi Nakamoto8 => 702c45e5b15aa54b625d68dd947f1597...
I am Satoshi Nakamoto9 => 7007cf7dd40f5e933cd89fff5b791ff0...
I am Satoshi Nakamoto10 => c2f38c81992f4614206a21537bd634a...
I am Satoshi Nakamoto11 => 7045da6ed8a914690f087690e1e8d66...
I am Satoshi Nakamoto12 => 60f01db30c1a0d4cbce2b4b22e88b9b...
I am Satoshi Nakamoto13 => 0ebc56d59a34f5082aaef3d66b37a66...
I am Satoshi Nakamoto14 => 27ead1ca85da66981fd9da01a8c6816...
I am Satoshi Nakamoto15 => 394809fb809c5f83ce97ab554a2812c...
I am Satoshi Nakamoto16 => 8fa4992219df33f50834465d3047429...
I am Satoshi Nakamoto17 => dca9b8b4f8d8e1521fa4eaa46f4f0cd...
I am Satoshi Nakamoto18 => 9989a401b2a3a318b01e9ca9a22b0f3...
I am Satoshi Nakamoto19 => cda56022ecb5b67b2bc93a2d764e75f...
```

Image source:
http://chimera.labs.oreilly.com/books/1234000001802/ch08.html#_proof_of_work_algorithm

CRYPTOGRAPHIC HASH FUNCTIONS

PREIMAGE RESISTANCE

Preimage resistance:

Given H(x), it is computationally difficult to determine x.

<ins>Fingerprint analogy:</ins>

Whose fingerprint is this?

Image source: https://spiritegg.com/wp-content/uploads/2016/03/63180952_fingerprint_types624.jpg

CRYPTOGRAPHIC HASH FUNCTIONS

SECOND PREIMAGE RESISTANCE

Second preimage resistance:

Given x, it is computationally difficult to find some value x’ such that H(x) == H(x’)

Fingerprint analogy:

Can you find someone with the same fingerprint as you?

CRYPTOGRAPHIC HASH FUNCTIONS

COLLISION RESISTANCE

Collision resistance:

It is computationally difficult to find x and y such that H(x) == H(y)

Fingerprint analogy:

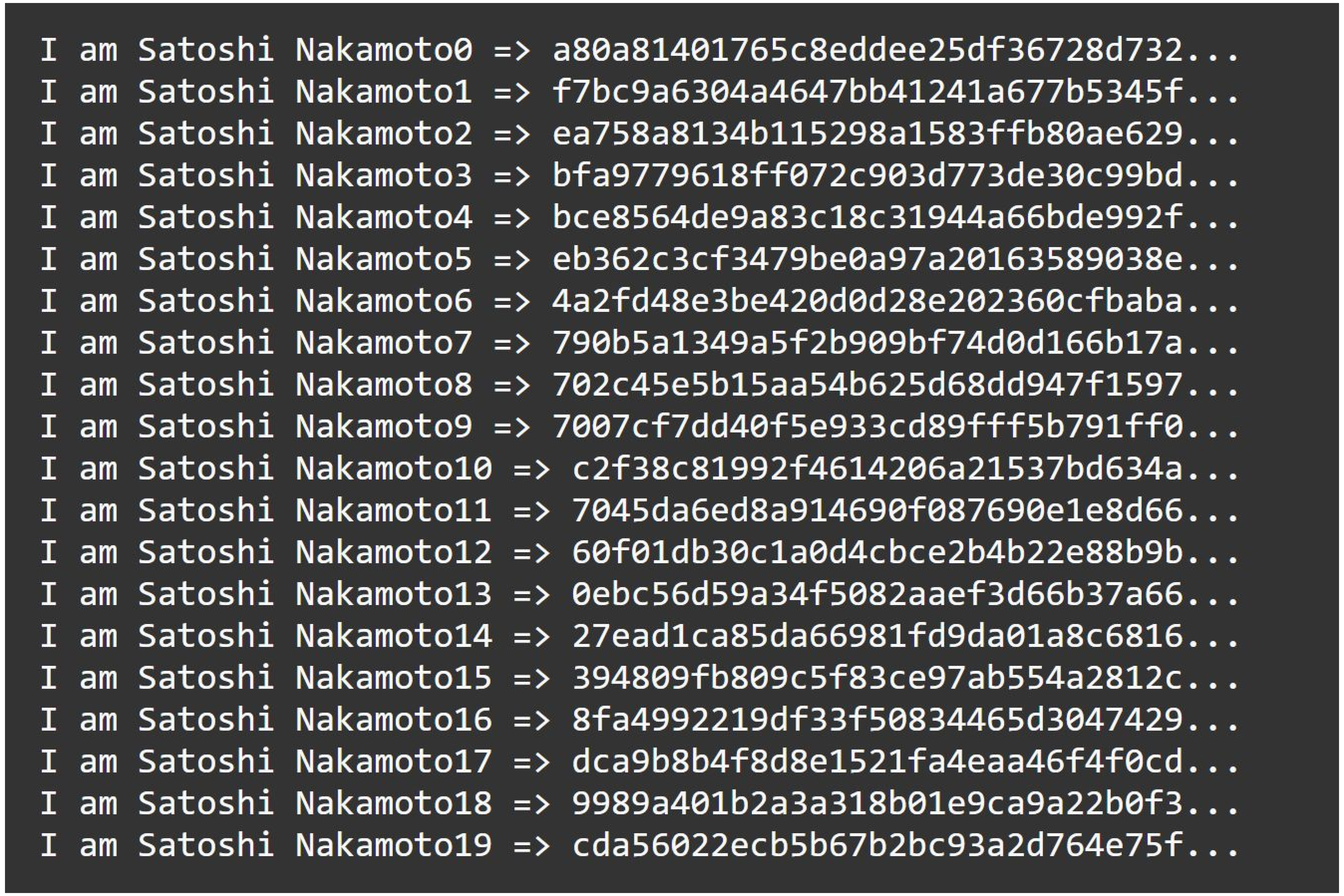
Can you find two random people with the same fingerprint?

CRYPTOGRAPHIC HASH FUNCTIONS

AVALANCHE EFFECT

Avalanche effect: a small change in the input produces a pseudorandom change in the output

- Often a significant different from the first output
- Prevents “hot or cold” game with inputs to produce or predict outputs



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I am Satoshi Nakamoto19 => cda56022ecb5b67b2bc93a2d764e75f...
```

CRYPTOGRAPHIC HASH FUNCTIONS

SHA-256^2

SHA-256: A cryptographic hash function designed by the NSA

Bitcoin uses **SHA-256^2** (“`SHA-256 squared`”), meaning that `H(x)` actually means `SHA256(SHA256(x))`

- See readings for clarifications and reasoning

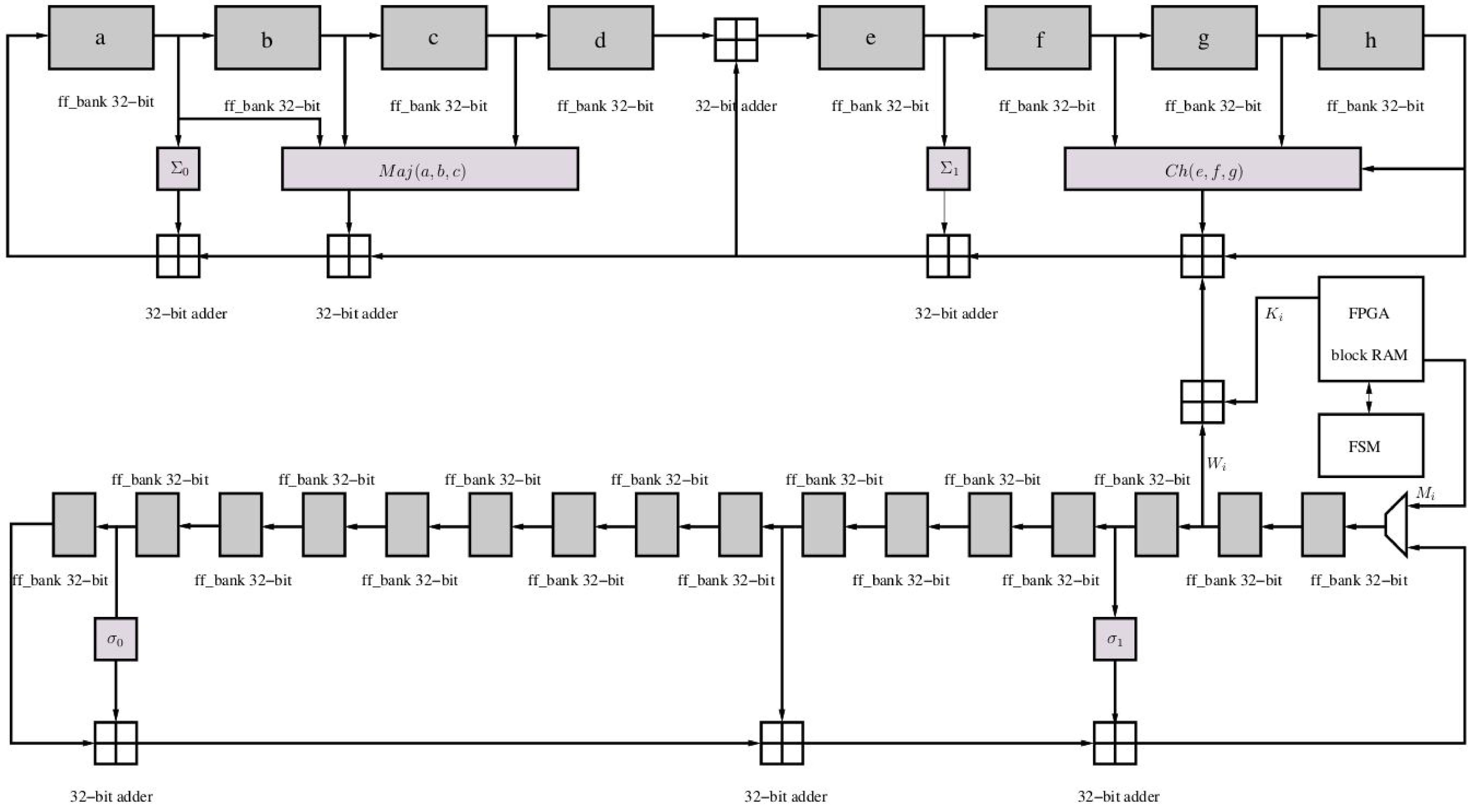


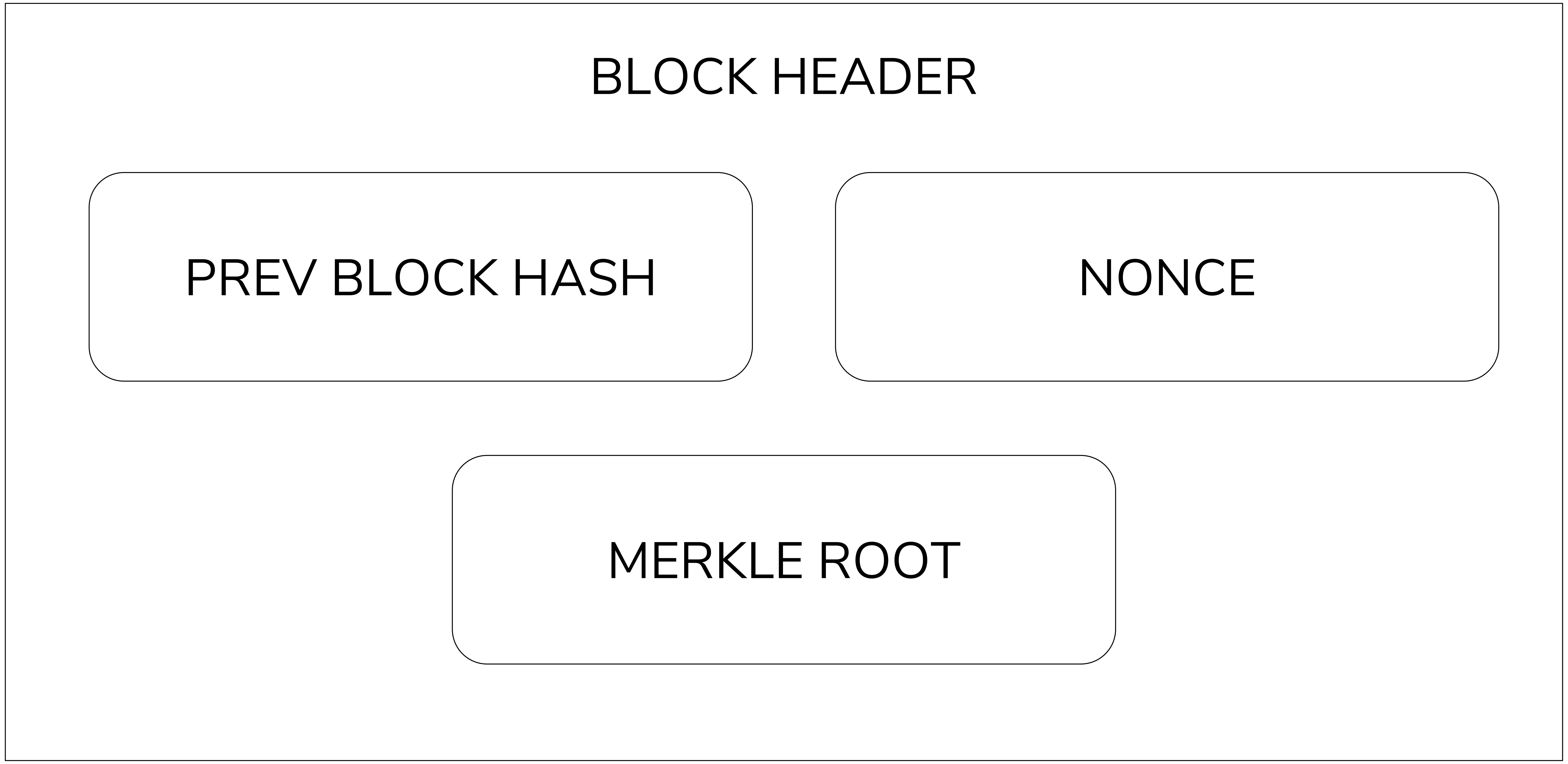
Image source:
https://opencores.org/usercontent,img,1375985843

2

A TAMPER-EVIDENT DATABASE

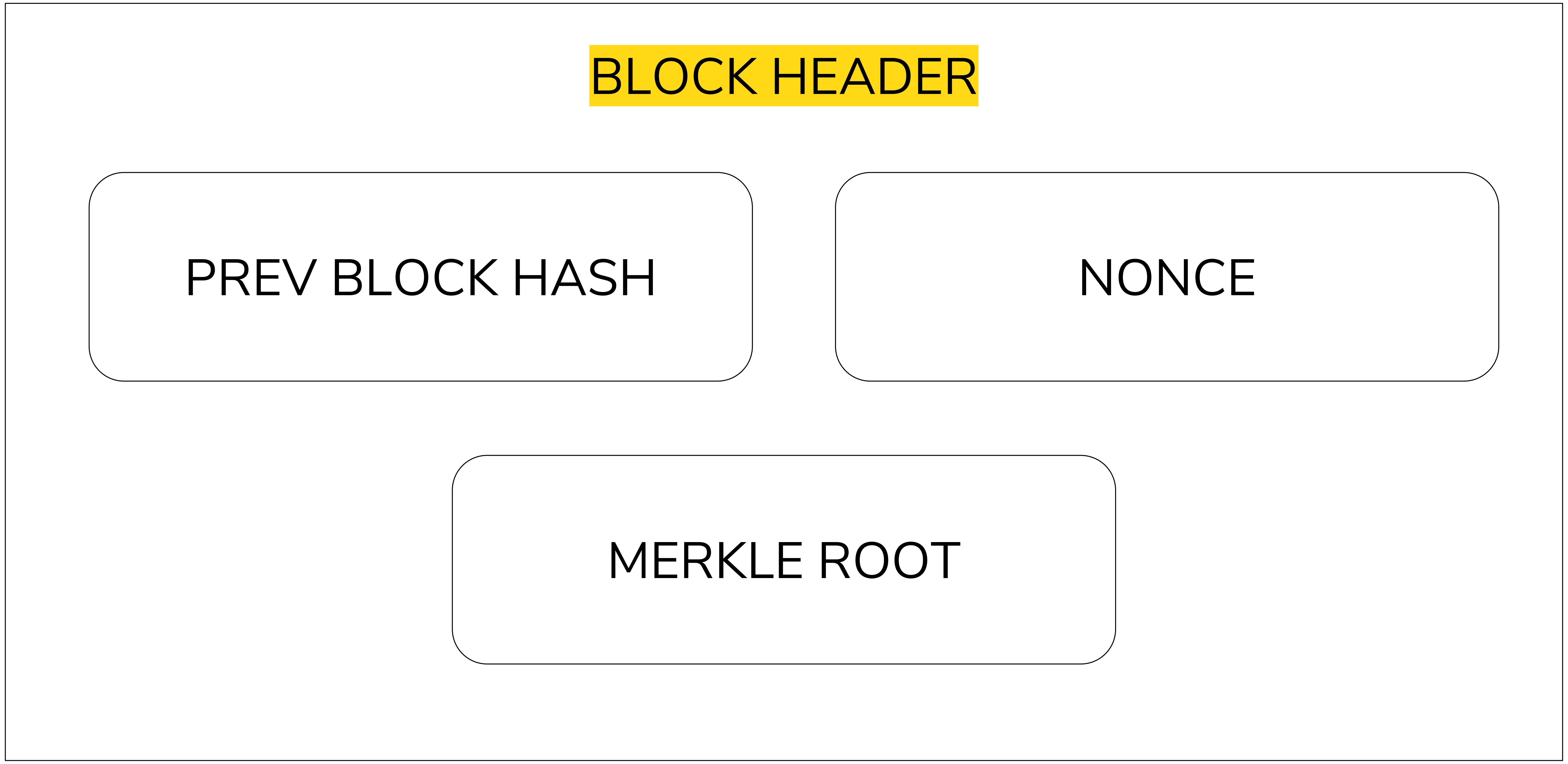
A TAMPER-EVIDENT DATABASE

DISSECTING THE BLOCKCHAIN



A TAMPER-EVIDENT DATABASE

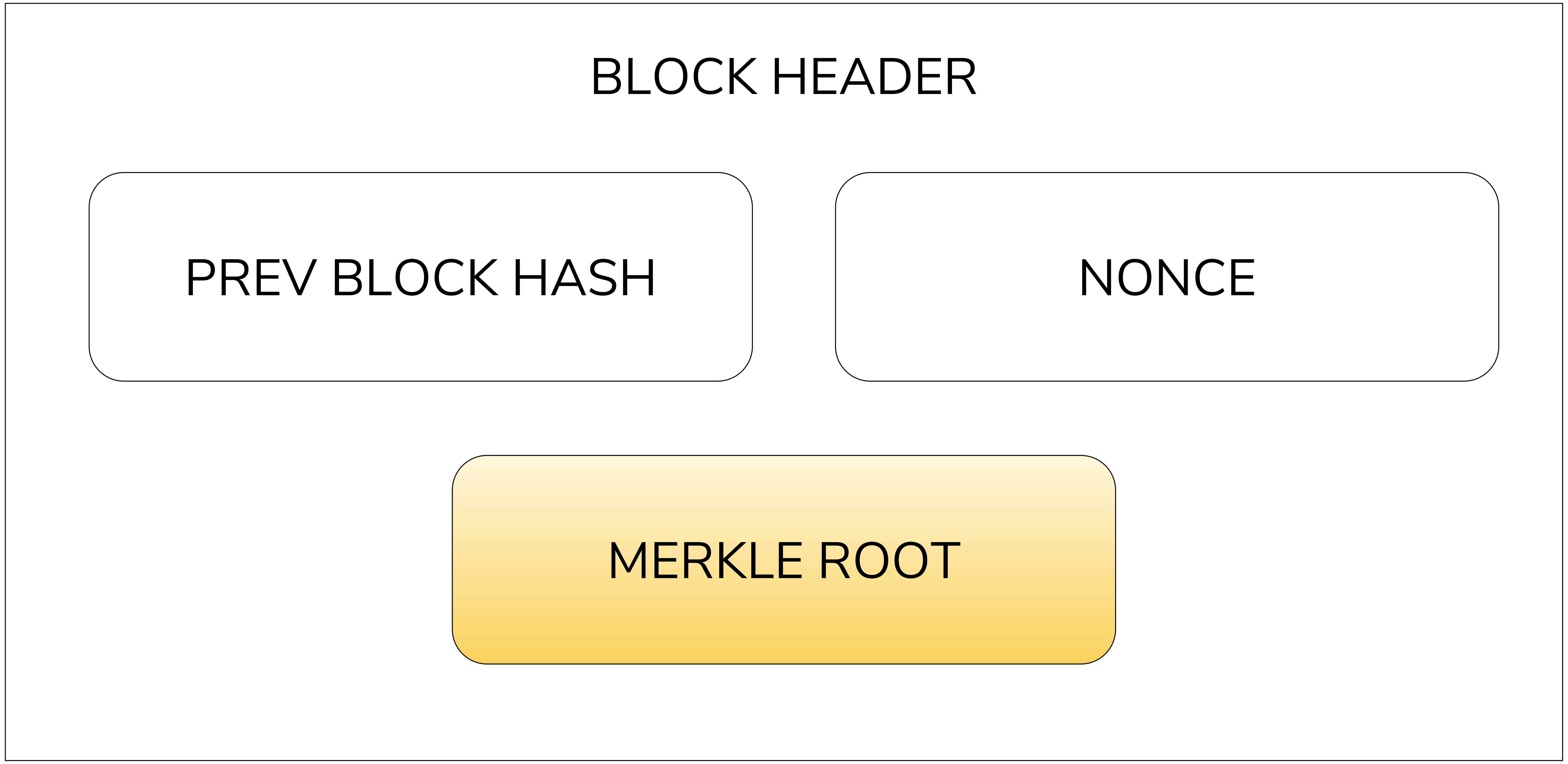
BLOCK HEADER



```
blockID = H(blockHeader) = H(prevBlockHash || merkleRoot || nonce)
```

