Blockchain Principles and Applications

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Most slides have been adapted from ECE/COS 470, Pramod Viswanath, Princeton 2024 and CS251, Dan Boneh, Stanford 2023.

Recap

Bitcoin blockchain: a sequence of block headers, 80 bytes each

H

BH_1

version	(4 bytes)
prev	(32 bytes)
time	(4 bytes)
bits	(4 bytes)
nonce	(4 bytes)
Tx root	(32 bytes)

80 bytes

H

BH_2

prev

Tx root

H

BH_3

prev

Tx root

...

coinbase Tx

coinbase Tx

Bitcoin blockchain: a sequence of block headers, 80 bytes each

time: time miner assembled the block. Self reported.
(block rejected if too far in past or future)

bits: proof of work difficulty
nonce: proof of work solution
} for choosing a proposer

Merkle tree: payer can give a short proof that Tx is in the block

new block every ≈10 minutes.

An example

Tx data

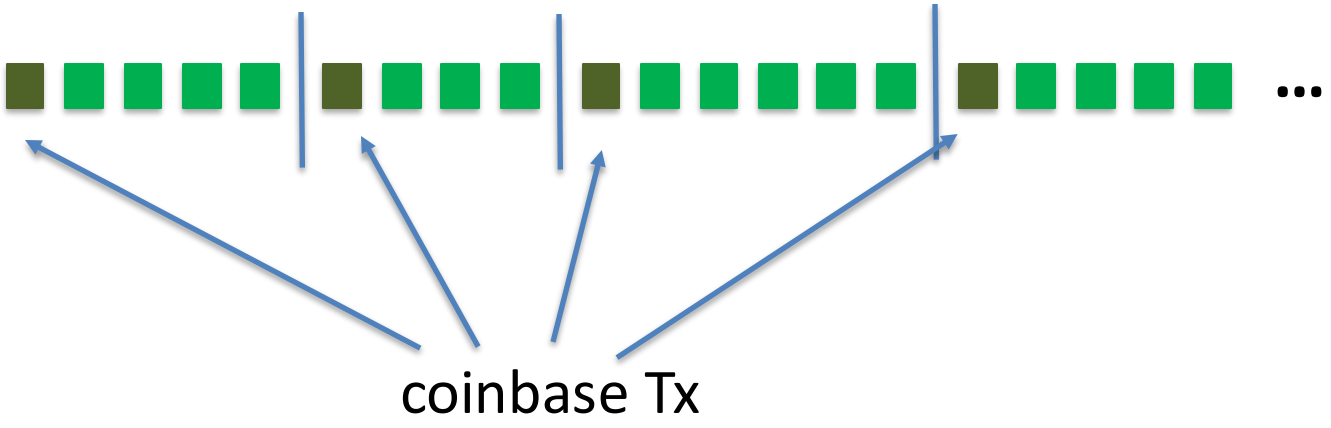
Height	Mined	Miner	Size	#Tx
648494	17 minutes	Unknown	1,308,663 bytes	1855
648493	20 minutes	SlushPool	1,317,436 bytes	2826
648492	59 minutes	Unknown	1,186,609 bytes	1128
648491	1 hour	Unknown	1,310,554 bytes	2774
648490	1 hour	Unknown	1,145,491 bytes	2075
648489	1 hour	Poolin	1,359,224 bytes	2622

Block 648493

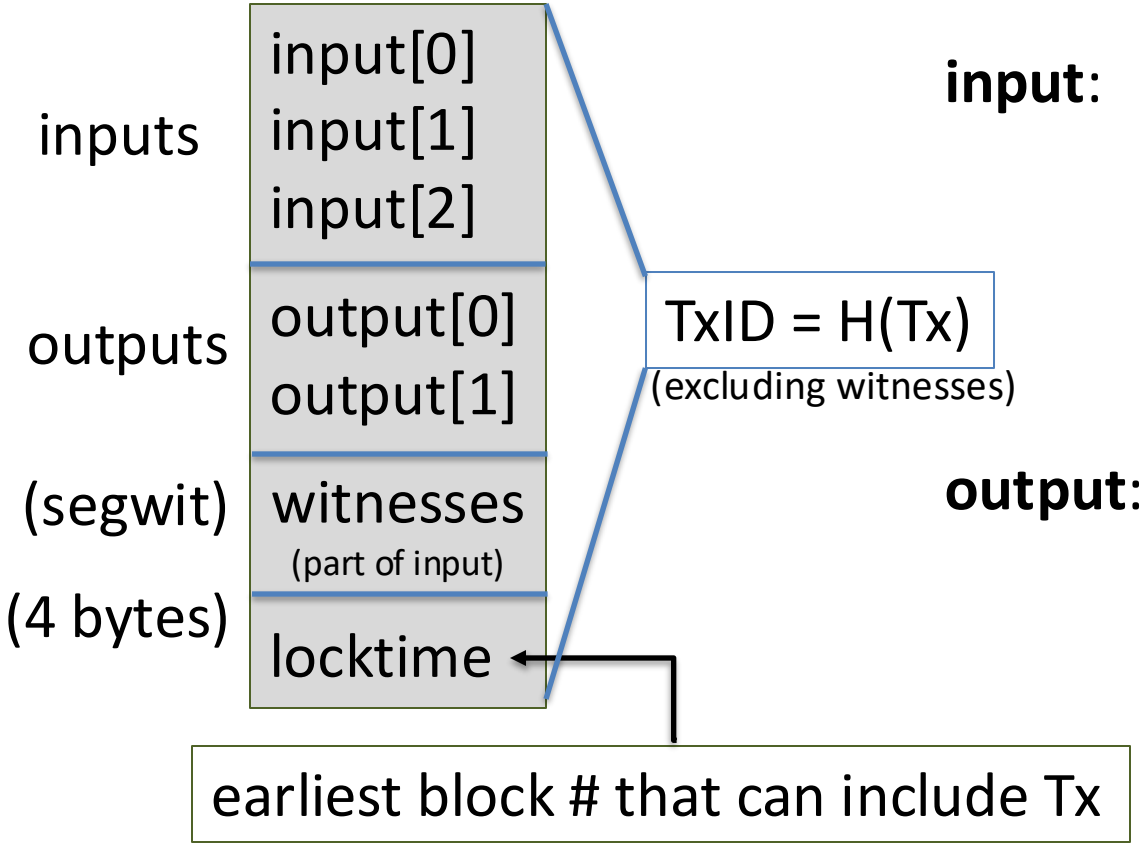
Timestamp	2020-09-15 17:25	
Height	648493	
Miner	SlushPool	(from coinbase Tx)
Number of Transactions	2,826	
Difficulty (D)	17,345,997,805,929.09	(adjusts every two weeks)
Merkle root	350cbb917c918774c93e945b960a2b3ac1c8d448c2e67839223bbcf595baff89	
Transaction Volume	11256.14250596 BTC	
Block Reward	6.25000000 BTC	
Fee Reward	0.89047154 BTC	(Tx fees given to miner in coinbase Tx)