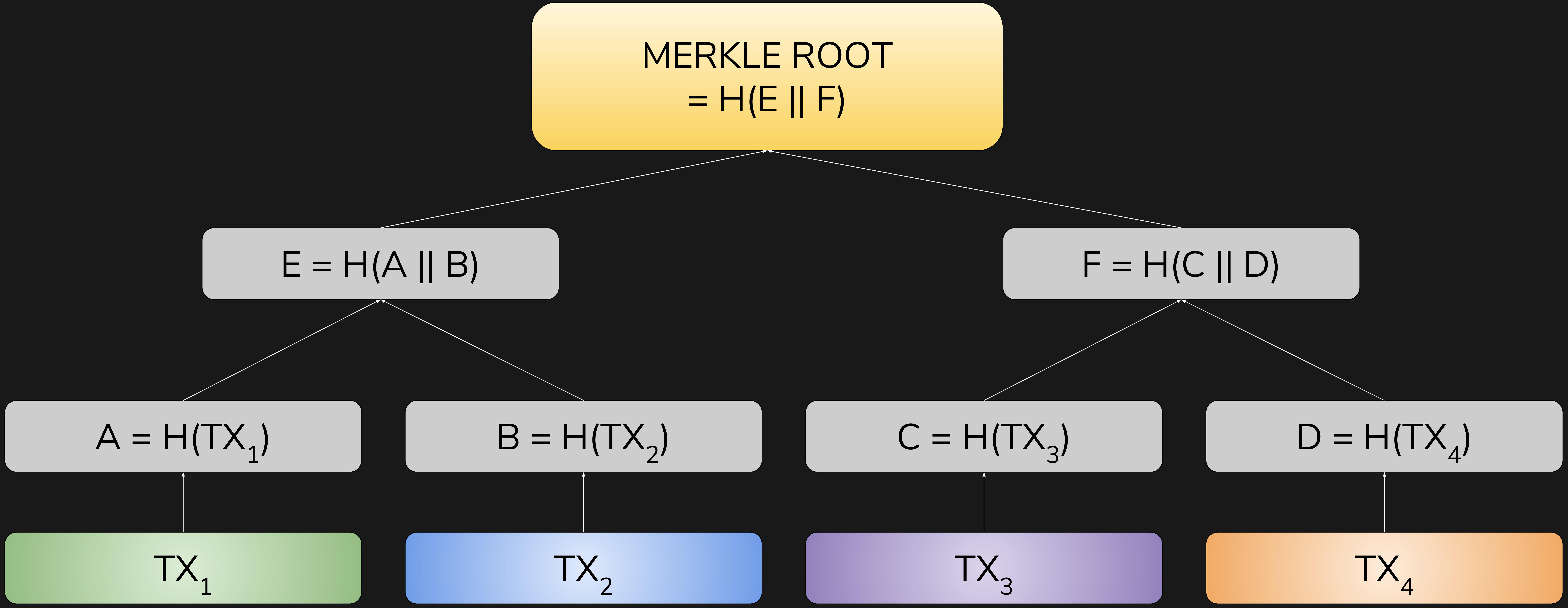
A TAMPER-EVIDENT DATABASE

MERKLE ROOT



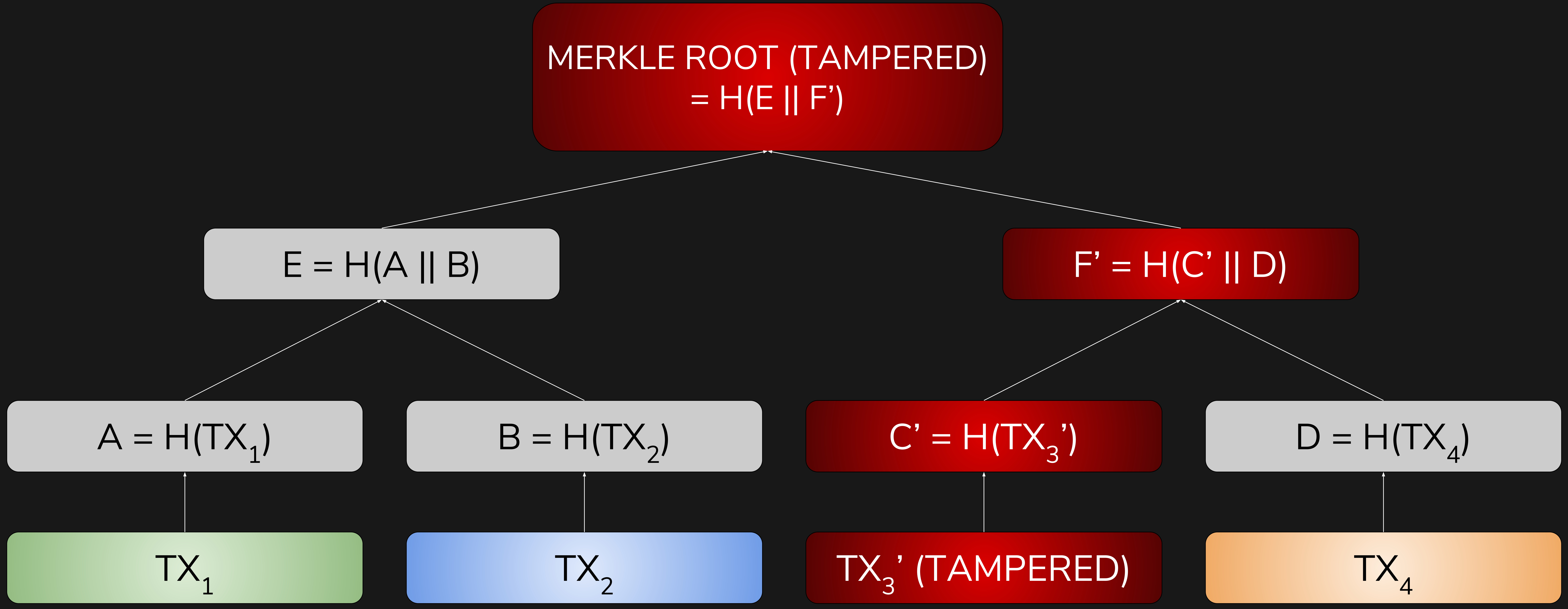
A TAMPER-EVIDENT DATABASE

MERKLE TREE



A TAMPER-EVIDENT DATABASE

GETTING TO THE ROOT OF THE PROBLEM



MERKLE ROOT (TAMPERED) = $H(E \| F')$

$E = H(A \| B)$

$F' = H(C' \| D)$

$A = H(TX_1)$

$B = H(TX_2)$

$C' = H(TX_3')$

$D = H(TX_4)$

TX_1

TX_2

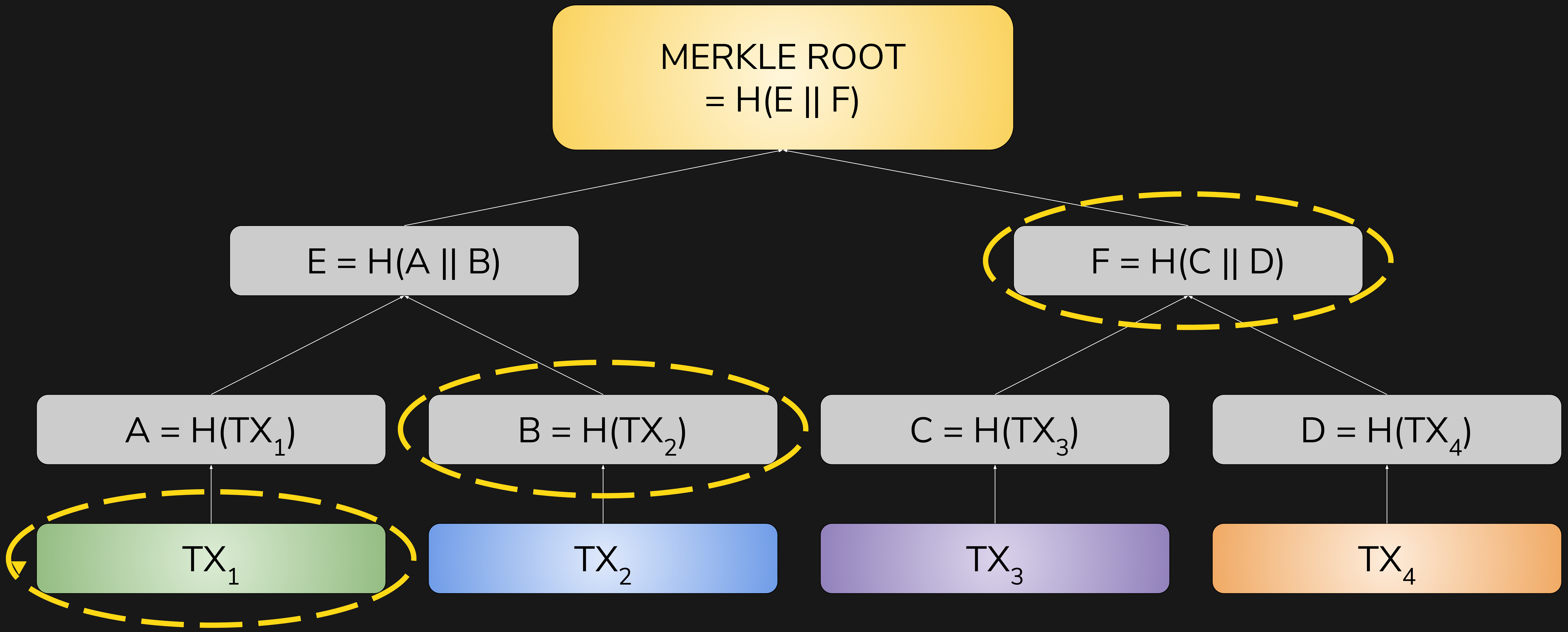
TX_3' (TAMPERED)

TX_4

AUTHOR: NADIR AKHTAR

A TAMPER-EVIDENT DATABASE

MERKLE BRANCH & PROOF OF INCLUSION



MERKLE ROOT = H(E || F)

E = H(A || B)

F = H(C || D)

A = $H(TX_1)$

B = $H(TX_2)$

C = $H(TX_3)$

D = $H(TX_4)$

TX_1

TX_2

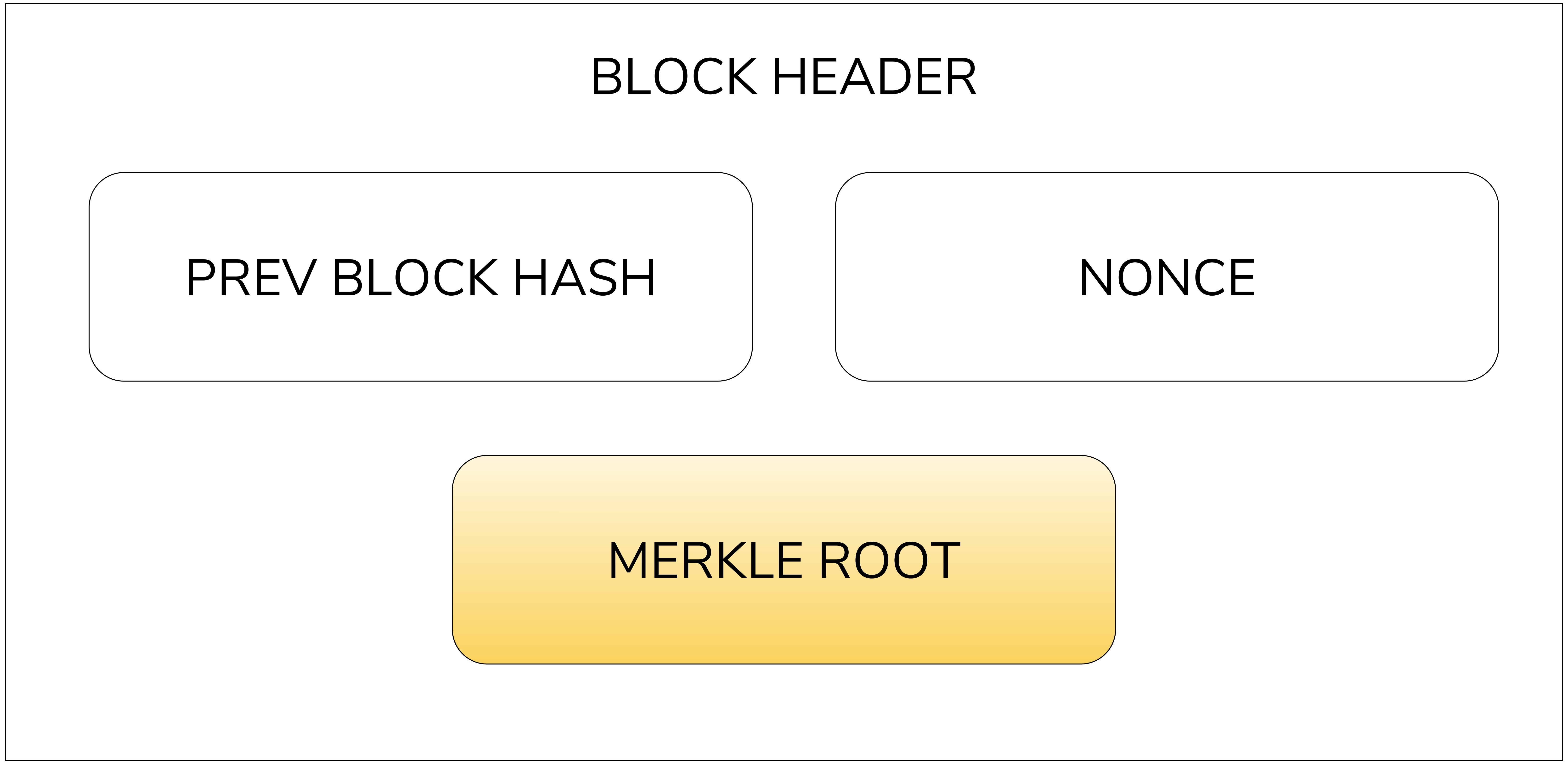
TX_3

TX_4

AUTHOR: NADIR AKHTAR

A TAMPER-EVIDENT DATABASE

MERKLE ROOT



BLOCK HEADER

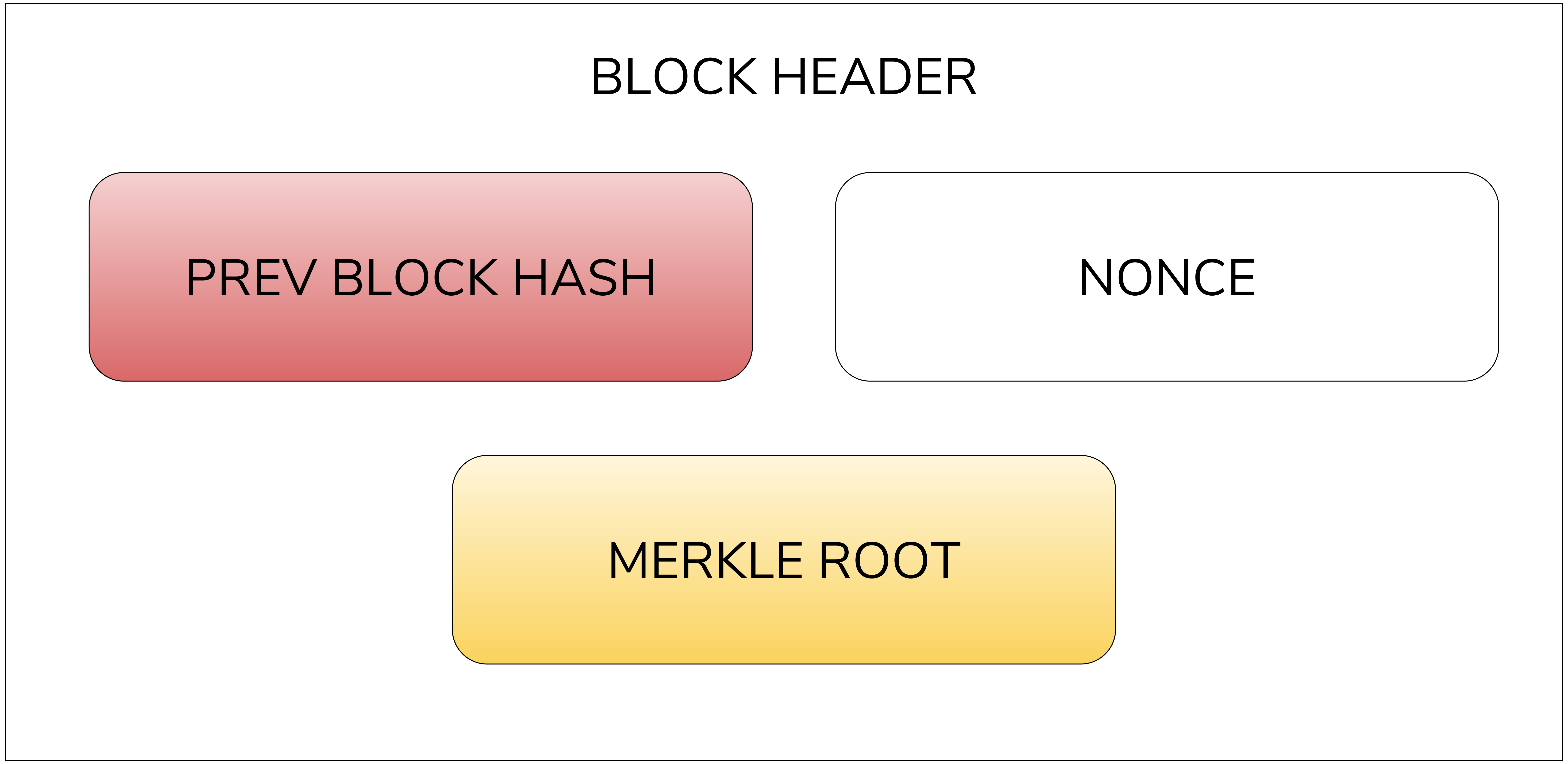
PREV BLOCK HASH

NONCE

MERKLE ROOT

A TAMPER-EVIDENT DATABASE

PREV BLOCK HASH


BLOCK HEADER

PREV BLOCK HASH

NONCE

MERKLE ROOT

A TAMPER-EVIDENT DATABASE

PROTECTING THE CHAIN

BLOCK HEADER
PREV BLOCK HASH
NONCE
MERKLE ROOT
BLOCK HEADER
PREV BLOCK HASH
NONCE
MERKLE ROOT
BLOCK HEADER
PREV BLOCK HASH
NONCE
MERKLE ROOT
SHA256(SHA256(x))

```
prevBlockHash = H(prevBlockHash || merkleRoot || nonce)
```

AUTHOR: NADIR AKHTAR

A TAMPER-EVIDENT DATABASE

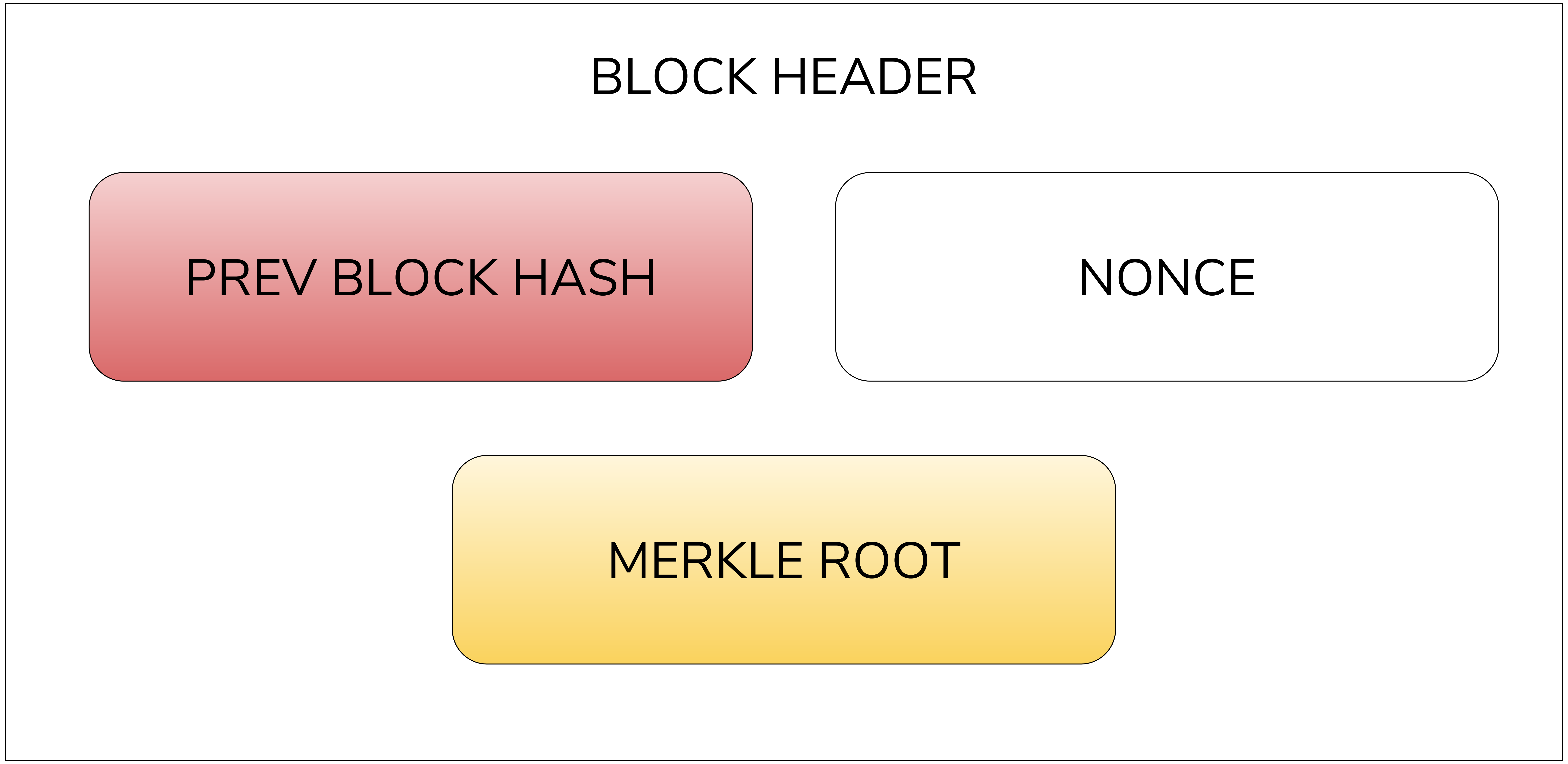
PROTECTING THE CHAIN

BLOCK HEADER
PREV BLOCK HASH
NONCE
MERKLE ROOT
BLOCK HEADER'
PREV BLOCK HASH
NONCE
MERKLE ROOT'
(TAMPERED)
BLOCK HEADER'
PREV BLOCK HASH'
NONCE
MERKLE ROOT
SHA256(SHA256(x))

```
prevBlockHash = H(prevBlockHash || merkleRoot || nonce)
```

A TAMPER-EVIDENT DATABASE

PREV BLOCK HASH



BLOCK HEADER

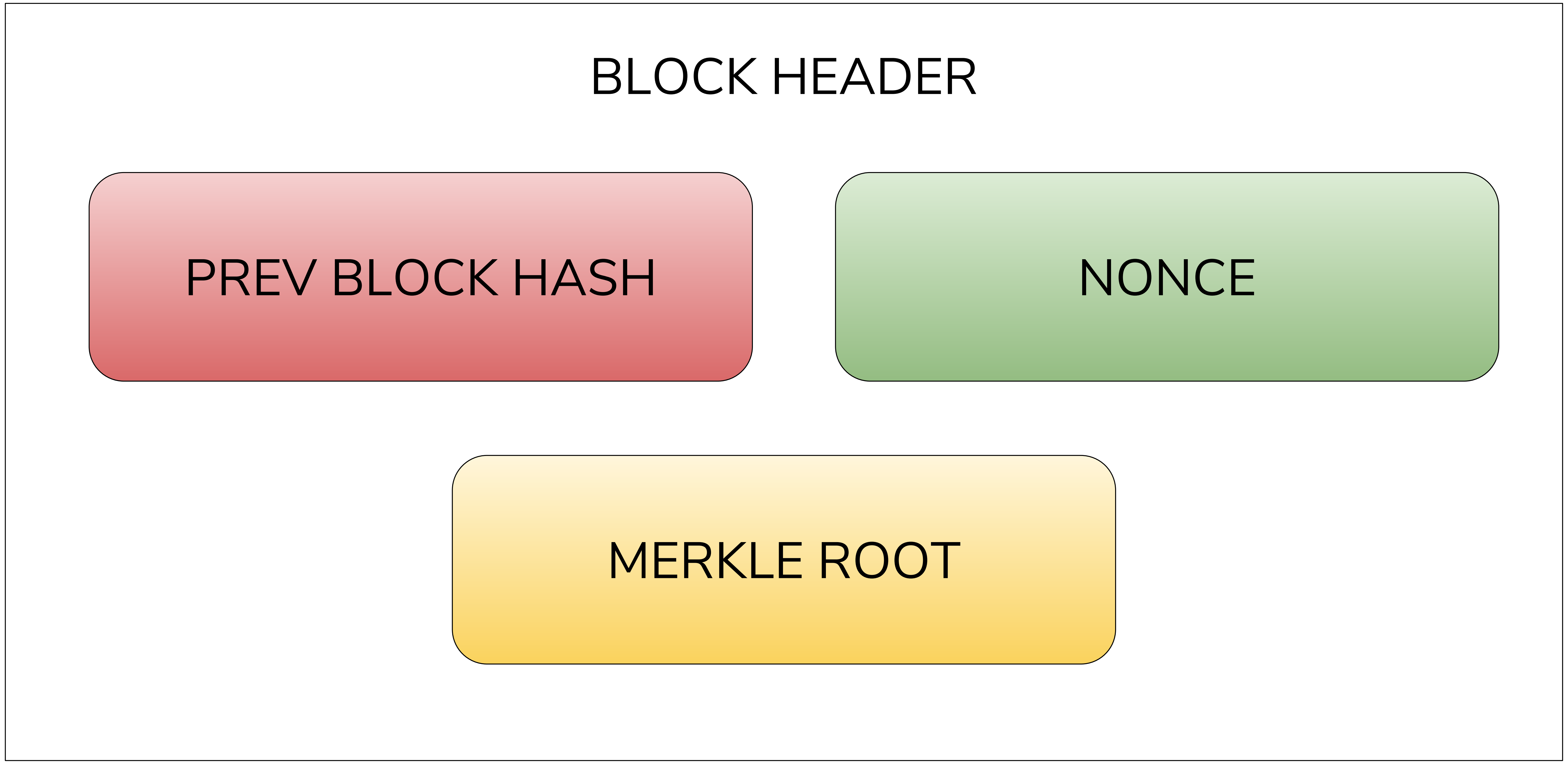
PREV BLOCK HASH

NONCE

MERKLE ROOT

A TAMPER-EVIDENT DATABASE

NONCE



A TAMPER-EVIDENT DATABASE

PARTIAL PREIMAGE HASH PUZZLE

Bitcoin's partial preimage hash puzzle: A problem with a requirement to find a nonce that satisfies the following inequality:

```
H(prevBlockHash || merkleRoot || nonce) < target
```

- Used to implement Proof-of-Work in Bitcoin (and every other PoW cryptocurrency)

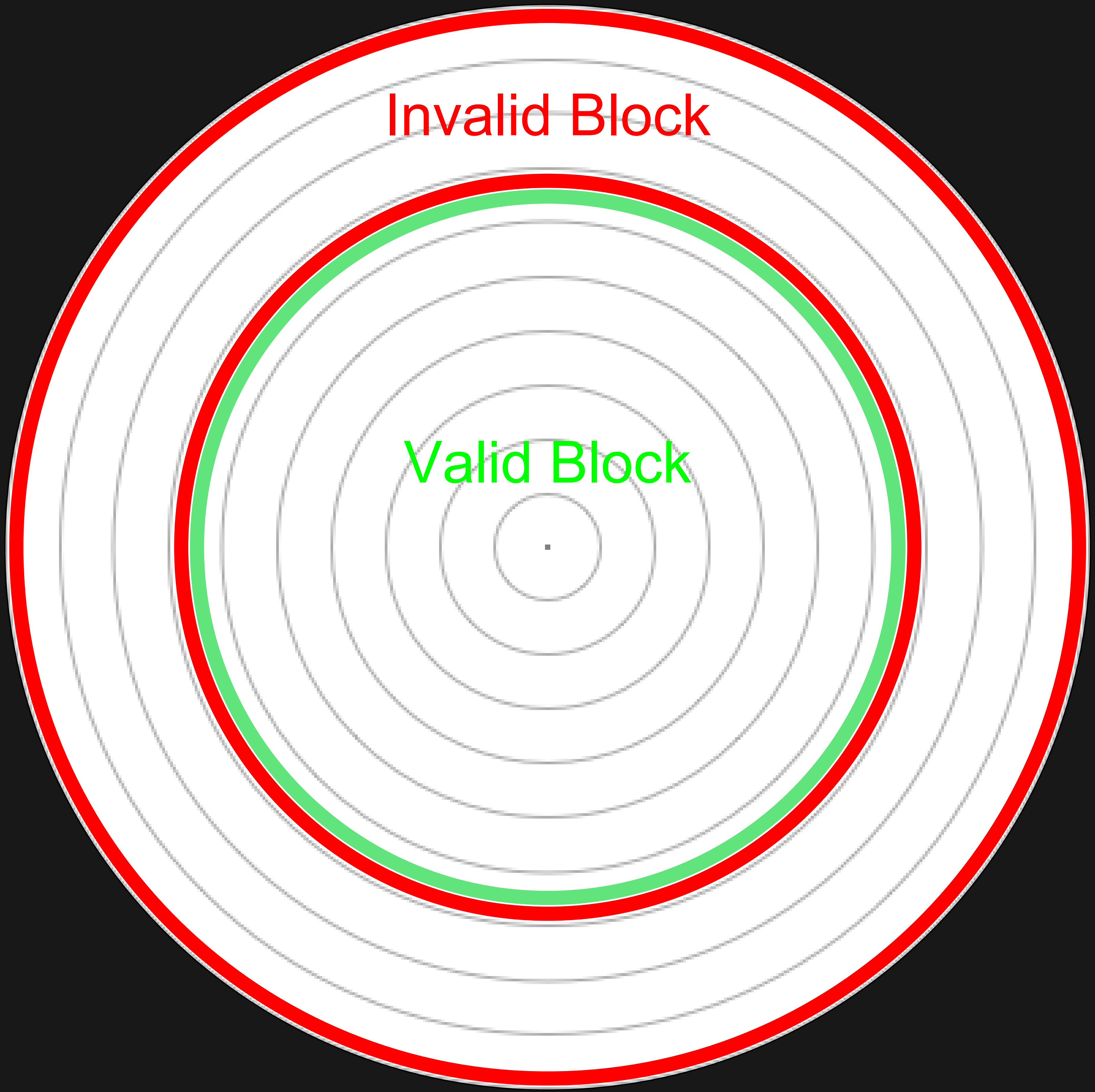
Hash puzzles need to be:

1. Computationally difficult.
2. Parameterizable.
3. Easily verifiable.

A TAMPER-EVIDENT DATABASE

MINING

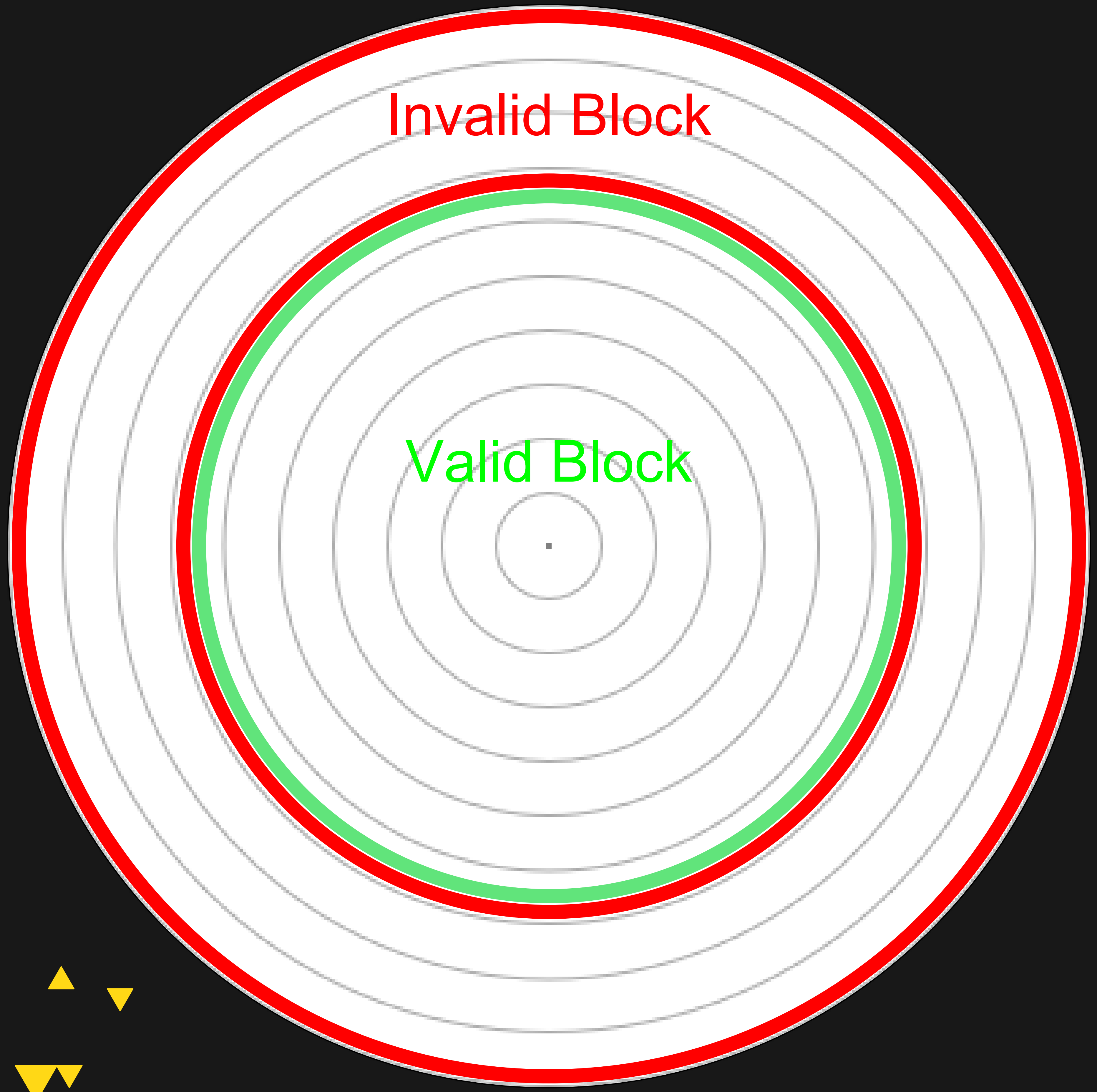
- **Mining** is like throwing darts at a target while blindfolded:
  - Equal likelihood of hitting any part of the target
  - Faster throwers ⇒ more hits / second
- Miners look for a hash below an algorithmically decided target



```
H(prevBlockHash || merkleRoot || nonce) < target
```

A TAMPER-EVIDENT DATABASE

BLOCK DIFFICULTY



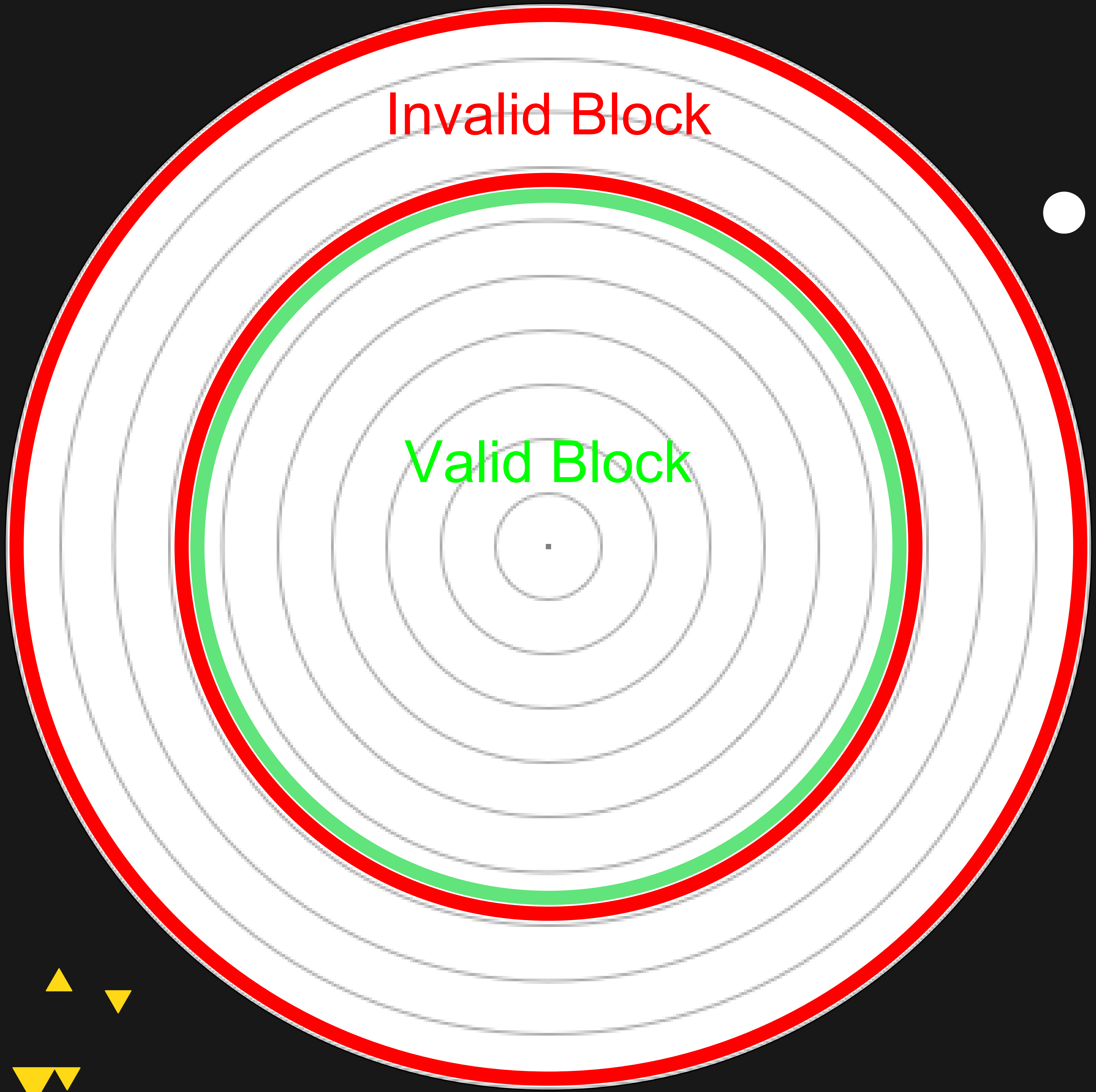
Difficulty: A representation of the expected number of computations required to find a block

- Implemented as requirement of leading number of 0s
- Adjusts with global hashrate
- `difficulty *= two_weeks / time_to_mine_prev_2016_blocks`
  - Technically every 2015 blocks

```
H(prevBlockHash || merkleRoot || nonce) < target
```

A TAMPER-EVIDENT DATABASE

BLOCK DIFFICULTY

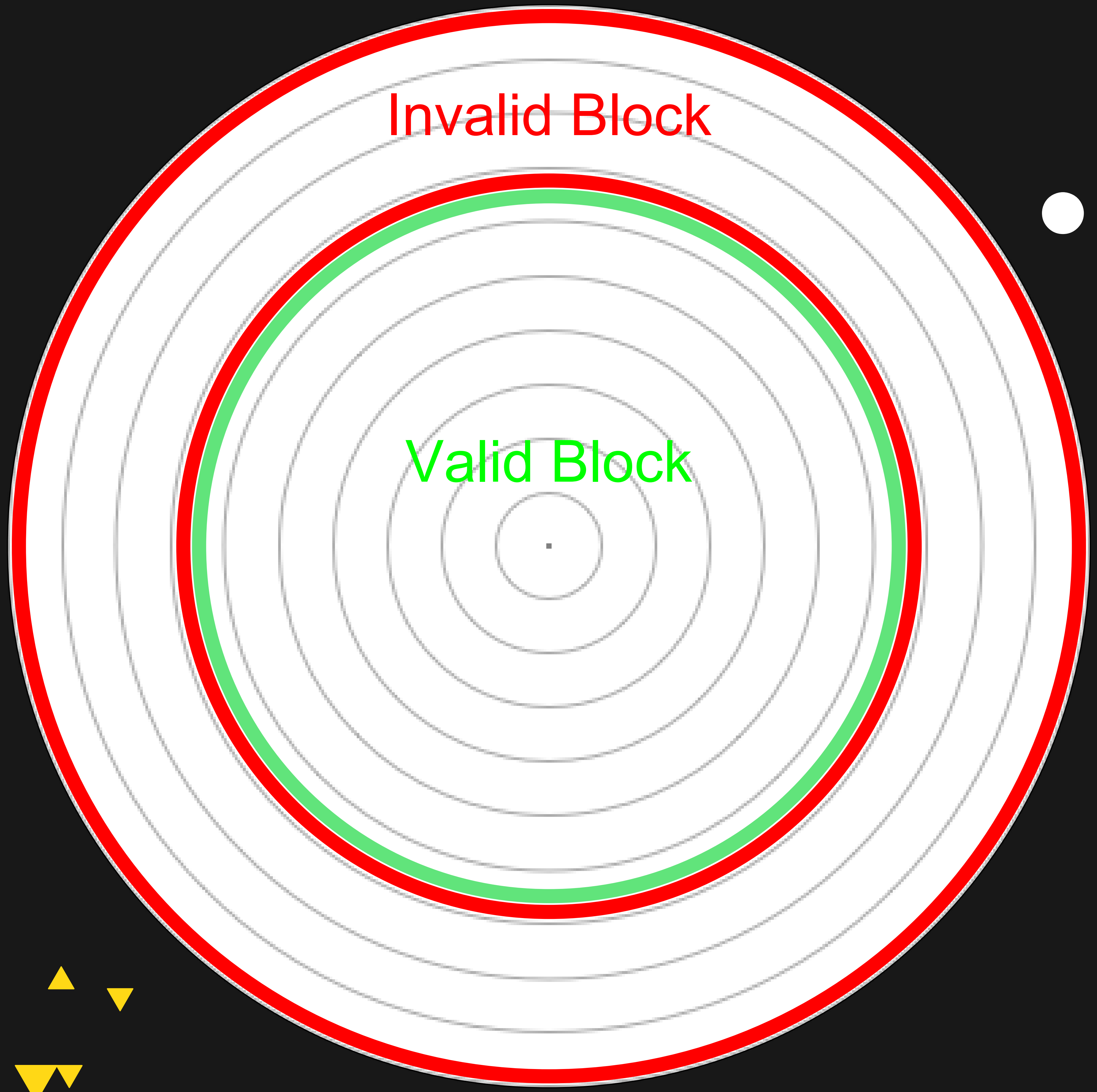


- **Sanity check** (difficulty = 10):
    - What is the new difficulty when `two_weeks` = `time_to_mine_prev_2016_blocks?`

```
difficulty *= two_weeks / time_to_mine_prev_2016_blocks
```

A TAMPER-EVIDENT DATABASE

BLOCK DIFFICULTY

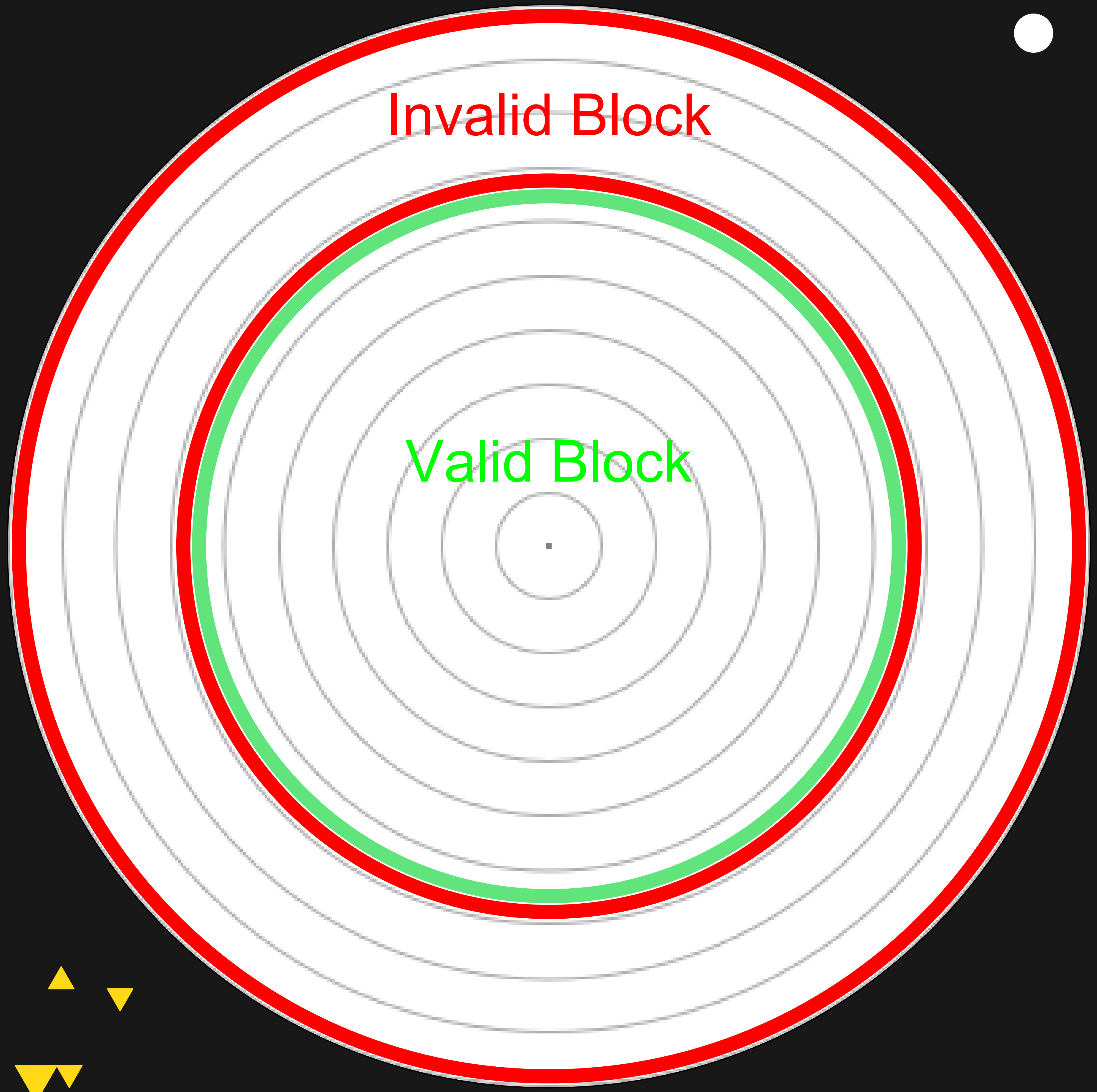


- **Sanity check** (difficulty = 10):
  - What is the new difficulty when `two_weeks` = `time_to_mine_prev_2016_blocks`?
    (Answer: 10. Difficulty stays the same!)

```
difficulty *= two_weeks / time_to_mine_prev_2016_blocks
```

A TAMPER-EVIDENT DATABASE

BLOCK DIFFICULTY

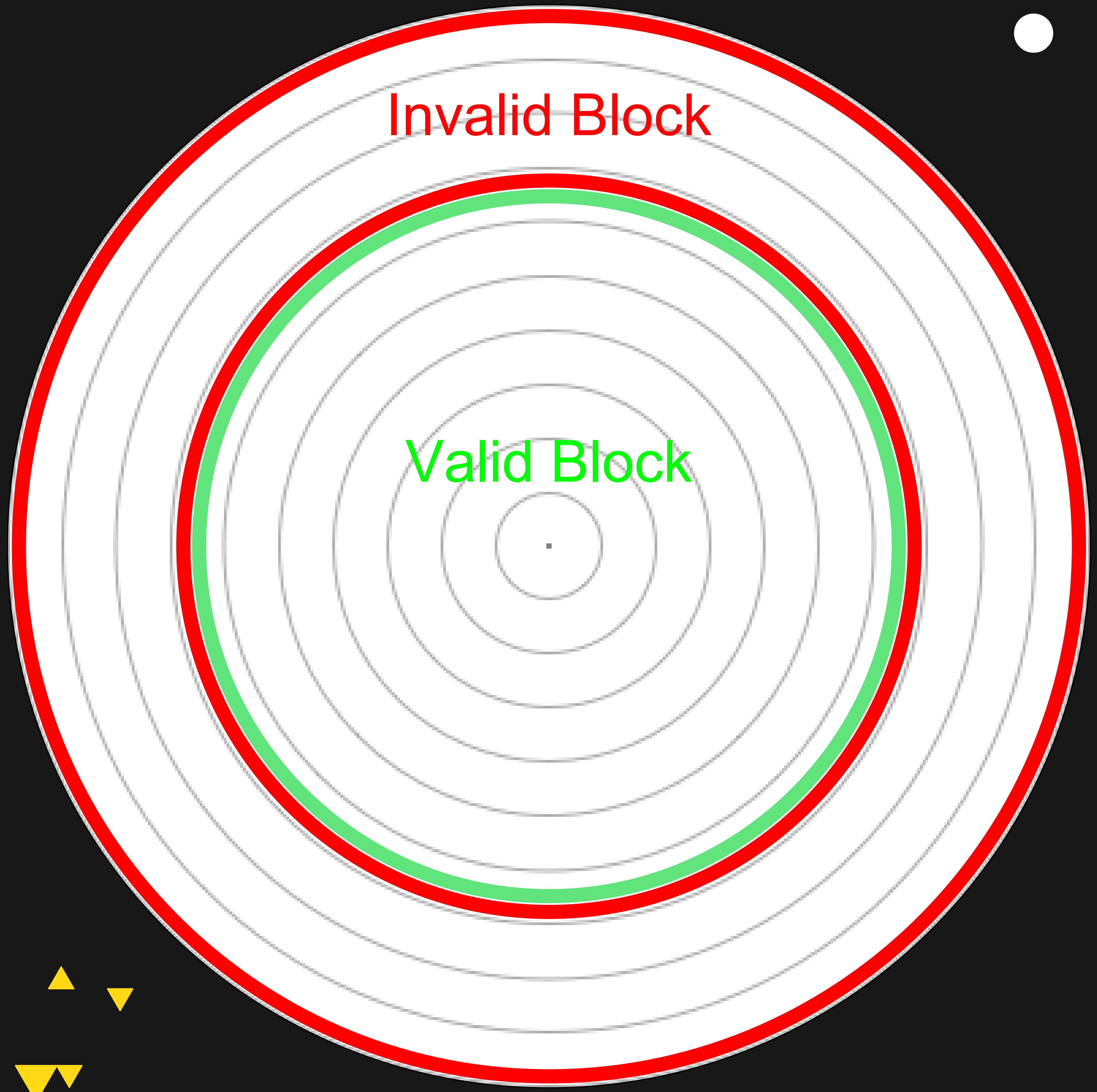


- **Sanity check** (difficulty = 10):
  - What does difficulty equal when:
    - `time_to_mine = one_week?`
    - `time_to_mine = four_weeks?`

```
difficulty *= two_weeks / time_to_mine_prev_2016_blocks
```

A TAMPER-EVIDENT DATABASE

BLOCK DIFFICULTY

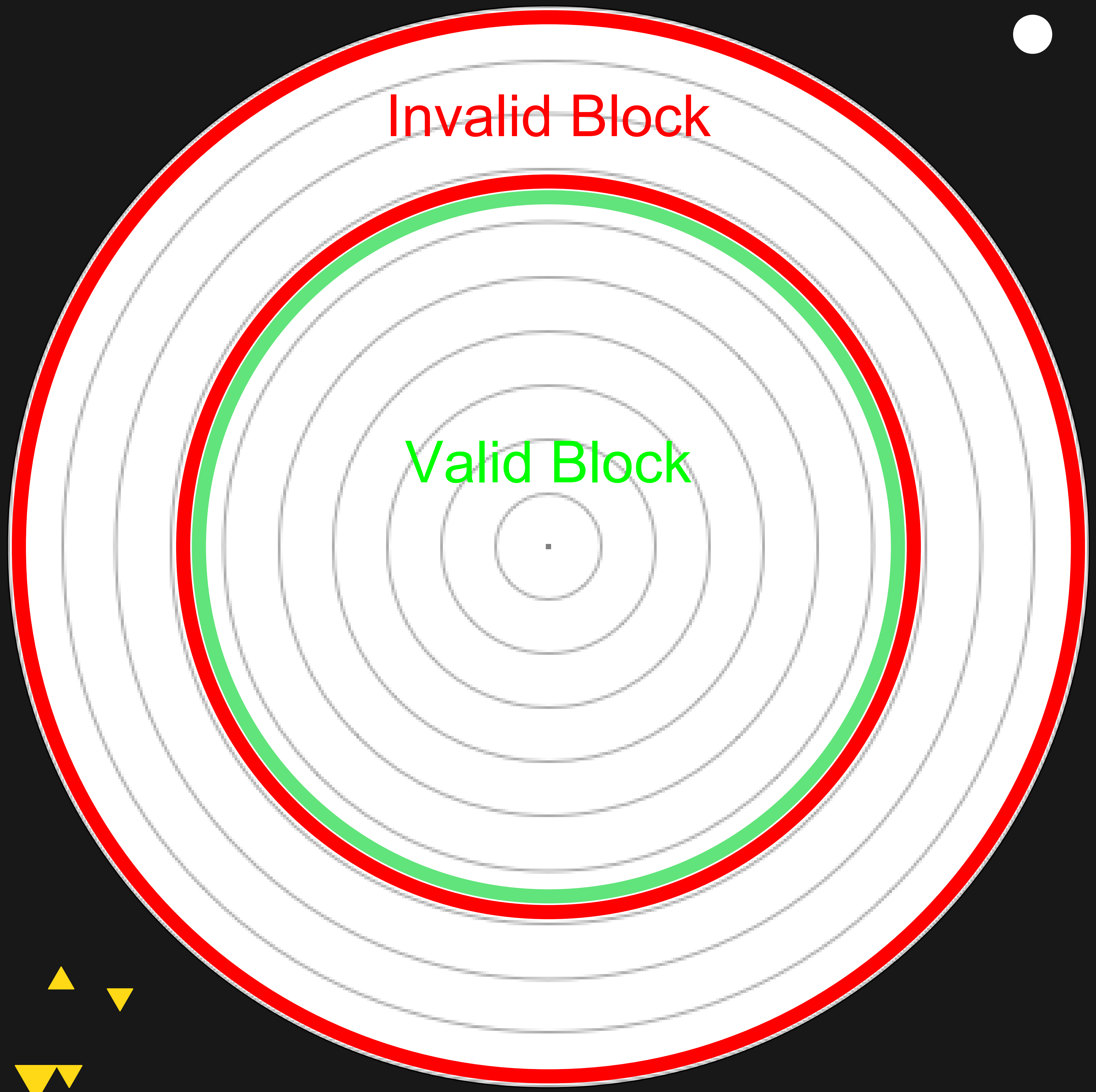


- **Sanity check** (difficulty = 10):
  - What does difficulty equal when:
    - `time_to_mine = one_week?`
      (Answer: 20)
    - `time_to_mine = four_weeks?`

```
difficulty *= two_weeks / time_to_mine_prev_2016_blocks
```

A TAMPER-EVIDENT DATABASE

BLOCK DIFFICULTY



- **Sanity check** (difficulty = 10):
  - What does difficulty equal when:
    - `time_to_mine = one_week?`

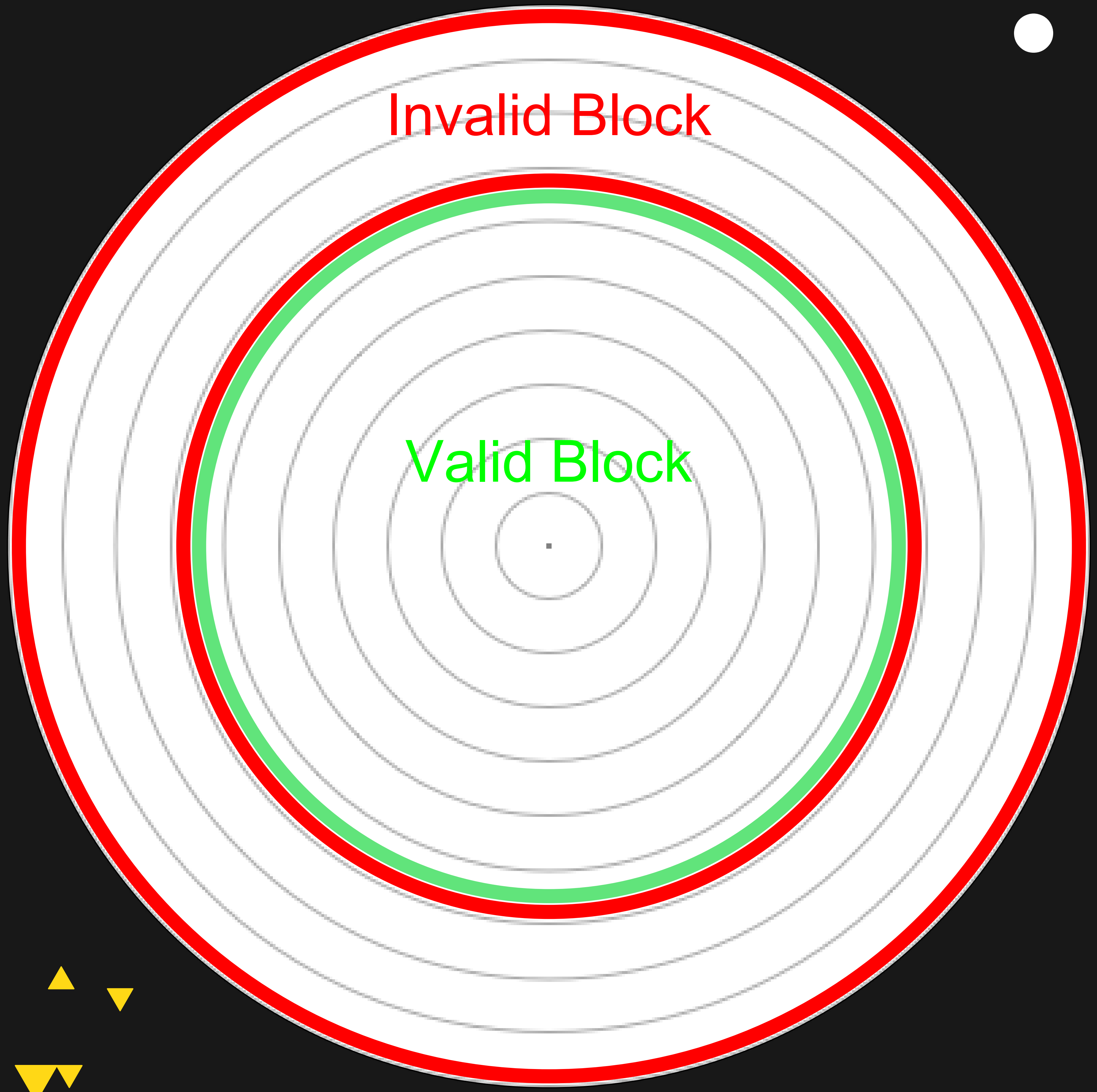
      (Answer: 20)
    - `time_to_mine = four_weeks?`

      (Answer: 5)

```
difficulty *= two_weeks / time_to_mine_prev_2016_blocks
```

A TAMPER-EVIDENT DATABASE

BLOCK DIFFICULTY



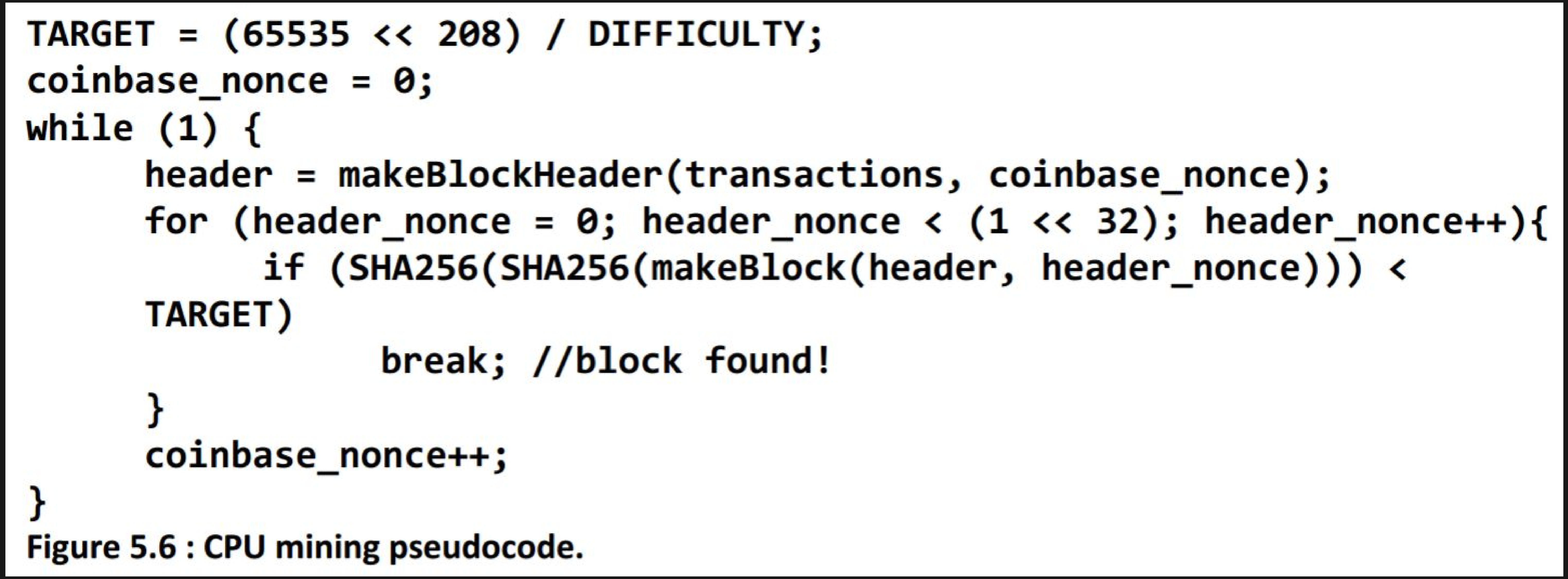
- **Sanity check** (difficulty = 10):
  - What does difficulty equal when:
    - `time_to_mine = one_week?` (Answer: 20)
    - `time_to_mine = four_weeks?` (Answer: 5)
  - Difficulty is inversely proportional to `time_to_mine`.)

```
difficulty *= two_weeks / time_to_mine_prev_2016_blocks
```

AUTHOR: NADIR AKHTAR

A TAMPER-EVIDENT DATABASE

MINING PSEUDOCODE



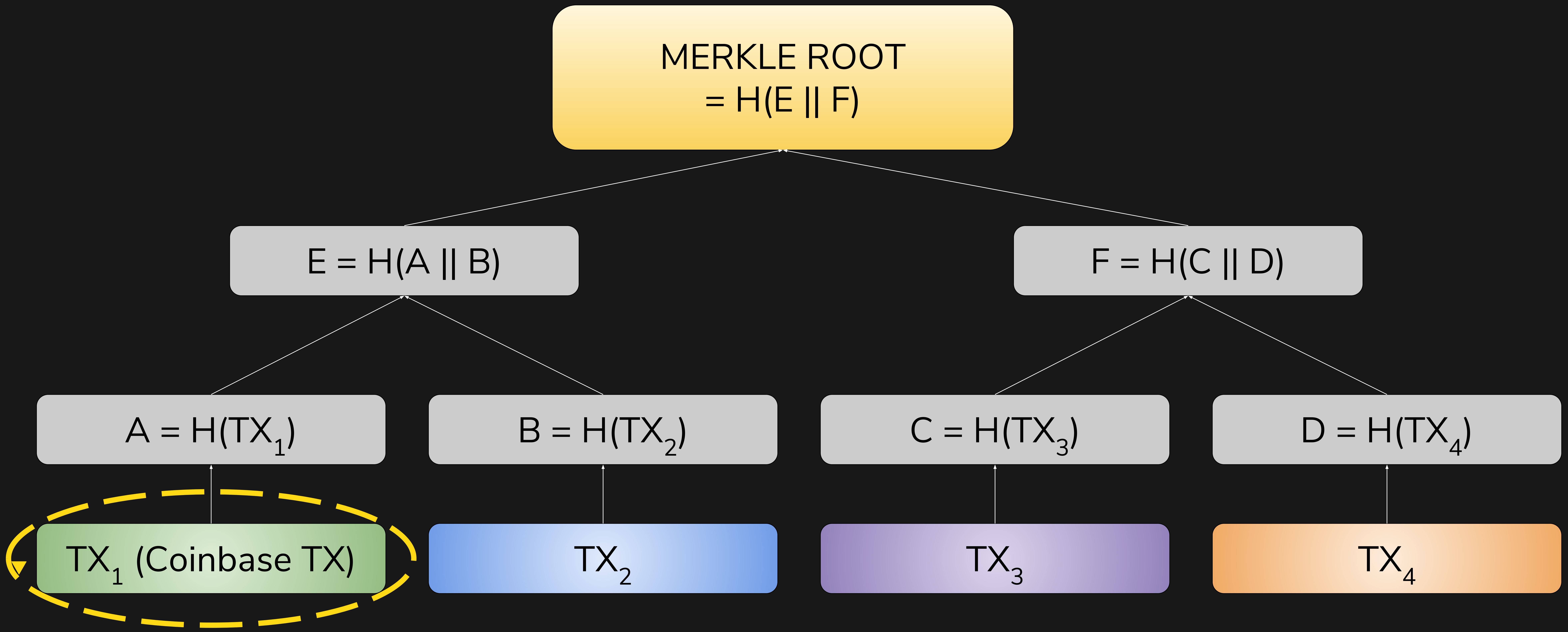
```
TARGET = (65535 << 208) / DIFFICULTY;
coinbase_nonce = 0;
while (1) {
        header = makeBlockHeader(transactions, coinbase_nonce);
        for (header_nonce = 0; header_nonce < (1 << 32); header_nonce++){
                if (SHA256(SHA256(makeBlock(header, header_nonce))) <
        TARGET)
                        break; //block found!
        }
        coinbase_nonce++;
}
```

Figure 5.6 : CPU mining pseudocode.

Source: (from Princeton Textbook, 5.2)

A TAMPER-EVIDENT DATABASE

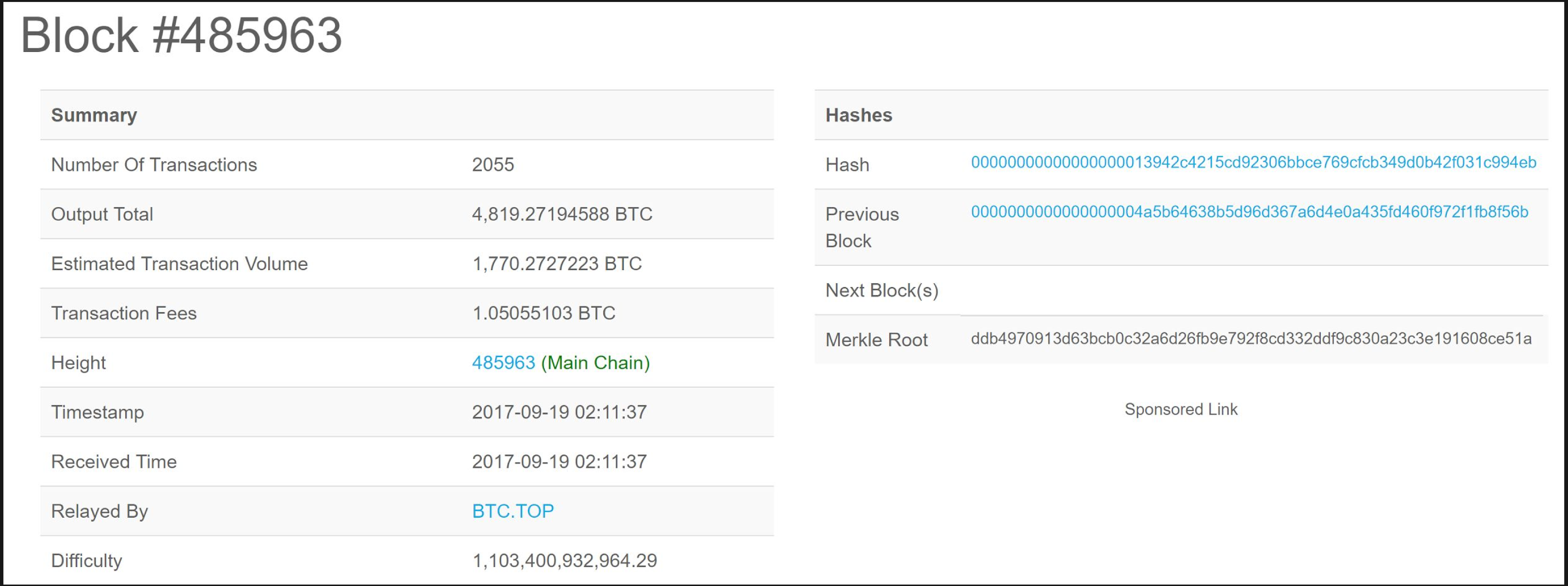
COINBASE TRANSACTION



AUTHOR: NADIR AKHTAR

A TAMPER-EVIDENT DATABASE

EXAMPLE BLOCK



Block #485963

Summary	
Number Of Transactions	2055
Output Total	4,819.27194588 BTC
Estimated Transaction Volume	1,770.2727223 BTC
Transaction Fees	1.05055103 BTC
Height	485963 (Main Chain)
Timestamp	2017-09-19 02:11:37
Received Time	2017-09-19 02:11:37
Relayed By	BTC.TOP
Difficulty	1,103,400,932,964.29

Hashes	
Hash	00000000000000000013942c4215cd92306bbce769cfcb349d0b42f031c994eb
Previous Block	0000000000000000004a5b64638b5d96d367a6d4e0a435fd460f972f1fb8f56b
Next Block(s)	
Merkle Root	ddb4970913d63bcb0c32a6d26fb9e792f8cd332ddf9c830a23c3e191608ce51a

Sponsored Link

Source: https://blockchain.info/block/00000000000000000013942c4215cd92306bbce769cfcb349d0b42f031c994eb

AUTHOR: NADIR AKHTAR

3 SIGS, ECDSA, AND ADDRESSES

DIGITAL SIGNATURE SCHEMES (DSS)

EXAMPLE

ALICE

BOB

private key:

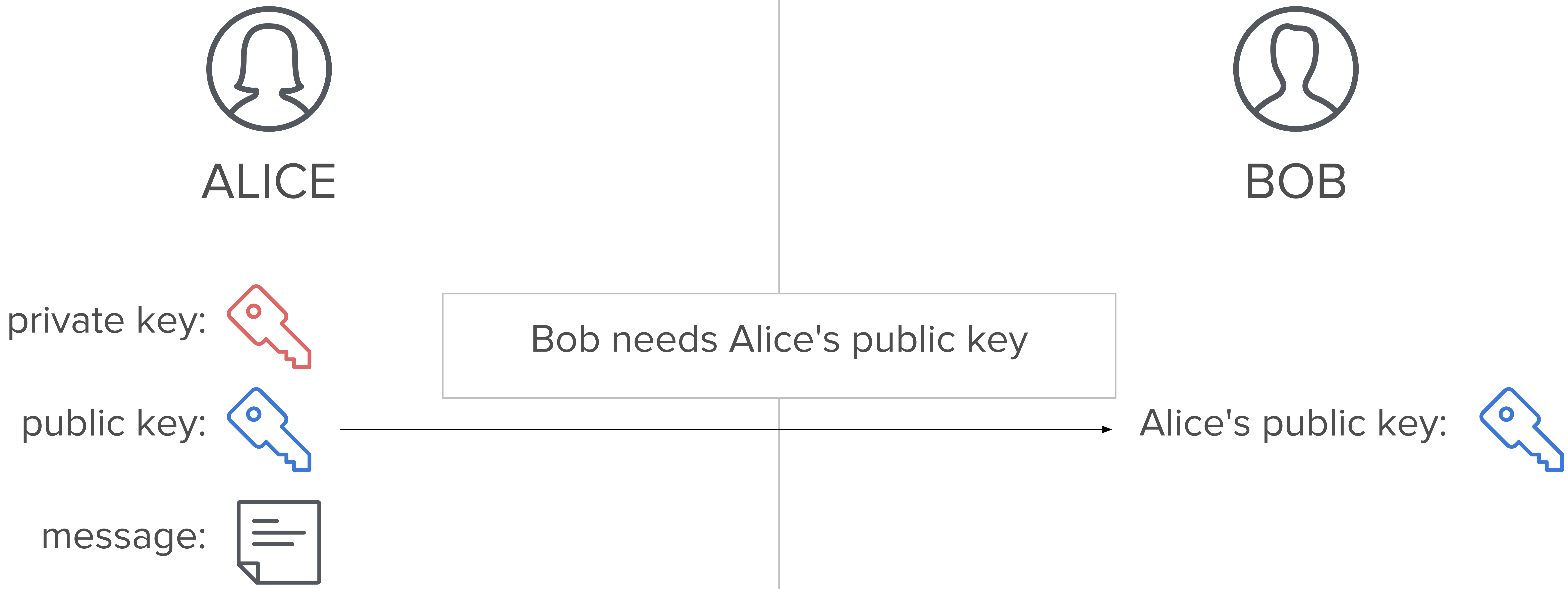
public key:

message:

Alice uses ECDSA to generate private and public keys

DIGITAL SIGNATURE SCHEMES (DSS)

EXAMPLE



ALICE

BOB

private key:

public key:

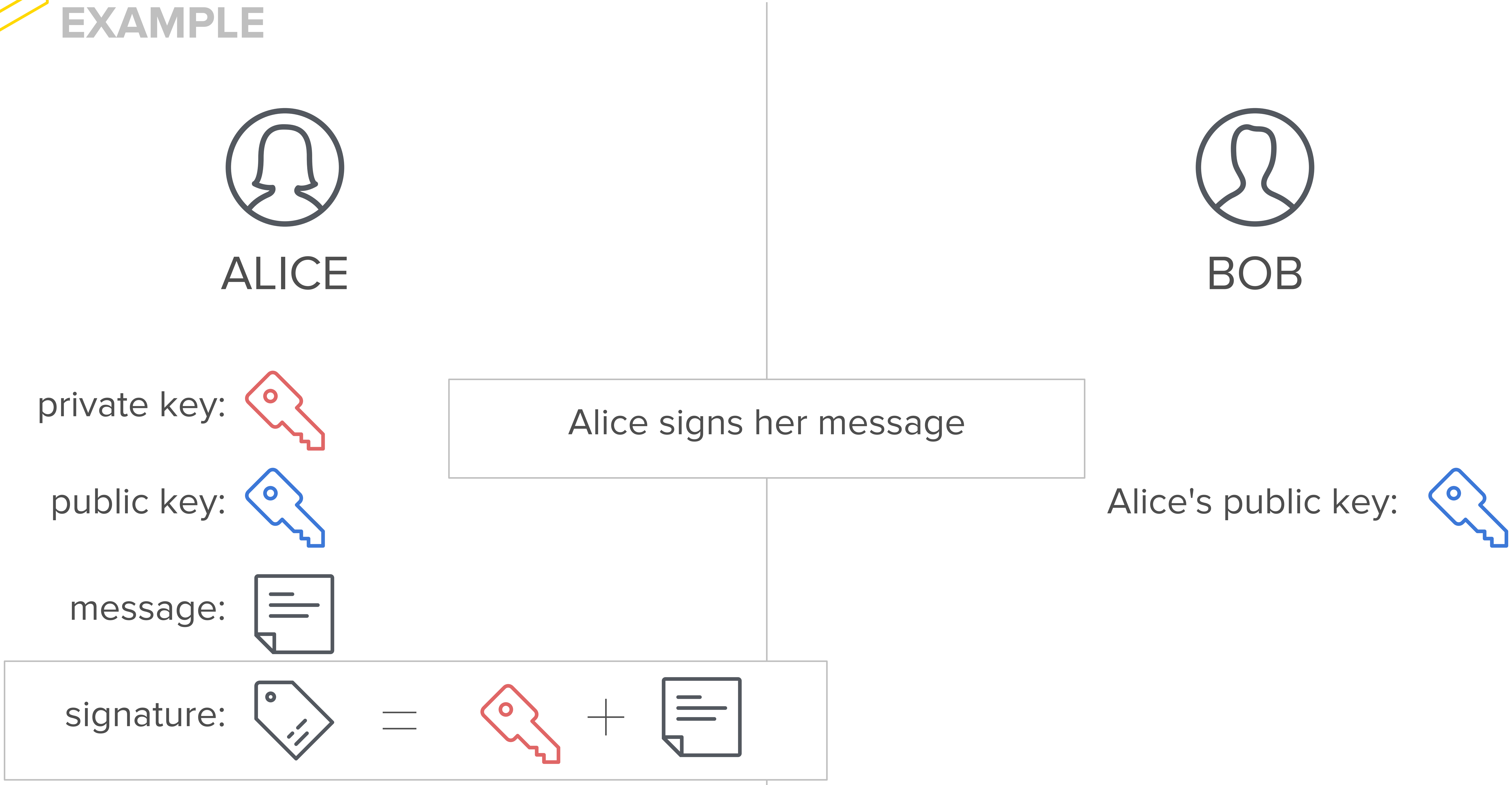
message:

Bob needs Alice's public key

Alice's public key:

DIGITAL SIGNATURE SCHEMES (DSS)

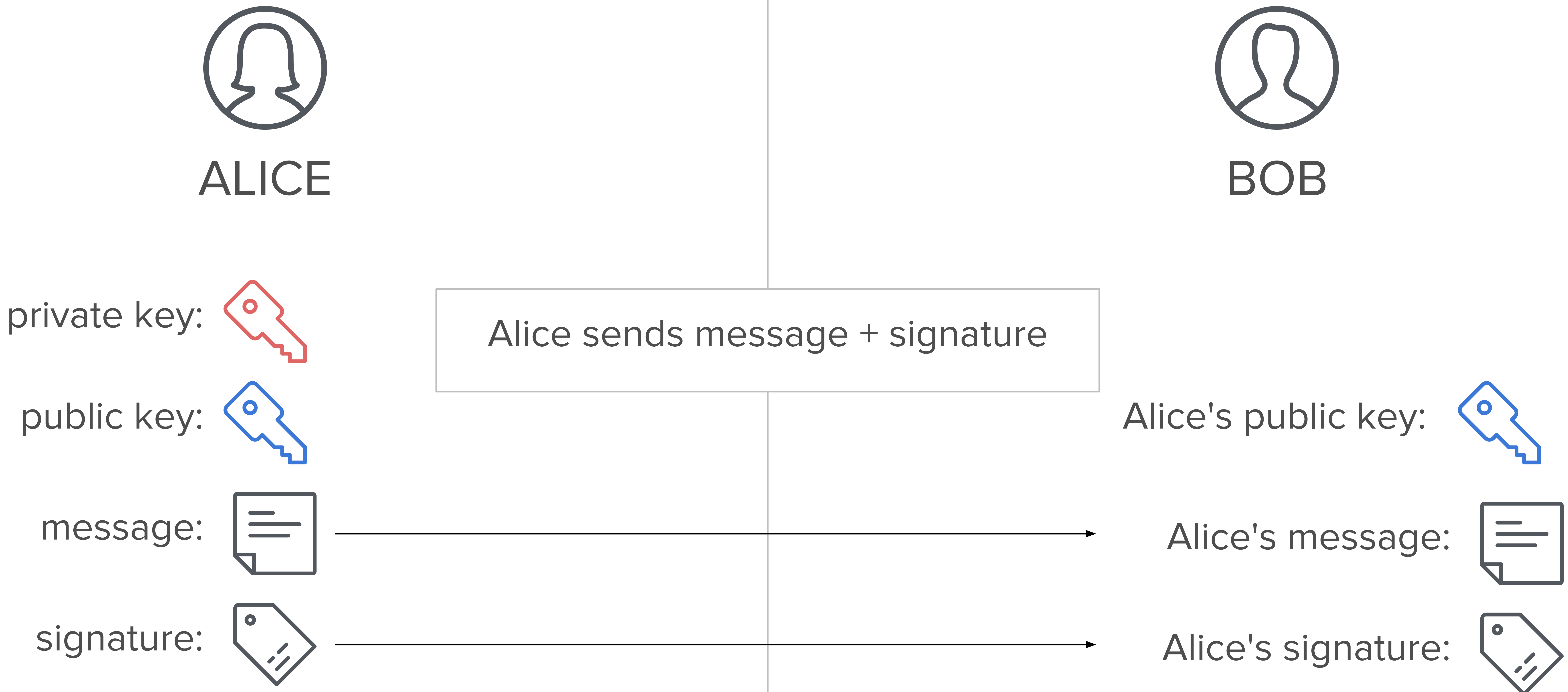
EXAMPLE



Alice signs her message

DIGITAL SIGNATURE SCHEMES (DSS)

EXAMPLE



ALICE

BOB

private key:

public key:

message:

signature:

Alice sends message + signature

Alice's public key:

Alice's message:

Alice's signature:

DIGITAL SIGNATURE SCHEMES (DSS)

EXAMPLE

ALICE

private key: 🔑

public key: 🔑

message: 📄

signature: 🏷

Bob can easily verify if Alice signed

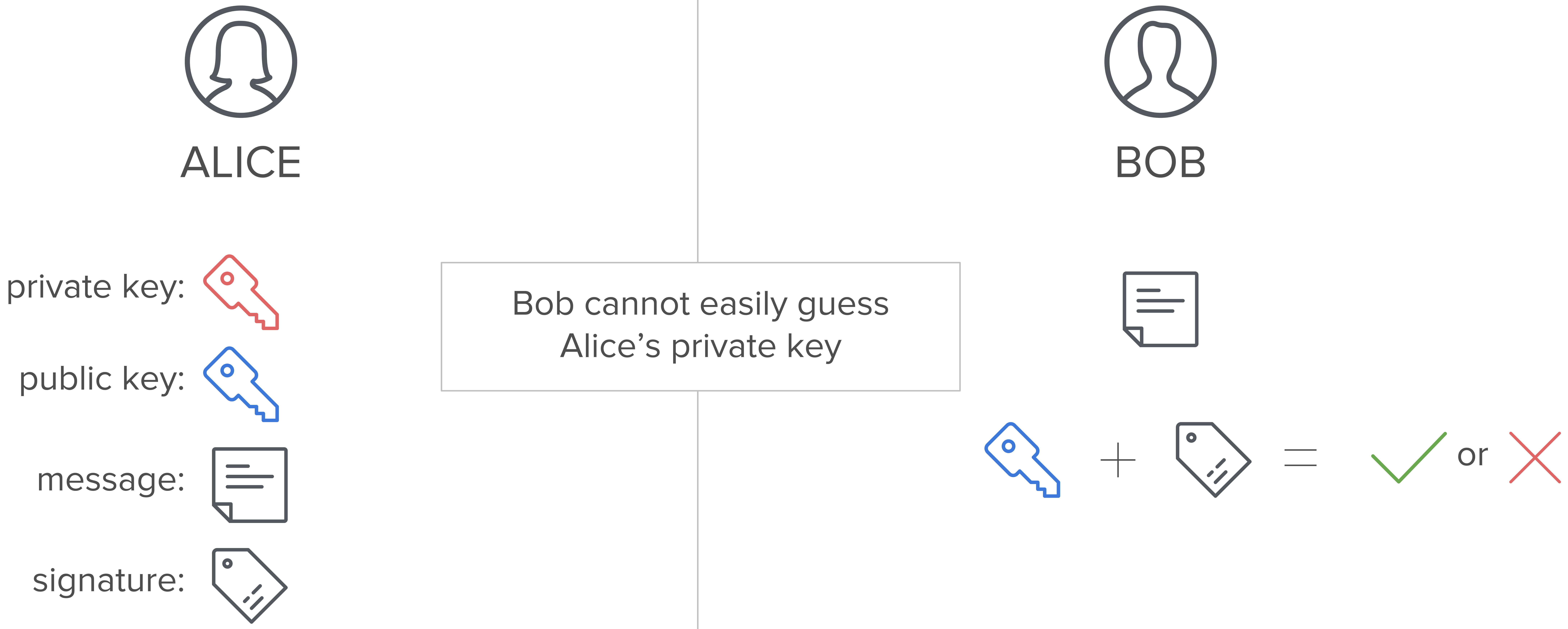
BOB

📄

🔑 + 🏷 = ✓ or ✗

DIGITAL SIGNATURE SCHEMES (DSS)

EXAMPLE



Bob cannot easily guess Alice's private key

AUTHOR: PHILIP HAYES

DIGITAL SIGNATURE SCHEMES (DSS)

DSS SECURITY DEFINITION

Recipients given the (message, signature) pair should be able to verify:

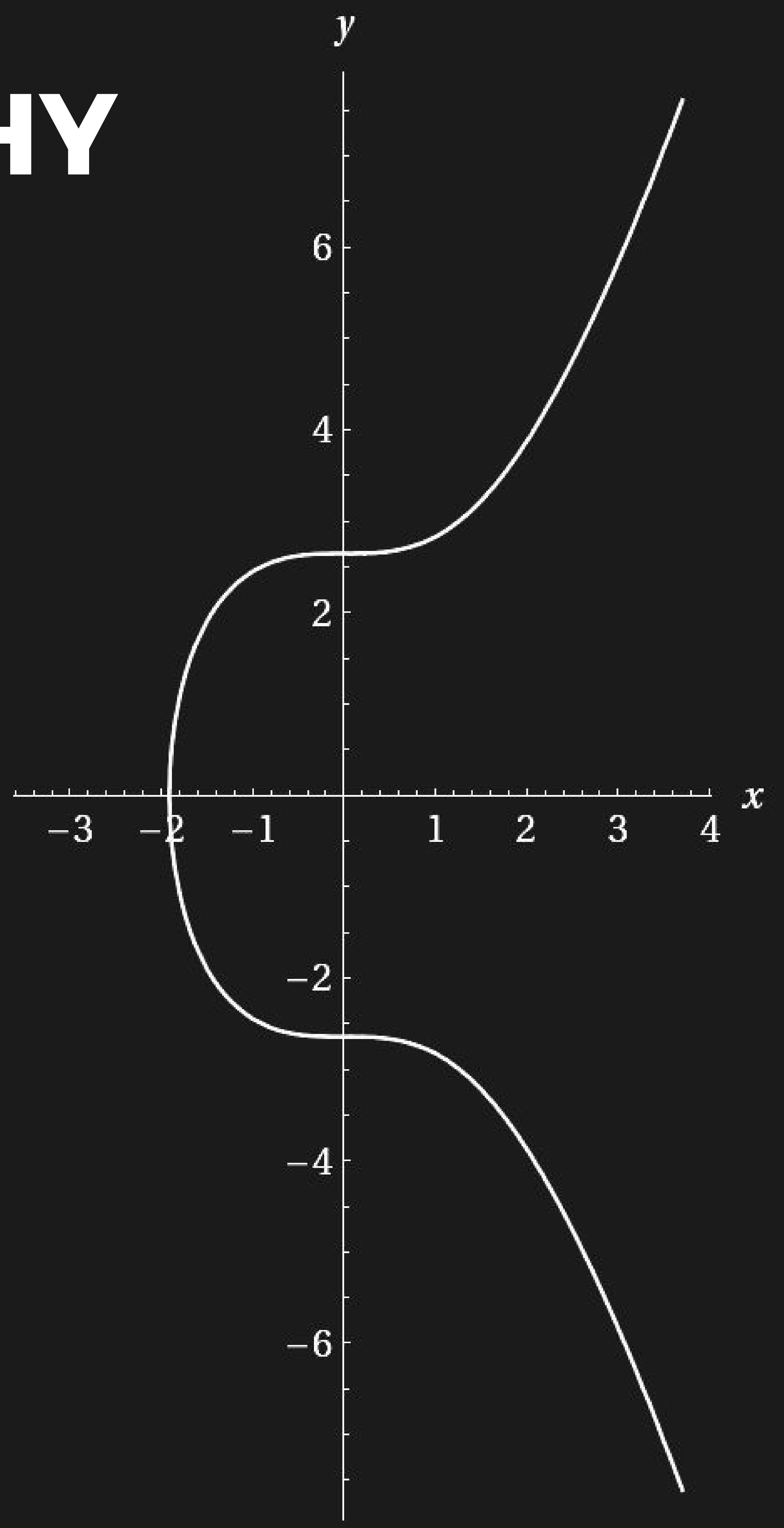
- **Message Origin**: original sender (owner of private key) has authorized this message/transaction
- **Non-repudiation**: original sender (owner of private key) cannot backtrack
- **Message Integrity**: message cannot have been modified since sending

ELLIPTIC CURVE CRYPTOGRAPHY

PART 1: ELLIPTIC CURVE

- Bitcoin uses **ECDSA** (Elliptic Curve Digital Signature Algorithm) to produce private and public keys
- The Elliptic Curve is defined by some mathematical function
  - **Bitcoin's Elliptic Curve**:

    secp256k1 : $Y^2 = (X^3 + 7)$ over $(\mathbf{F}_p)$
- For cryptographic purposes, we use elliptic curves over a **finite field** (for key size)



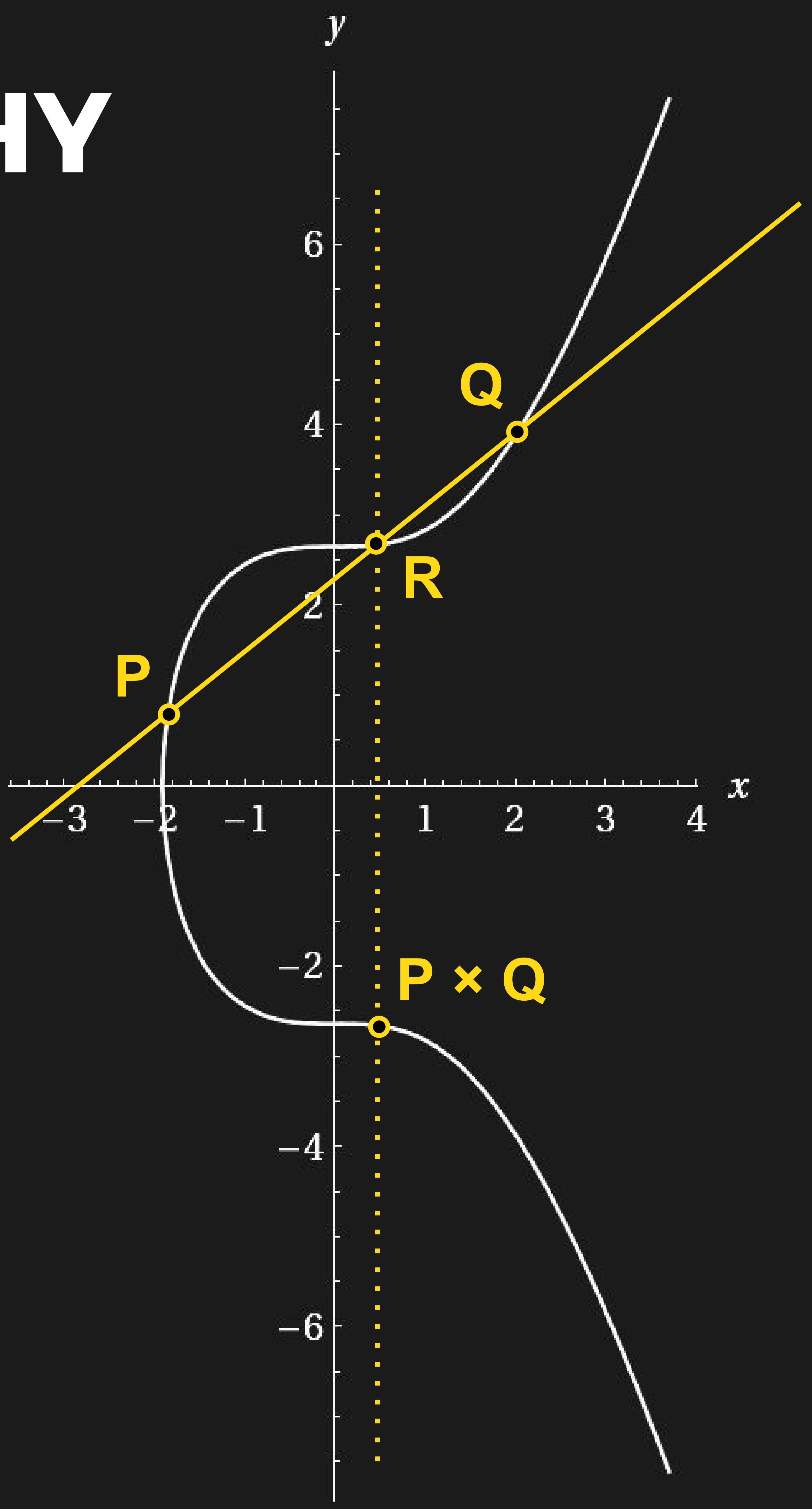
y^2 = x^3 + 7 | Computed by Wolfram|Alpha

AUTHOR: PHILIP HAYES & GLORIA ZHAO

ELLIPTIC CURVE CRYPTOGRAPHY

PART 2: CHORD-TANGENT PROCESS

- We can do “multiplication” repeatedly using lines and points on our elliptic curve, a trapdoor function
  - We define a group law on an elliptic curve using the **chord-tangent process - “point multiplication”**
- Given two different elliptic curve points, **P** and **Q**, we define **P × Q** by:
  - Using the line intersecting **P** and **Q** to find final point, **R**
  - Reflecting **R** across the x-axis to obtain another point defined as **P × Q**
- We do this ***m*** (very large) times: $\mathbf{P^m = P \times P \times P \times P \times \ldots \times P}$



y^2 = x^3 + 7 | Computed by Wolfram|Alpha

AUTHOR: PHILIP HAYES & GLORIA ZHAO

ELLIPTIC CURVE CRYPTOGRAPHY

PART 3: SECURITY OF ECC - TRAPDOOR FUNCTION

- ECDSA generates private and public keys in Bitcoin:

private key = m

public key = $\mathbf{P^m}$ = P × P × P × P × … × P

address = *RIPEMD160*(*SHA256*(P^m))

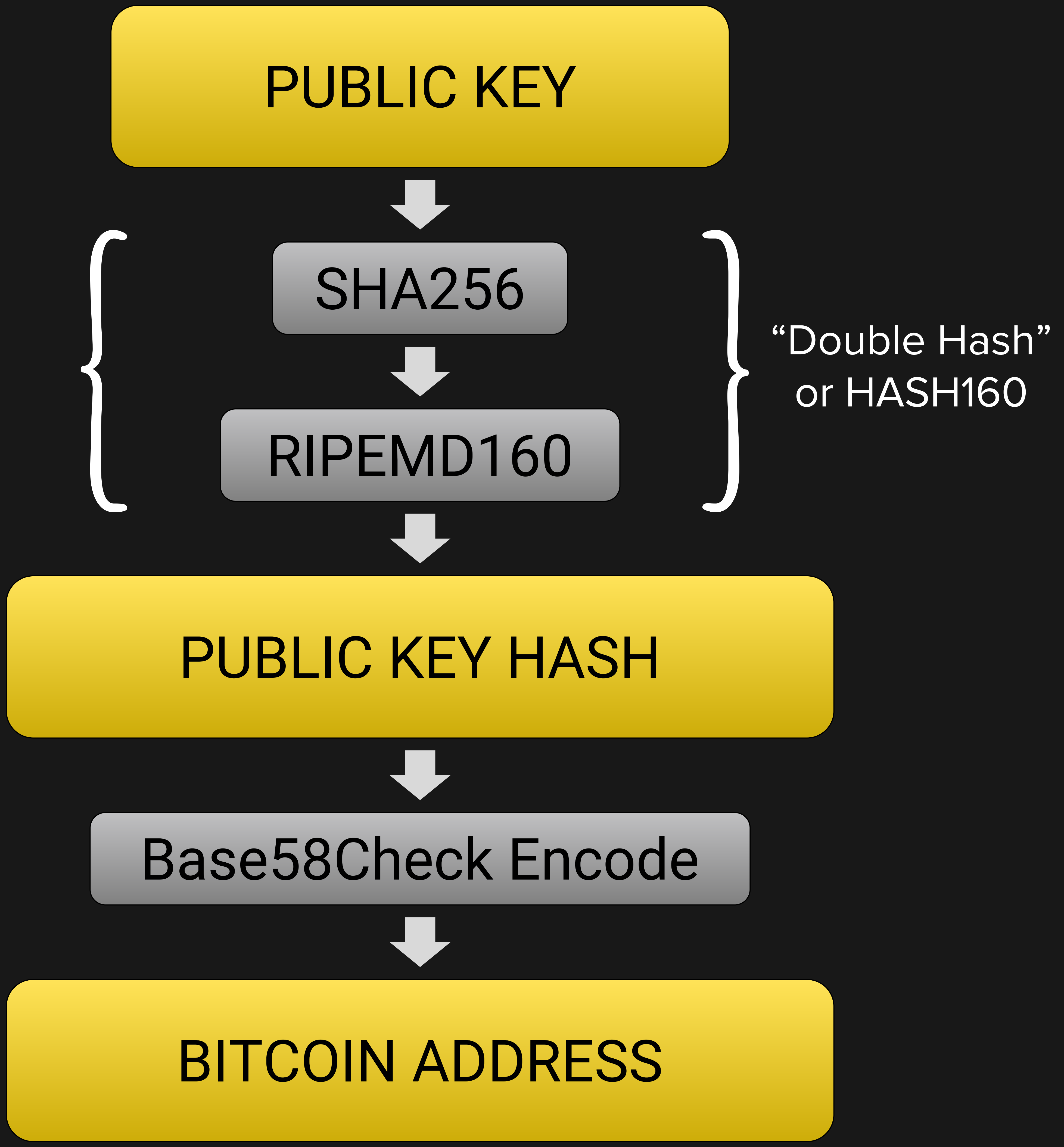
- How can we get m from P^m?

$$m = \log_m (P^m) ?$$

- ⇒ **Discrete Logarithm Problem** is computationally infeasible (over certain fields and curves), thus ECC is a "trapdoor function"
    - no sub-exponential time algorithm

PUBLIC KEY TO BITCOIN ADDRESS

PUBLIC KEY TO PUBKEYHASH



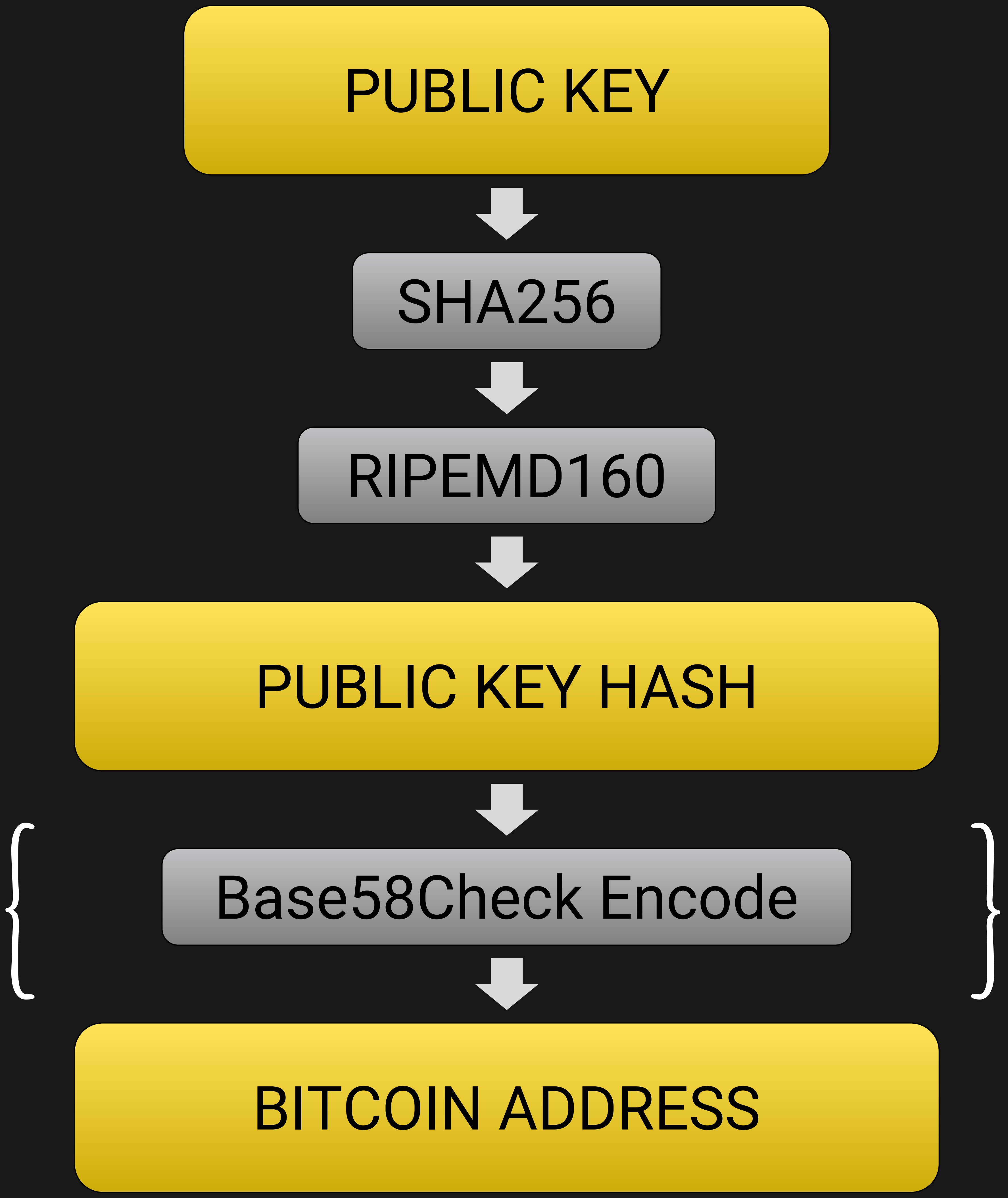
```
PUBKEYHASH = RIPEMD160(SHA256(K))
```

- where K = public key
- SHA-256 (Secure Hashing Algorithm)
  - Used extensively in bitcoin scripts and mining
- RIPEMD (RACE Integrity Primitives Evaluation Message Digest)
  - Produces 160-bit (20-byte) number

AUTHOR: GLORIA ZHAO

PUBLIC KEY TO BITCOIN ADDRESS

PUBLIC KEY HASH TO ADDRESS



PUBLIC KEY

SHA256

RIPEMD160

PUBLIC KEY HASH

Base58Check Encode

BITCOIN ADDRESS

- Bitcoin Addresses are Base58Check Encoded
  - Base-58 alphabet: 1234567890ABCDEFGHIJKLMNOPQRSTUVW XYZabcdefghijklmnopqrstuvwxyz
  - 58 characters (omits 0, O, I, l)
- prefix: “version byte” based on type of data
  - makes it easy for people to read address
- checksum: 4-byte error-checking code appended to the end of an address
  - `checksum = SHA256(SHA256(prefix + data)`, first 4 bytes
  - Decoding software uses checksum to validate address

4

BITCOIN SCRIPT

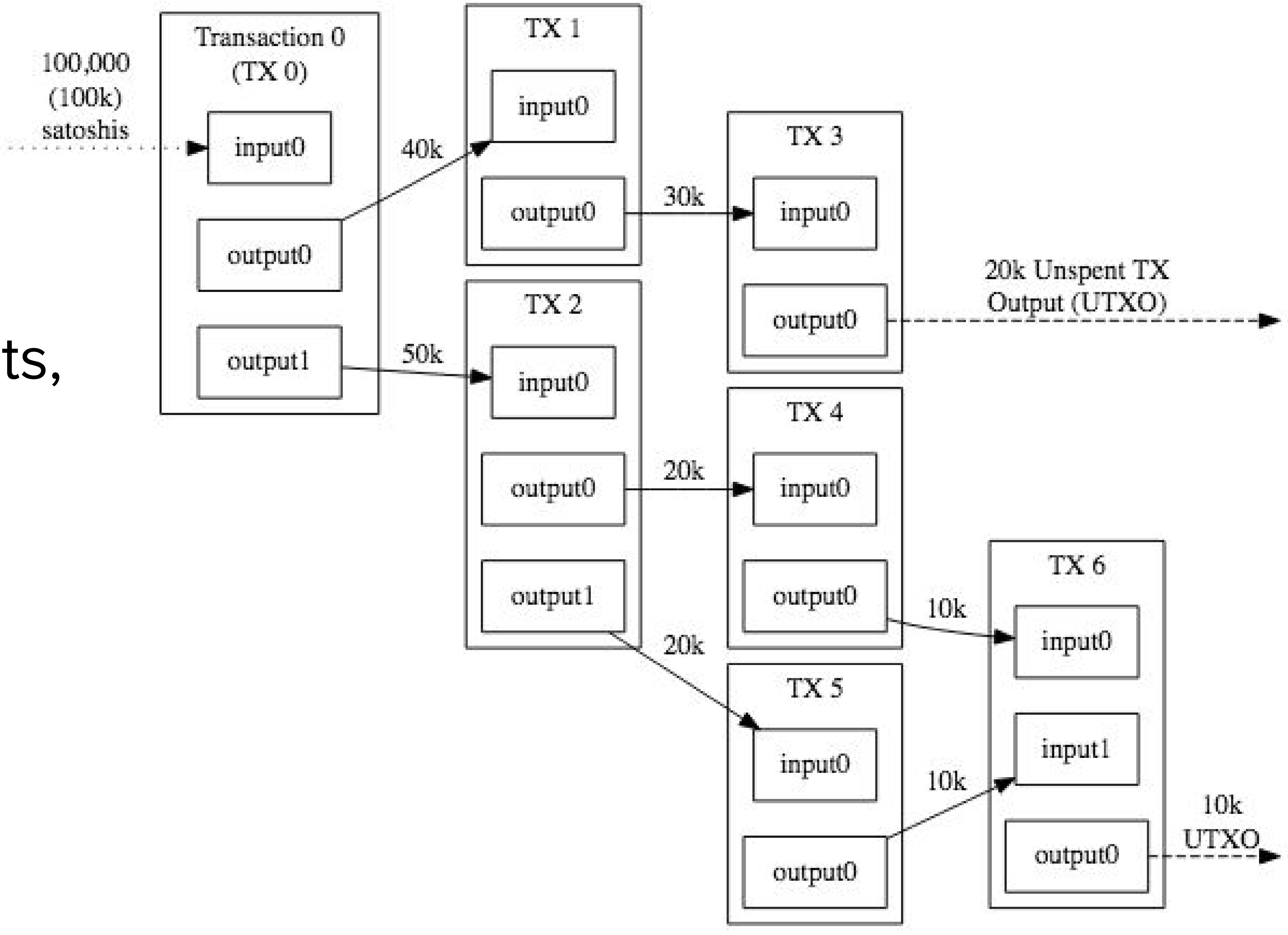
BITCOIN SCRIPTS

REMEMBER THE UTXO MODEL?

Source: Bitcoin Developer Guide

Reminders:

- Bitcoin uses a UTXO model
- Transactions map inputs to outputs,
- Transactions contain signature of owner of funds
- Spending Bitcoin is **redeeming** previous transaction outputs

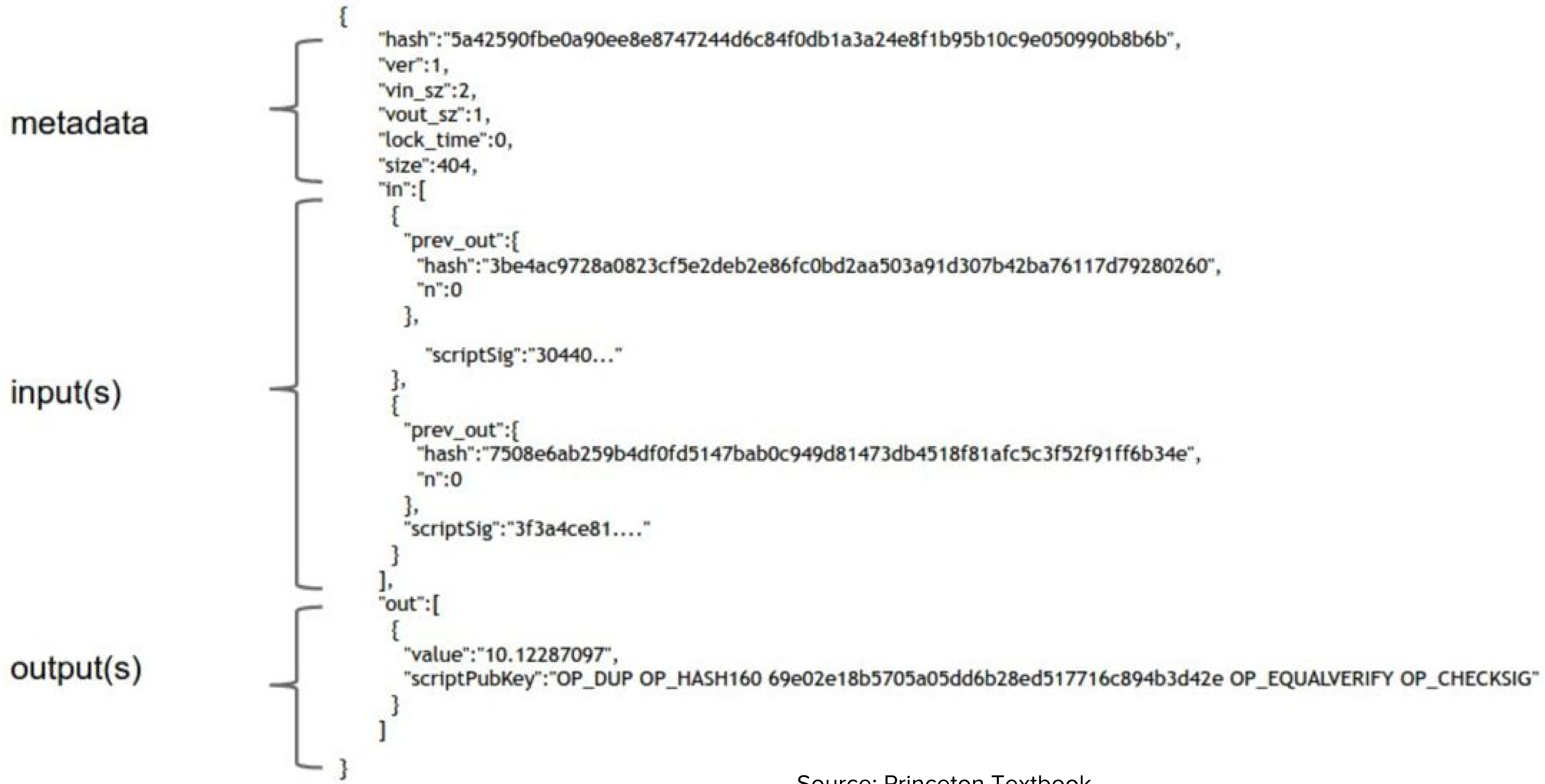


Triple-Entry Bookkeeping (Transaction-To-Transaction Payments) As Used By Bitcoin

AUTHOR: MAX FANG

BLOCKCHAIN AT BERKELEY

CONTENTS OF A TRANSACTION


metadata
input(s)
output(s)

```
{
   "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"
    }
   ]
}
```

Source: Princeton Textbook

CONTENTS OF A TRANSACTION - METADATA

```
{
  “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”: “7508e6ab259b4df0fd5147bab0c949d81473db4518f8afc5c3f52f91ff6b34e”,
              “n”: 0
          },
          “scriptSig”: “3f3a4ce81….”
      }
  ],
  “out”: [
      {
          “value”: 10.12287097”,
          “scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”
      }
  ]
}
```

hash or “ID”
of this transaction

CONTENTS OF A TRANSACTION - METADATA

```
{
  "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": "7508e6ab259b4df0fd5147bab0c949d81473db4518f8afc5c3f52f91ff6b34e",
              "n": 0
          },
          "scriptSig": "3f3a4ce81…."
      }
  ],
  "out": [
      {
          "value": 10.12287097",
          "scriptPubKey": "OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG"
      }
  ]
}
```

size (number) of inputs

size (number) of outputs

hash or "ID"
of this transaction

CONTENTS OF A TRANSACTION - METADATA

```
{
  “hash”: “5a42590fbe0a90ee8e8747244d6c84f0db1a3a24e8f1b95b10c9e050990b8b6b”,
  “ver”: 1,
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  “lock_time”: 0,
  “size”: 404,
  “in”: [
      {
          “prev_out”: {
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              “n”: 0
          },
          “scriptSig”: “3f3a4ce81….”
      }
  ],
  “out”: [
      {
          “value”: 10.12287097”,
          “scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”
      }
  ]
}
```

version

size (number) of inputs

size (number) of outputs

lock time (useful for scripting)

size of transaction

hash or “ID”
of this transaction

CONTENTS OF A TRANSACTION - INPUTS

```
{
  “hash”: “5a42590fbe0a90ee8e8747244d6c84f0db1a3a24e8f1b95b10c9e050990b8b6b”,
  “ver”: 1,
  “vin_sz”: 2,
  “vout_sz”: 1,
  “lock_time”: 0,
  “size”: 404
```

remember these?

```
  “in”: [
    {
      “prev_out”: {
        “hash”: “3be4ac9728a0823cf5e2deb2e86fc0bd2aa503a91d307b42ba76117d79280260”,
        “n”: 0
      },
        “scriptSig”: “30440…”
    },
    {
      “prev_out”: {
        “hash”: “7508e6ab259b4df0fd5147bab0c949d81473db4518f8afc5c3f52f91ff6b34e”,
        “n”: 0
      },
      “scriptSig”: “3f3a4ce81….”
    }
  ],
  “out”: [
    {
      “value”: 10.12287097”,
      “scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”
    }
```

CONTENTS OF A TRANSACTION - INPUTS

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{
    "hash": "5a42590fbe0a90ee8e8747244d6c84f0db1a3a24e8f1b95b10c9e050990b8b6b",
    "ver": 1,
    "vin_sz": 2,
    "vout_sz": 1,
    "lock_time": 0,
    "size": 404
  "in": [
     {
        "prev_out": {
           "hash": "3be4ac9728a0823cf5e2deb2e86fc0bd2aa503a91d307b42ba76117d79280260",
           "n": 0
        },
input 1:   "scriptSig": "30440…"
     },
     {
        "prev_out": {
           "hash": "7508e6ab259b4df0fd5147bab0c949d81473db4518f8afc5c3f52f91ff6b34e",
           "n": 0
        },
input 2: "scriptSig": "3f3a4ce81…."
     }
  ],
    "out": [
        {
            "value": 10.12287097",
            "scriptPubKey": "OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG"
        }
```

remember these?

ID of previous transactions being referenced

CONTENTS OF A TRANSACTION - INPUTS

```
{
    “hash”: “5a42590fbe0a90ee8e8747244d6c84f0db1a3a24e8f1b95b10c9e050990b8b6b”,
    “ver”: 1,
    “vin_sz”: 2,
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    “lock_time”: 0,
    “size”: 404
    “in”: [
        {
            “prev_out”: {
                “hash”: “3be4ac9728a0823cf5e2deb2e86fc0bd2aa503a91d307b42ba76117d79280260”,
                “n”: 0
            },
input 1:        “scriptSig”: “30440…”
        },
        {
            “prev_out”: {
                “hash”: “7508e6ab259b4df0fd5147bab0c949d81473db4518f8afc5c3f52f91ff6b34e”,
                “n”: 0
            },
input 2:    “scriptSig”: “3f3a4ce81….”
        }
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        {
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            “scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”
        }
```

index of input in previous transaction

ID of previous transactions being referenced

index of input in previous transaction

CONTENTS OF A TRANSACTION - INPUTS

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    “size”: 404
    “in”: [
        {
            “prev_out”: {
                “hash”: “3be4ac9728a0823cf5e2deb2e86fc0bd2aa503a91d307b42ba76117d79280260”,
                “n”: 0  ←  index of input in previous transaction
            },
input 1:        “scriptSig”: “30440…”  ←  signature used to redeem previous transaction output
        },
        {
            “prev_out”: {
                “hash”: “7508e6ab259b4df0fd5147bab0c949d81473db4518f8afc5c3f52f91ff6b34e”,
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input 2:    “scriptSig”: “3f3a4ce81….”  ←  signature used to redeem previous transaction output
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        {
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        }
```

CONTENTS OF A TRANSACTION - OUTPUTS

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{
    “hash”: “5a42590fbe0a90ee8e8747244d6c84f0db1a3a24e8f1b95b10c9e050990b8b6b”,
    “ver”: 1,
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    “vout_sz”: 1,
    “lock_time”: 0,
    “size”: 404,
    “in”: [
        {
            “prev_out”: {
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                “scriptSig”: “30440…”
        },
        {
            “prev_out”: {
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                “n”: 0
            },
            “scriptSig”: “3f3a4ce81….”
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    “out”: [
        {
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            “scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”
        }
    ]
}
```

output amount (how much BTC is being sent)

type of script

output script

BITCOIN SCRIPTS

REMINDERS

Output “addresses” are actually scripts.

“scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”

➔ This particular Output Script: “This amount can be redeemed by the **public key** that hashes to address X, plus a **signature** from the owner of that public key”

- Inputs and outputs through scripting allows for future extensibility of Bitcoin.
- **Script or “Bitcoin Scripting Language”**: Language built specifically for Bitcoin
  - Stack based
  - Native support for cryptography
  - Simple, not turing complete (no loops)

AUTHOR: MAX FANG
EDITED BY: GLORIA ZHAO

Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE

“scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”

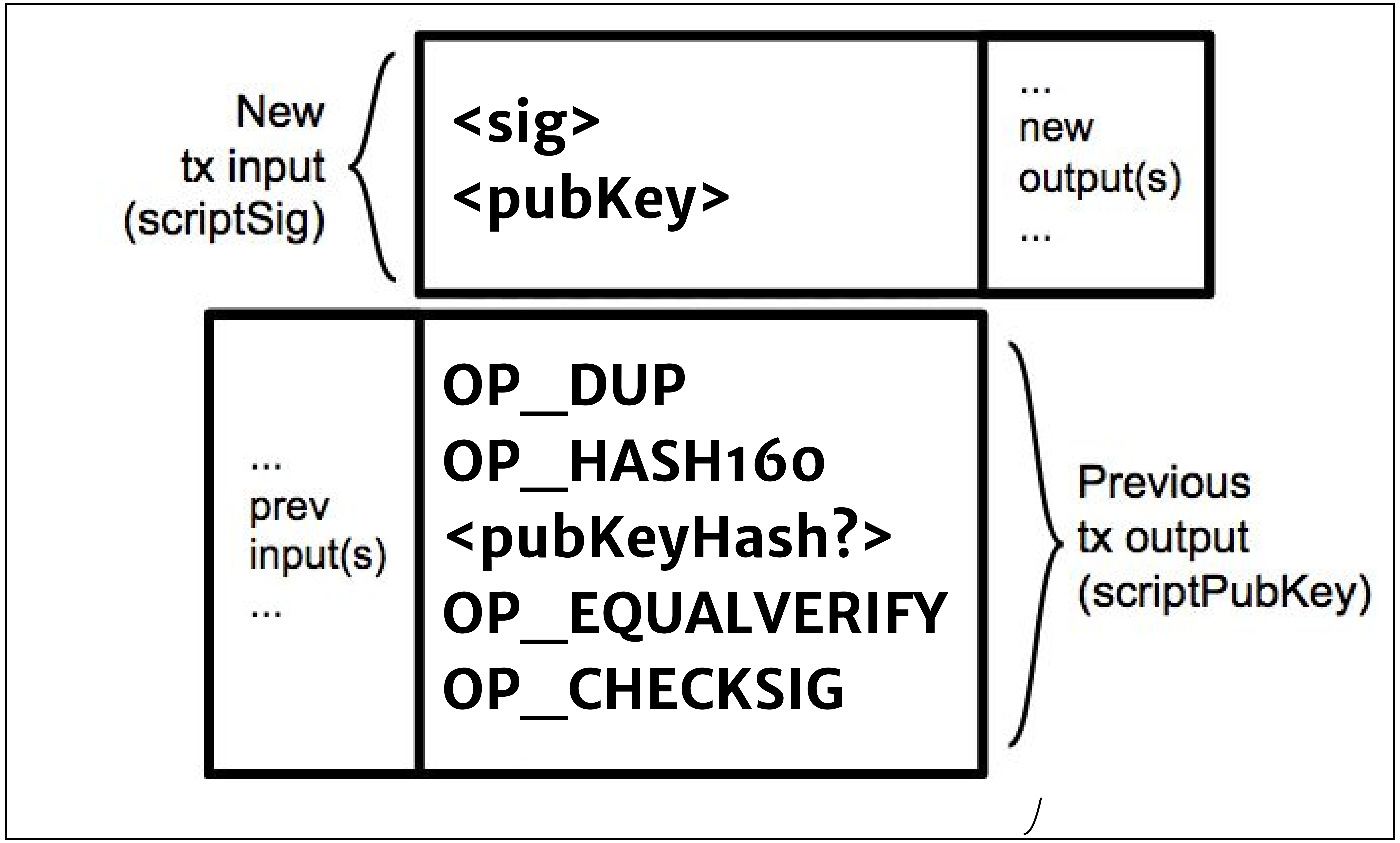


Figure: Two transactions along with their input and output scripts

- **locking script:** found in previous transaction output, specifies requirements for redeeming transaction
- **unlocking script (scriptSig):** found in transaction input, redeems the output of a previous transaction
- bitcoin validating node will execute the locking and unlocking scripts in sequence

Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE

“scriptPubKey”: “OP_DUP OP_HASH160 69e02e18b5705a05dd6b28ed517716c894b3d42e OP_EQUALVERIFY OP_CHECKSIG”

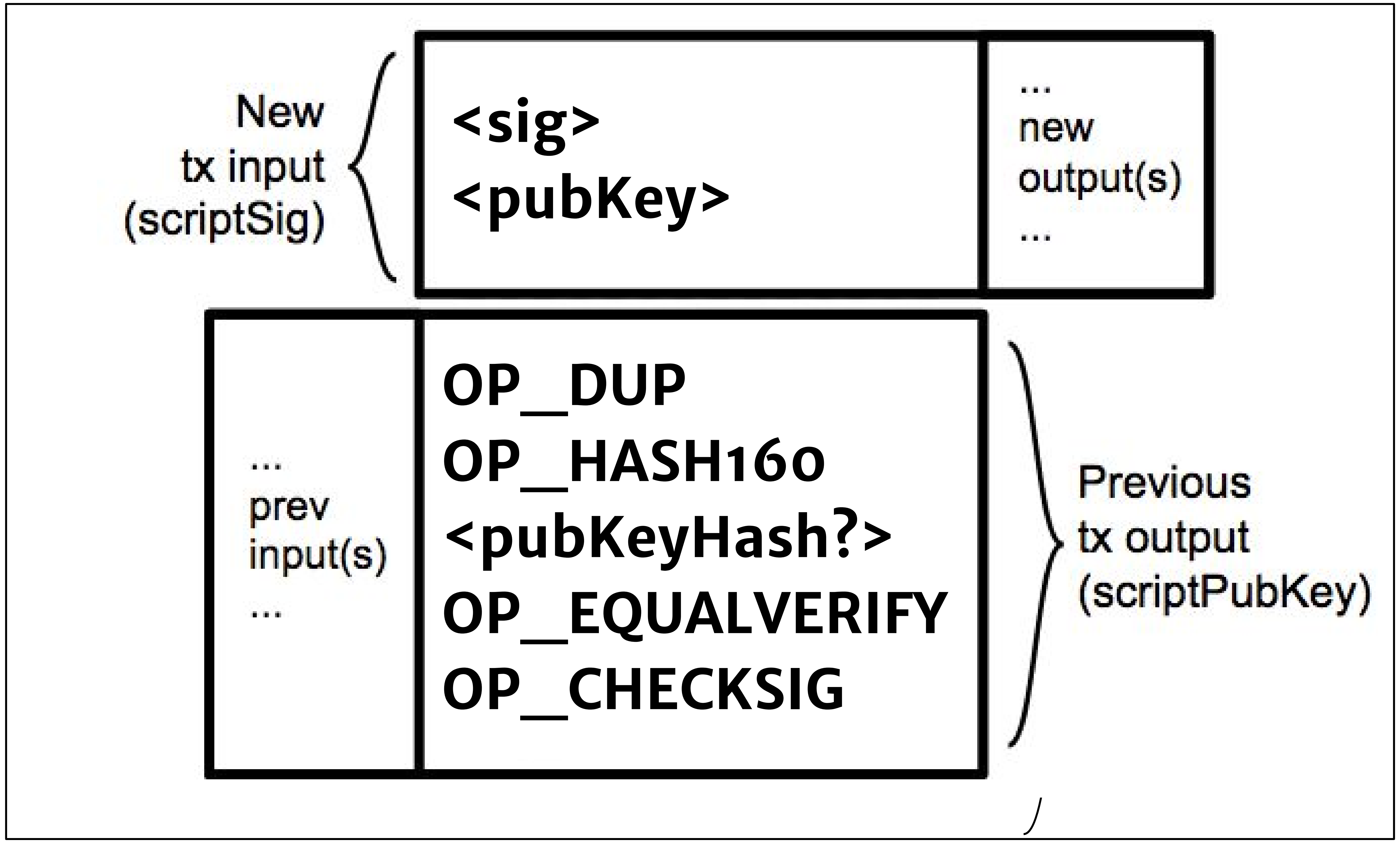


Figure: Two transactions along with their input and output scripts

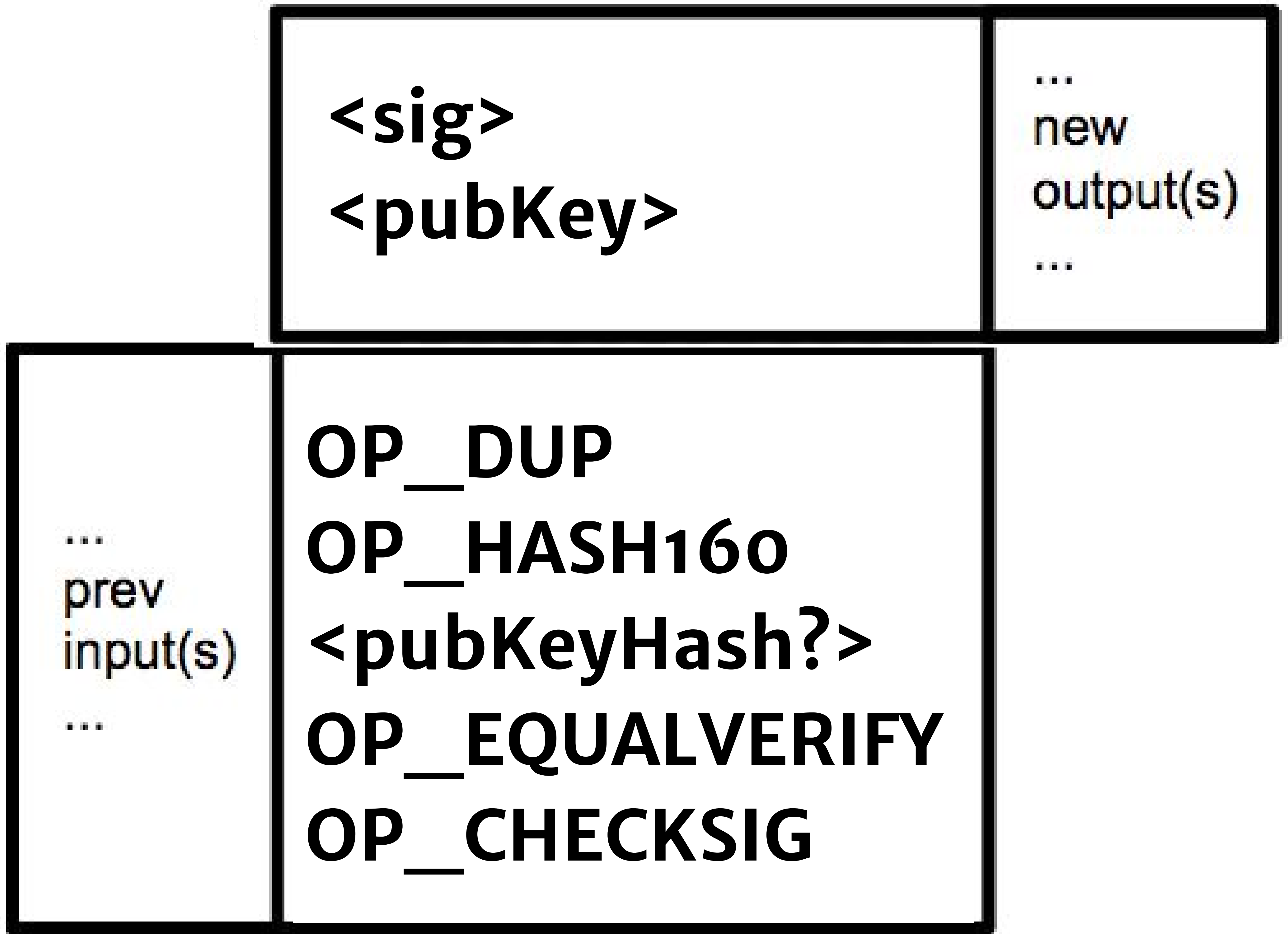
Code
Execution

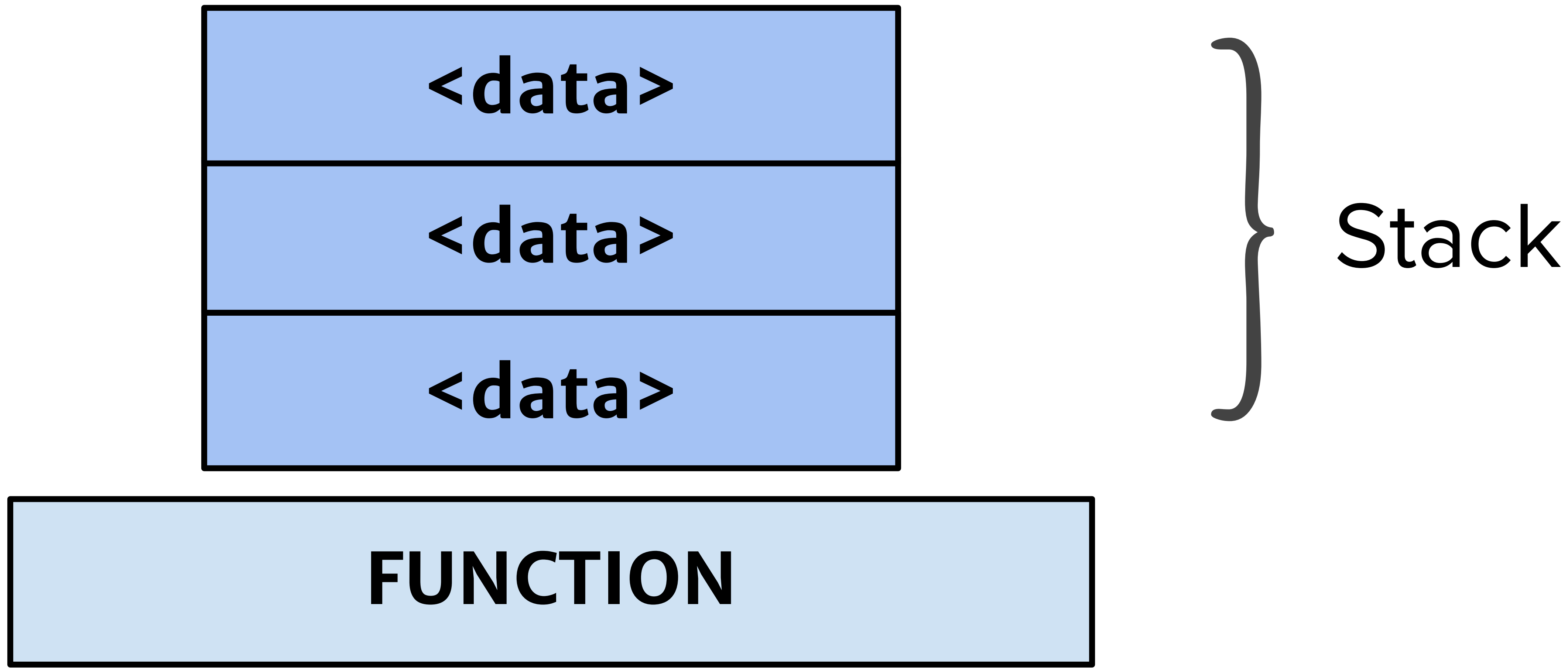
“scriptPubKey”: “
OP_DUP
OP_HASH160
69e02e18b5705a05dd6b28ed5
17716c894b3d42e
OP_EQUALVERIFY
OP_CHECKSIG”

Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION

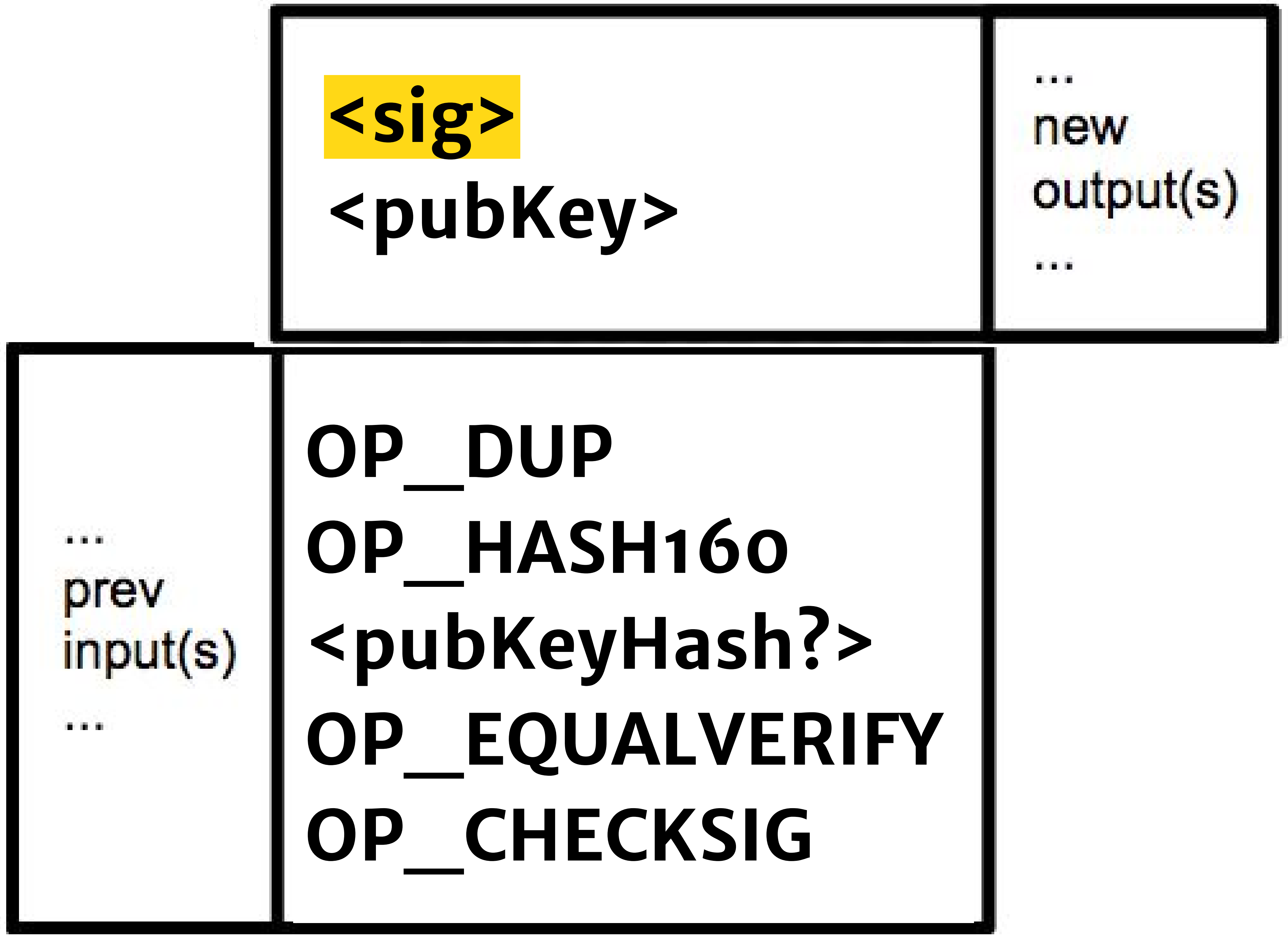




Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION

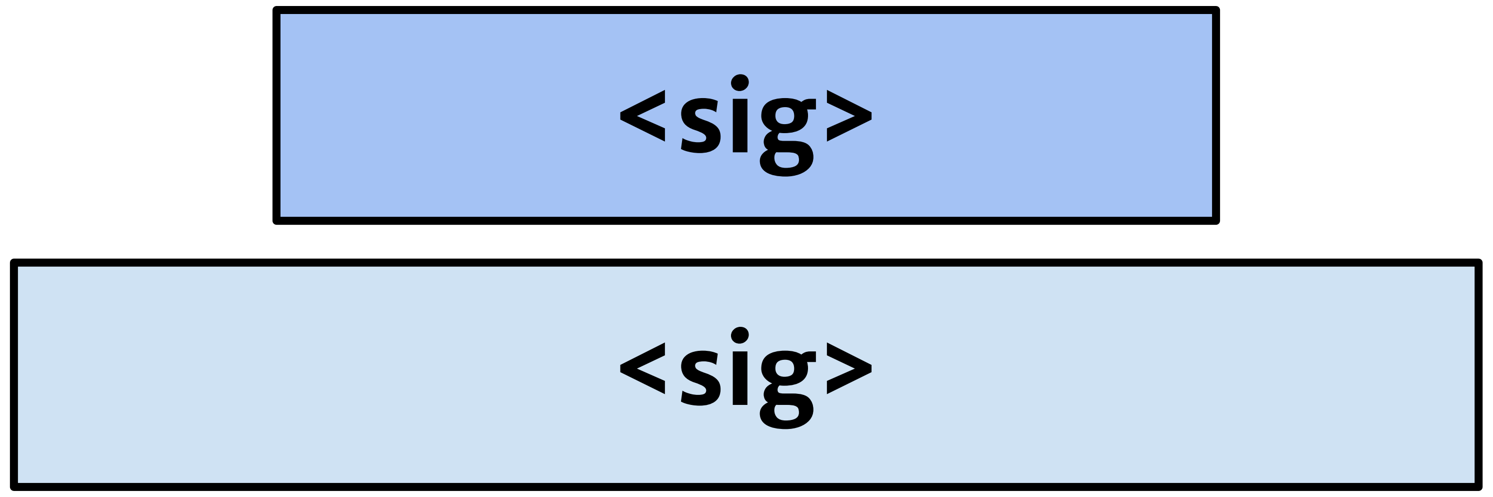


<sig>
<pubKey>

...
new
output(s)
...

...
prev
input(s)
...

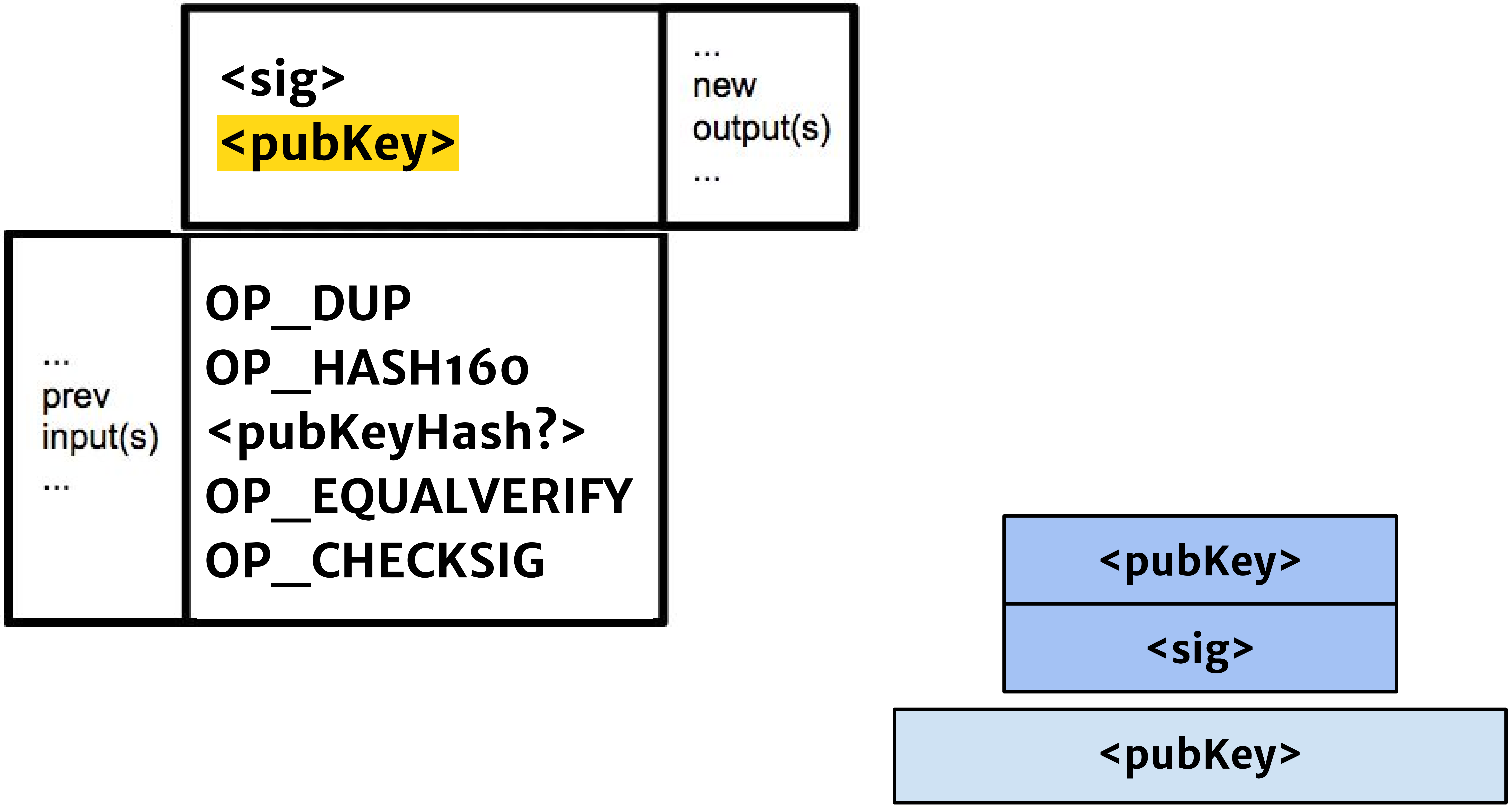
OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG



Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION



<sig>
<pubKey>

...
new
output(s)
...

...
prev
input(s)
...

```
OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG
```

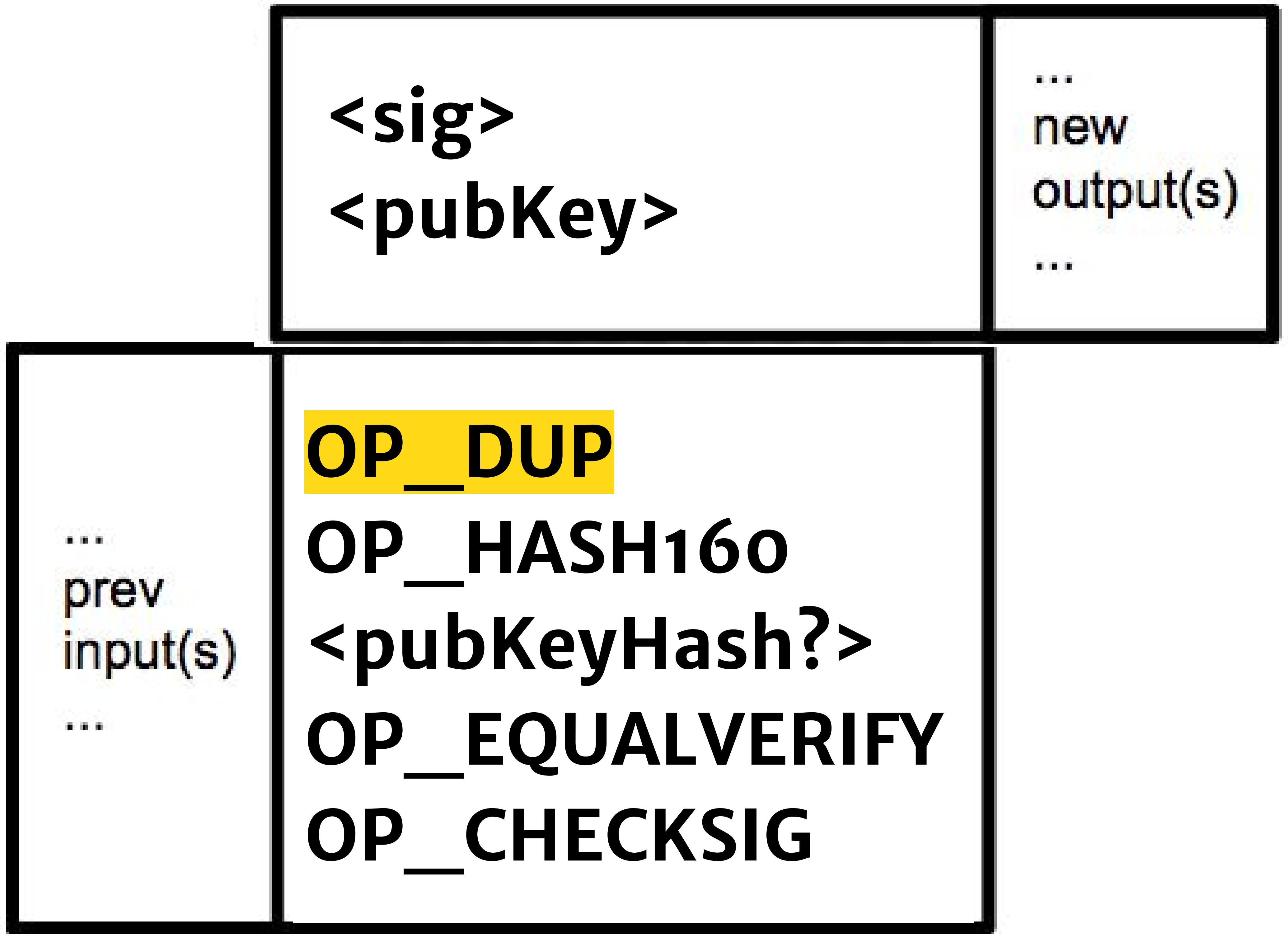
<pubKey>
<sig>
<pubKey>

AUTHOR: GLORIA ZHAO

Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION

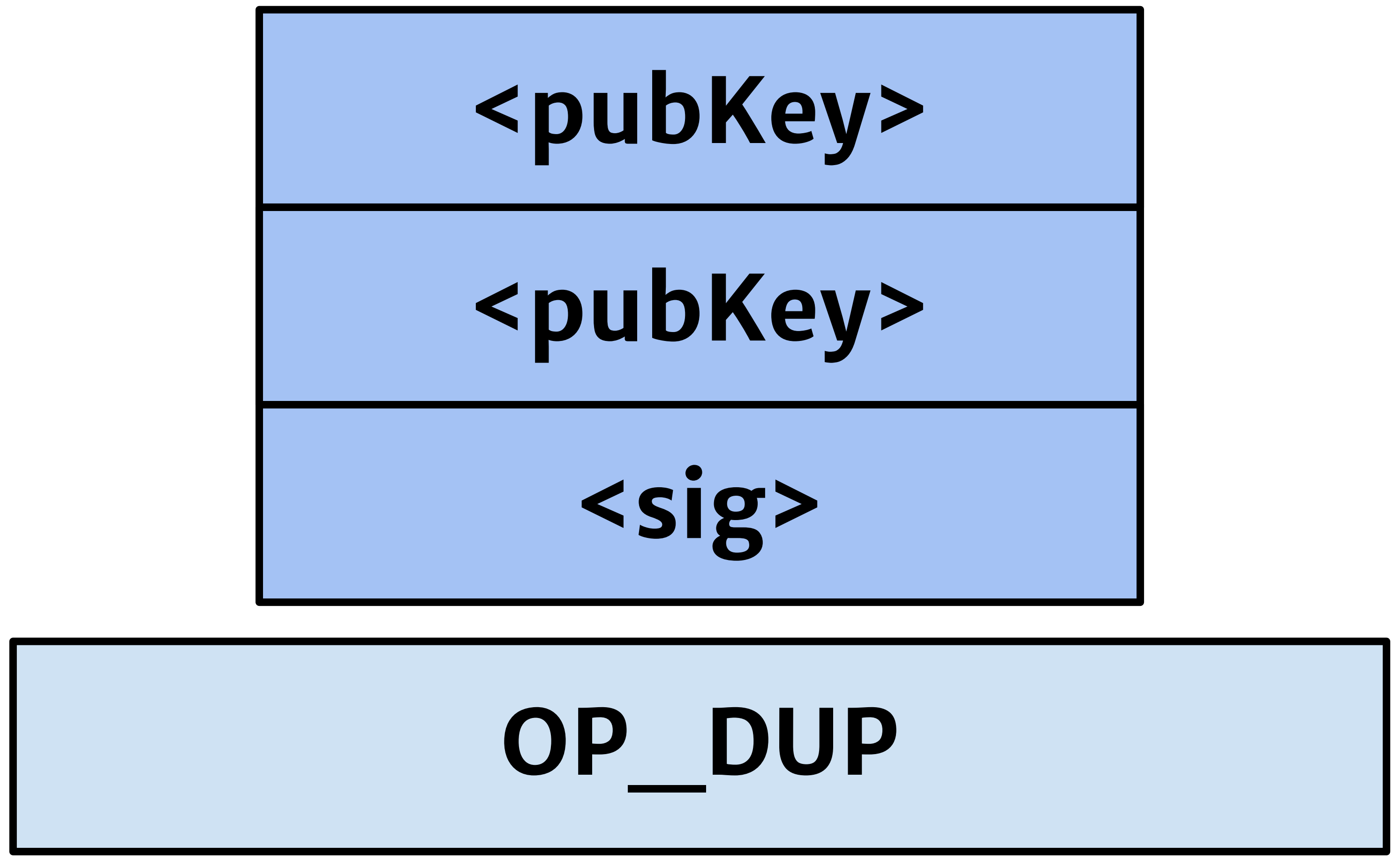


<sig>
<pubKey>

...
new
output(s)
...

...
prev
input(s)
...

OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG



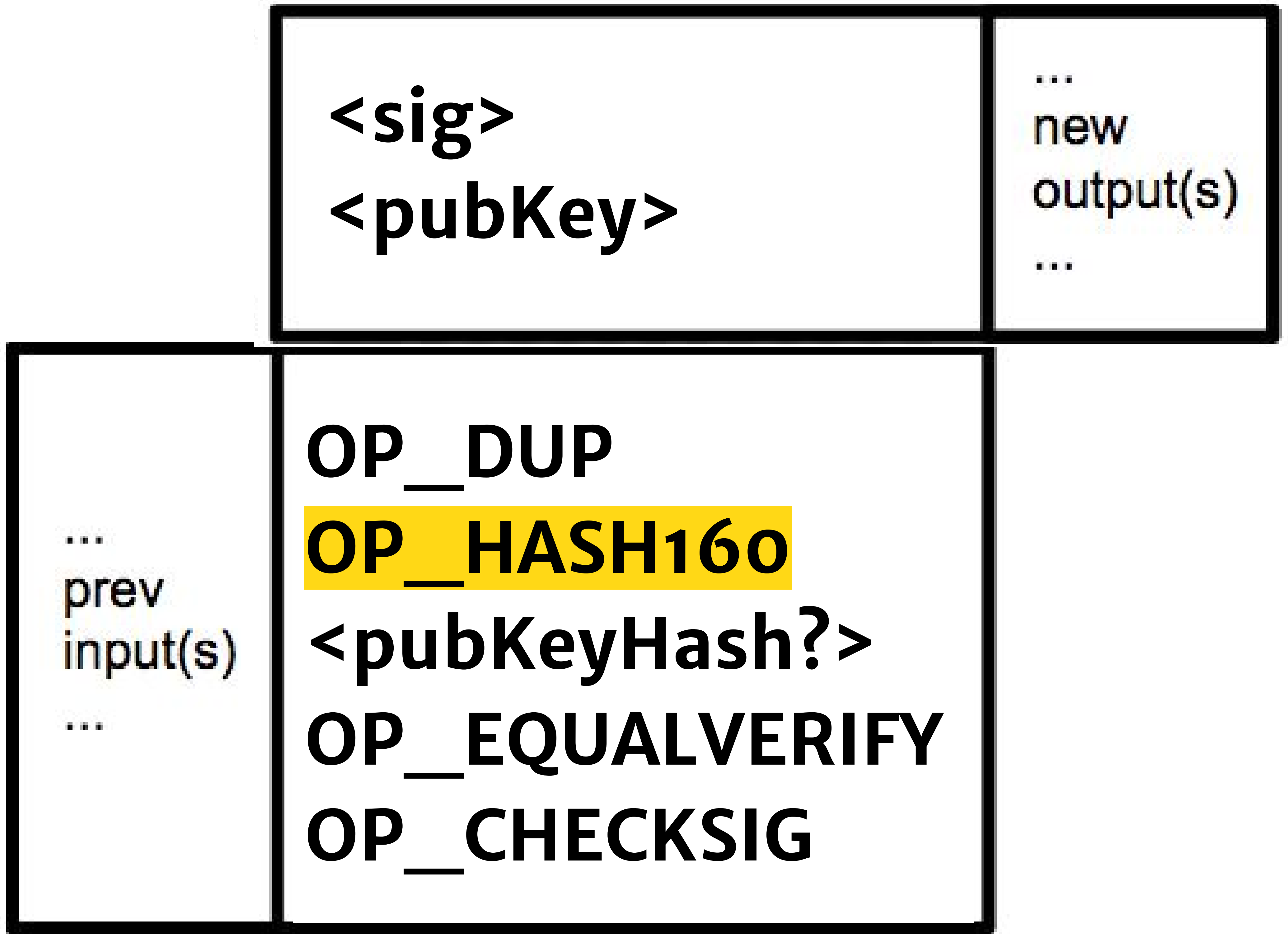
<pubKey>
<pubKey>
<sig>

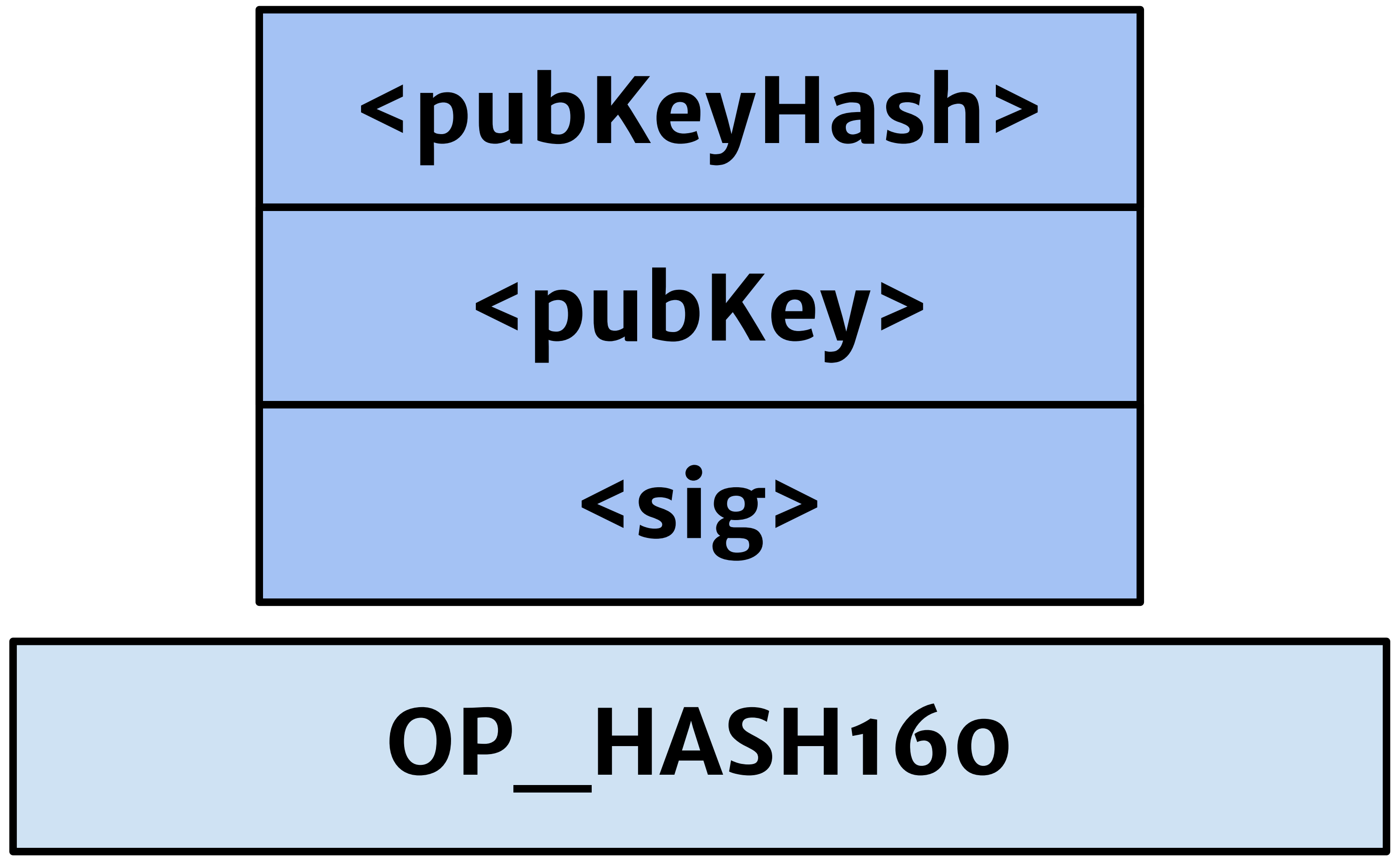
OP_DUP

Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION

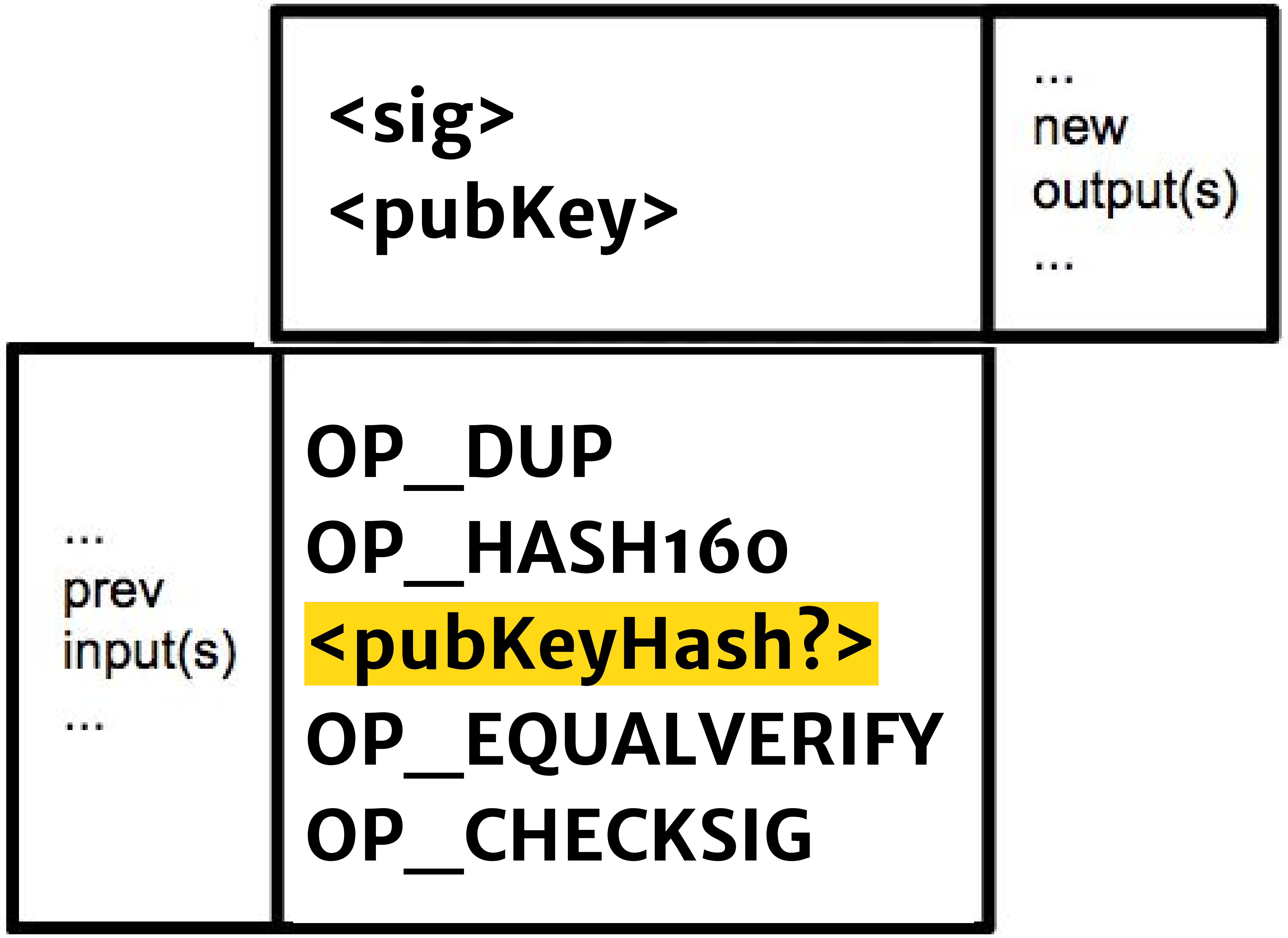




Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION

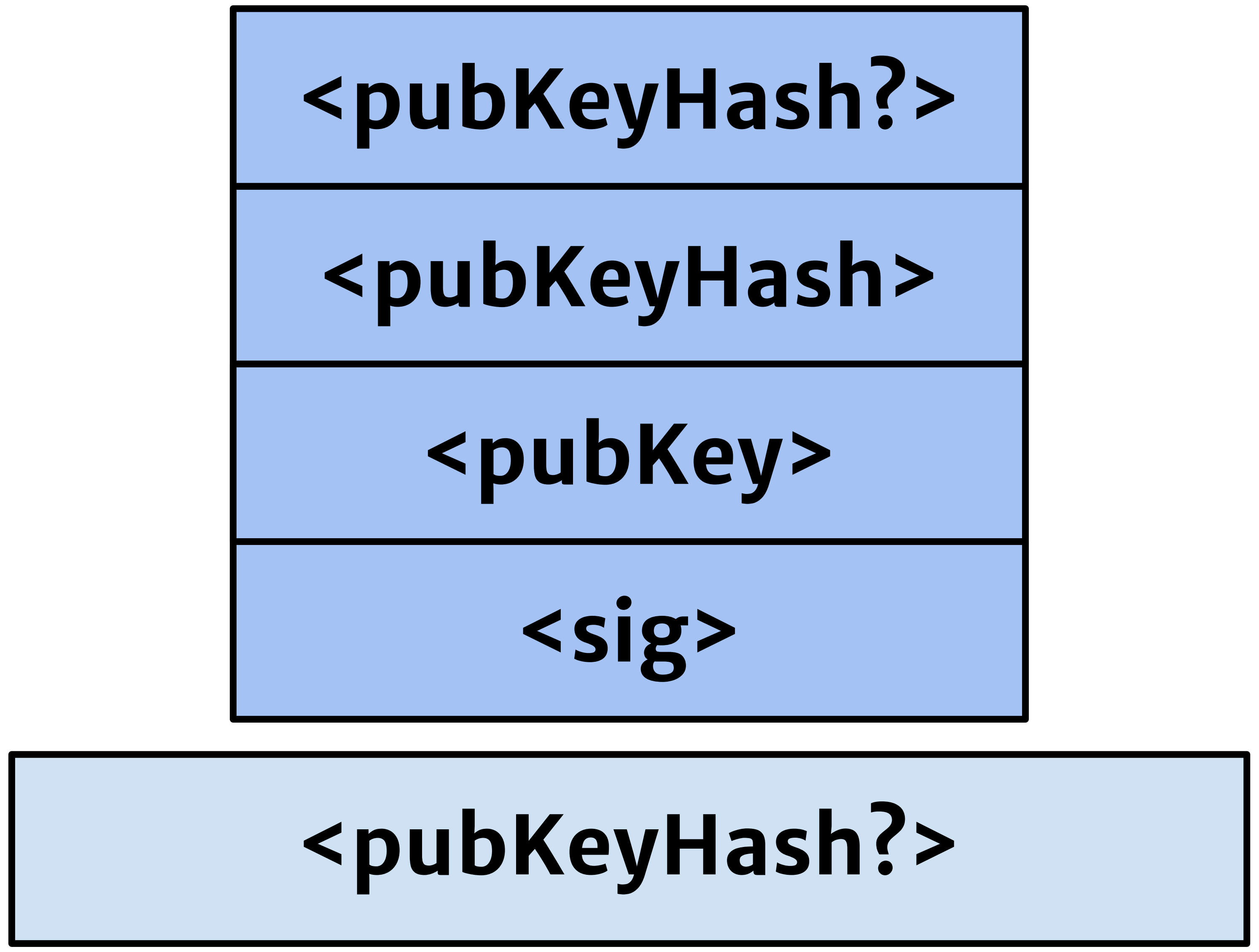


<sig>
<pubKey>

...
new
output(s)
...

...
prev
input(s)
...

OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG



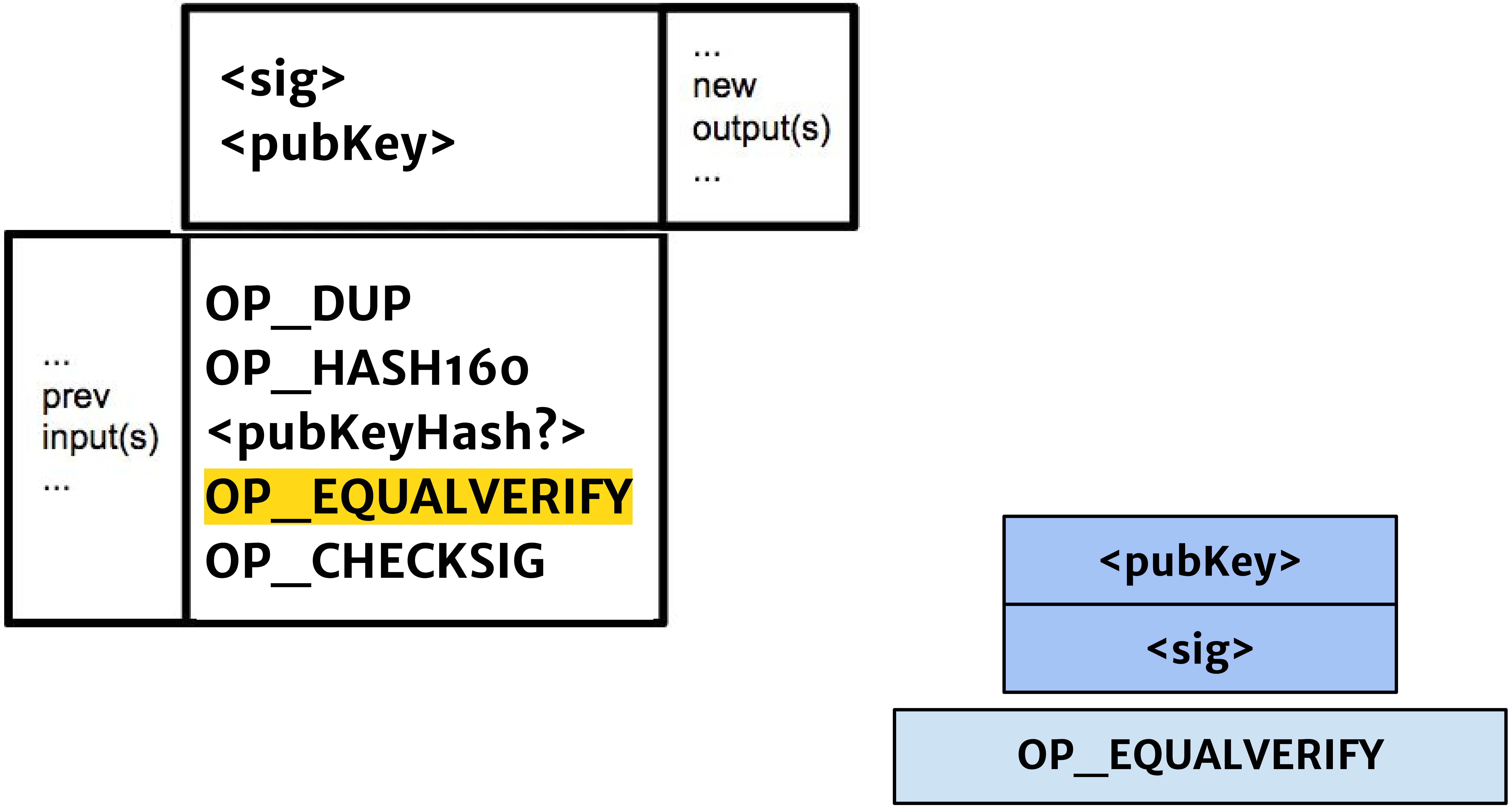
<pubKeyHash?>
<pubKeyHash>
<pubKey>
<sig>

<pubKeyHash?>

Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION



<sig>
<pubKey>

...
new
output(s)
...

...
prev
input(s)
...

OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG

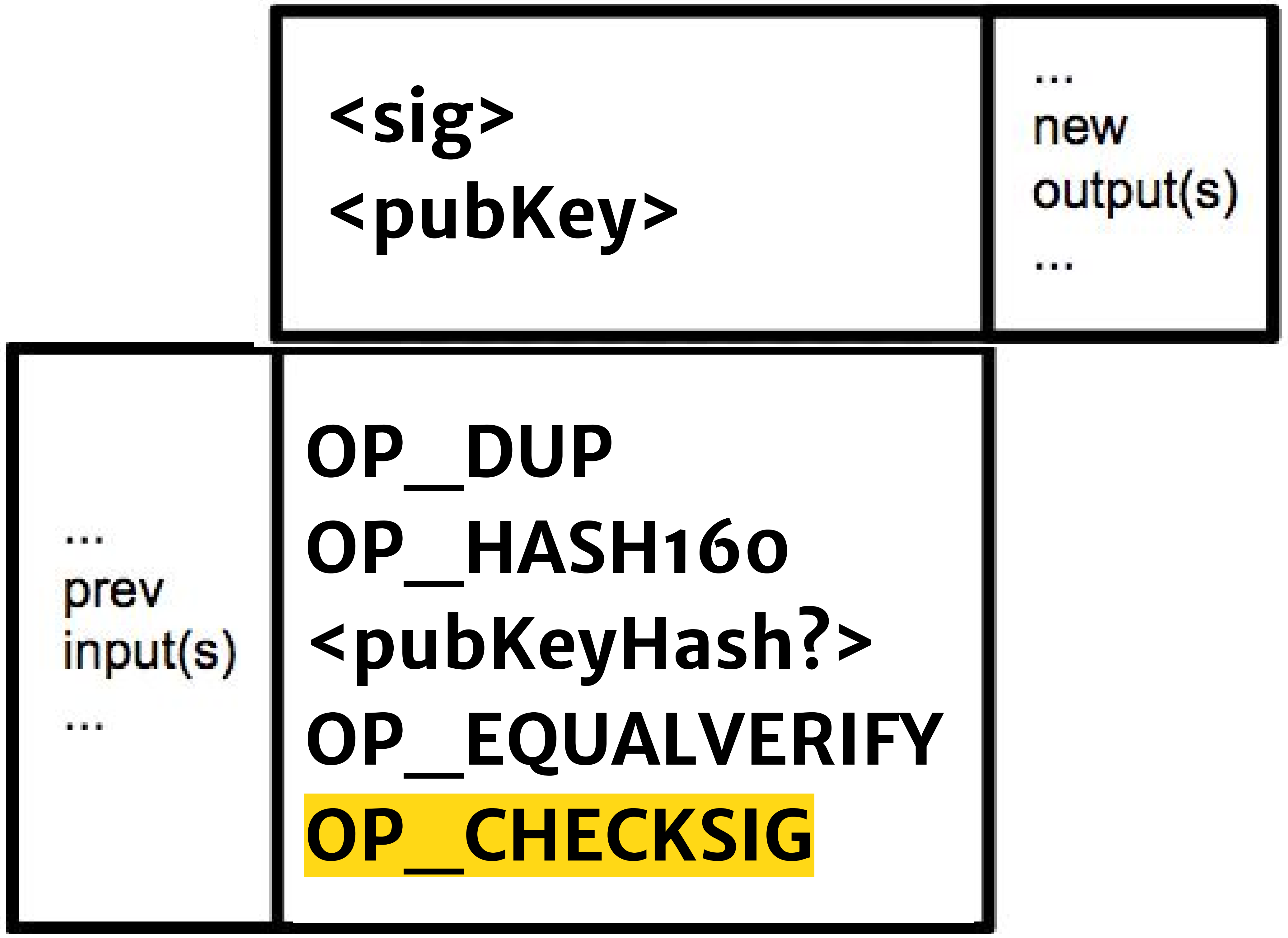
<pubKey>
<sig>

OP_EQUALVERIFY

Source: Princeton textbook

BITCOIN SCRIPTS

P2PKH EXAMPLE EXECUTION

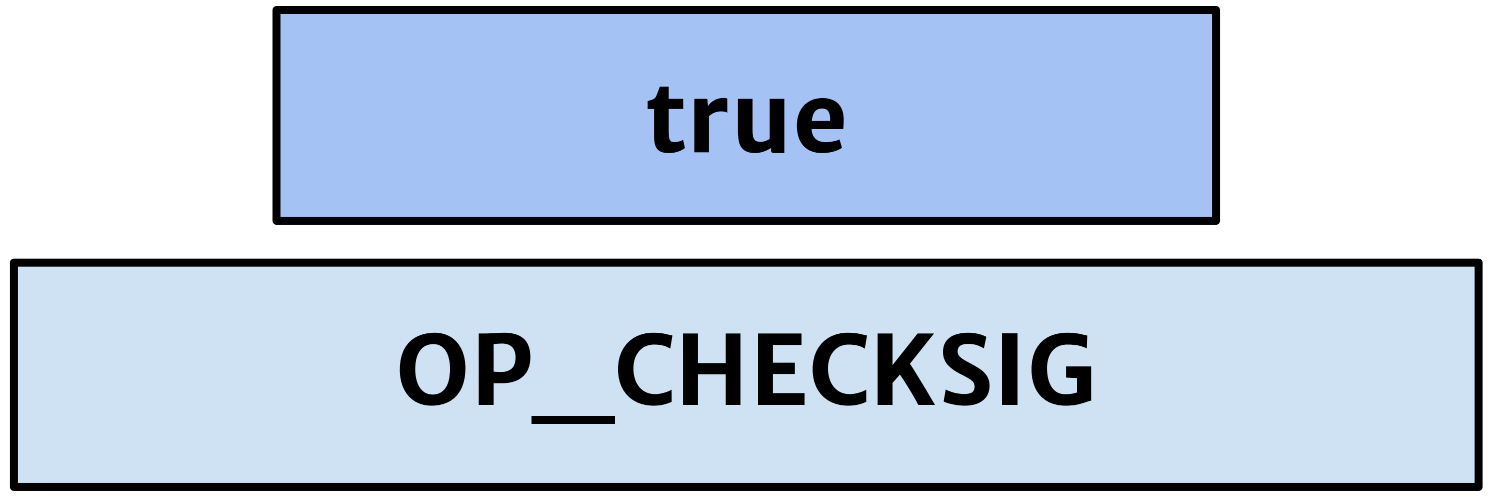


<sig>
<pubKey>

...
new
output(s)
...

...
prev
input(s)
...

OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG



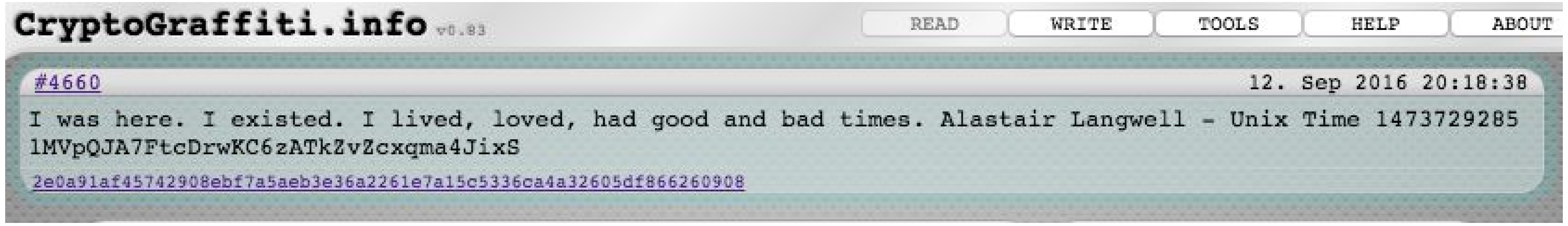
true

OP_CHECKSIG

Source: Princeton textbook

BITCOIN SCRIPTS

PROOF OF BURN



#4660 12. Sep 2016 20:18:38

I was here. I existed. I lived, loved, had good and bad times. Alastair Langwell - Unix Time 1473729285 1MVpQJA7FtcDrwKC6zATkZvZcxqma4JixS

2e0a91af45742908ebf7a5aeb3e36a2261e7a15c5336ca4a32605df866260908

Output script:

OP_RETURN
<arbitrary data>

How to write arbitrary data into the Bitcoin blockchain?

Proof of Burn

- OP_RETURN throws an error if reached
- Output script can't be spent - you prove that you destroyed some currency
- Anything after OP_RETURN is not processed, so arbitrary data can be entered

Use cases

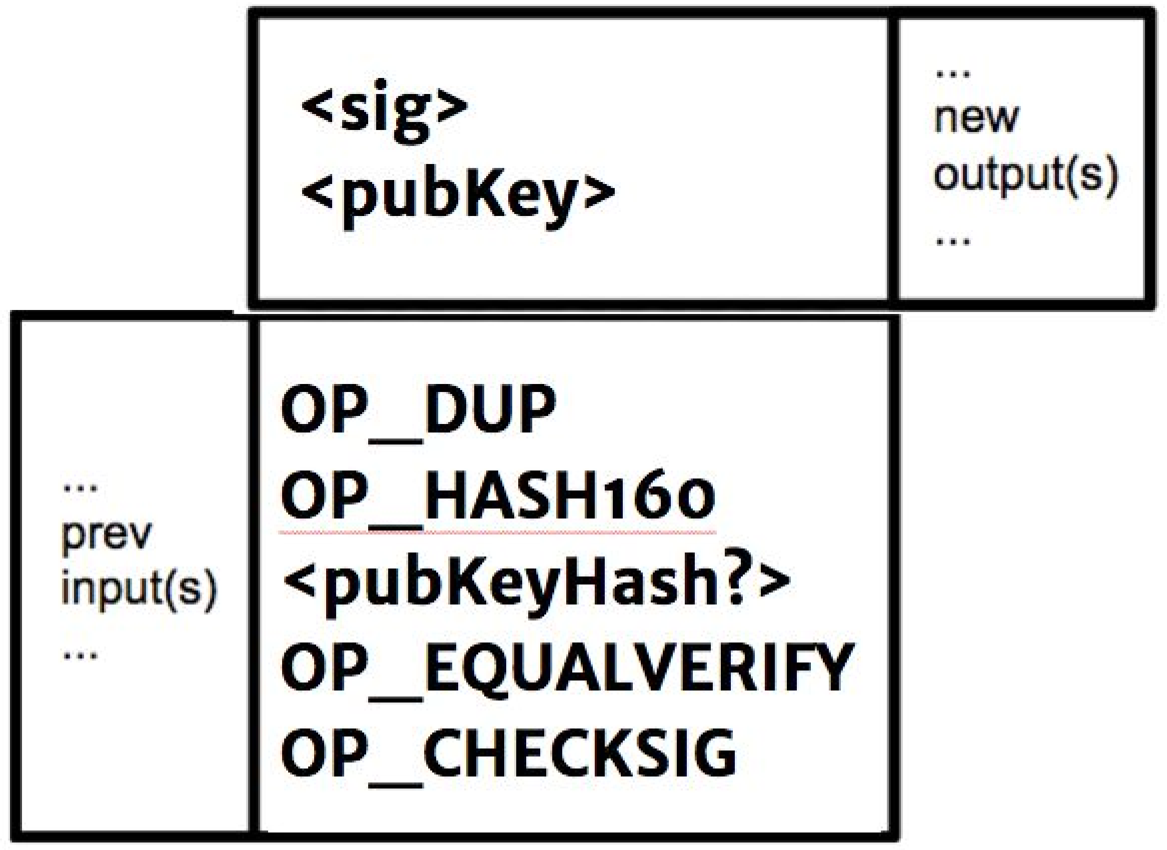
- Prove existence of something at a particular point in time
    - Ex. A word you coined, hash of a document/music/creative works
- Bootstrap CalCoin by requiring that you destroy some Bitcoin to get CalCoin

5 P2PKH & P2SH

P2PKH VS P2SH

WHO SPECIFIES THE SCRIPT?

- In Bitcoin, senders specify a locking script, recipients provide an unlocking script
- **Pay-to-Pub-Key-Hash (P2PKH):** Vendor (recipient of transaction) says “Send your coins to the hash of this Public Key.”
  - Simplest case
  - By far the most common case
- **Pay-to-Script-Hash (P2SH):** Vendor says “Send your coins to the hash of this Script; I will provide the script and the data to make the script evaluate to true when I redeem the coins.”
  - A vendor cannot say, “To pay me, write a complicated output script that will allow me to spend using multiple signatures.”



```
<sig>
<pubKey>
```

```
OP_DUP
OP_HASH160
<pubKeyHash?>
OP_EQUALVERIFY
OP_CHECKSIG
```

Simple P2PKH script - recipient only has to provide signature and public key

P2PKH VS P2SH

WHY P2SH?

Why Pay-to-Script-Hash?

- Offloads complicated script writing to recipients
- Makes more sense from a payer-payee standpoint
  - Merchant (rather than customer) is responsible for writing correct and secure script
  - Customer doesn't care what the script actually is
- P2SH is the most important improvement to Bitcoin since inception
- Example: **MultiSig**
  - *M* of *N* specified signatures can redeem and spend the output of this transaction

P2PKH VS P2SH

MULTISIG EXAMPLE

e.g. Nadir, Aparna, and Gloria are in charge of a joint account and make all spending decisions together:

2 of 3 MultiSig

ScriptSig (Unlocking Script)	**<sig1> <sig2> ... <sigm>**	sig1 sig2
ScriptPubKey (Redeeming Script)	**m <pubKey1> <pubKey2> ... N OP_CHECKMULTISIG**	2 PubKey1 PubKey2 PubKey3 3 OP_CHECKMULTISIG
Prev. Output Script (Locking Script)	**OP_HASH160 <hash?> OP_EQUALVERIFY**	OP_HASH160 <hash?> OP_EQUALVERIFY

← Nadir, Aparna, and Gloria provide the script for multisig redemption of coins

← Sender of transaction only has to provide this output script!

HOMEWORK

- Readings:
  - https://bitcoin.stackexchange.com/questions/8443/where-is-double-hashing-performed-in-bitcoin
  - Princeton 5.1 - 5.4 (pg. 131 - 157)
  - http://cryptorials.io/bitcoin-wallets-explained-how-to-choose-the-best-wallet-for-you/
  - (Optional) Bitcoin Developer Guide: https://bitcoin.org/en/developer-guide
    - There’s a lot -- don’t try to read it all in one day
  - (Optional) https://www.coindesk.com/bitcoin-hash-functions-explained/
  - (Optional) https://3583bytesready.net/2016/09/06/hash-puzzes-proofs-work-bitcoin/
  - (Optional) https://csrc.nist.gov/csrc/media/publications/fips/180/4/archive/2012-03-06/documents/fips180-4.pdf
    - Insane math (a blessing or a curse depending on your preferences)
- HW:
  - Either come up with a rock-paper-scissors scheme or analyze P2PKH vs P2SH -- will elaborate on Piazza