This lecture

View the blockchain as a sequence of Tx (append-only)



Tx structure (non-coinbase)



input:

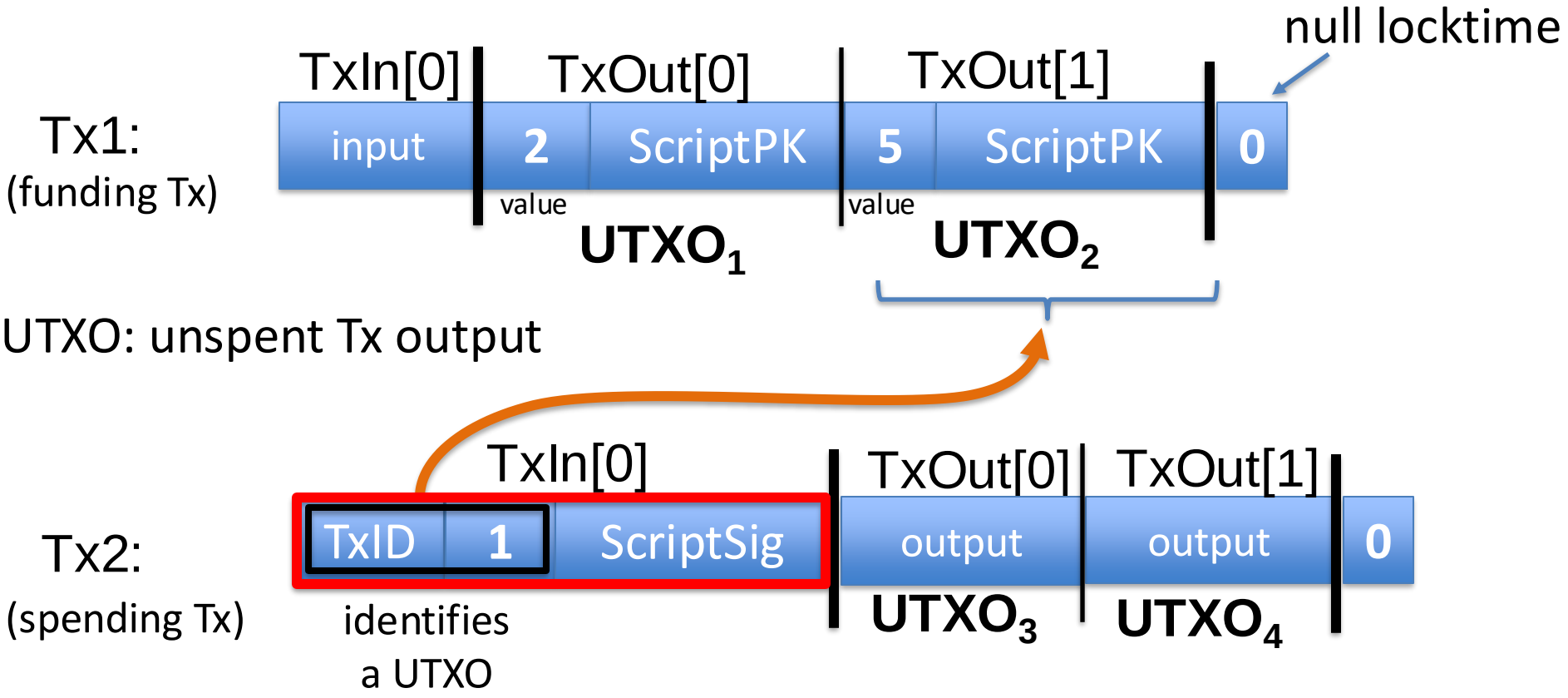
TxID	32 byte hash
out-index	4 byte index
ScriptSig	program
seq	ignore

output:

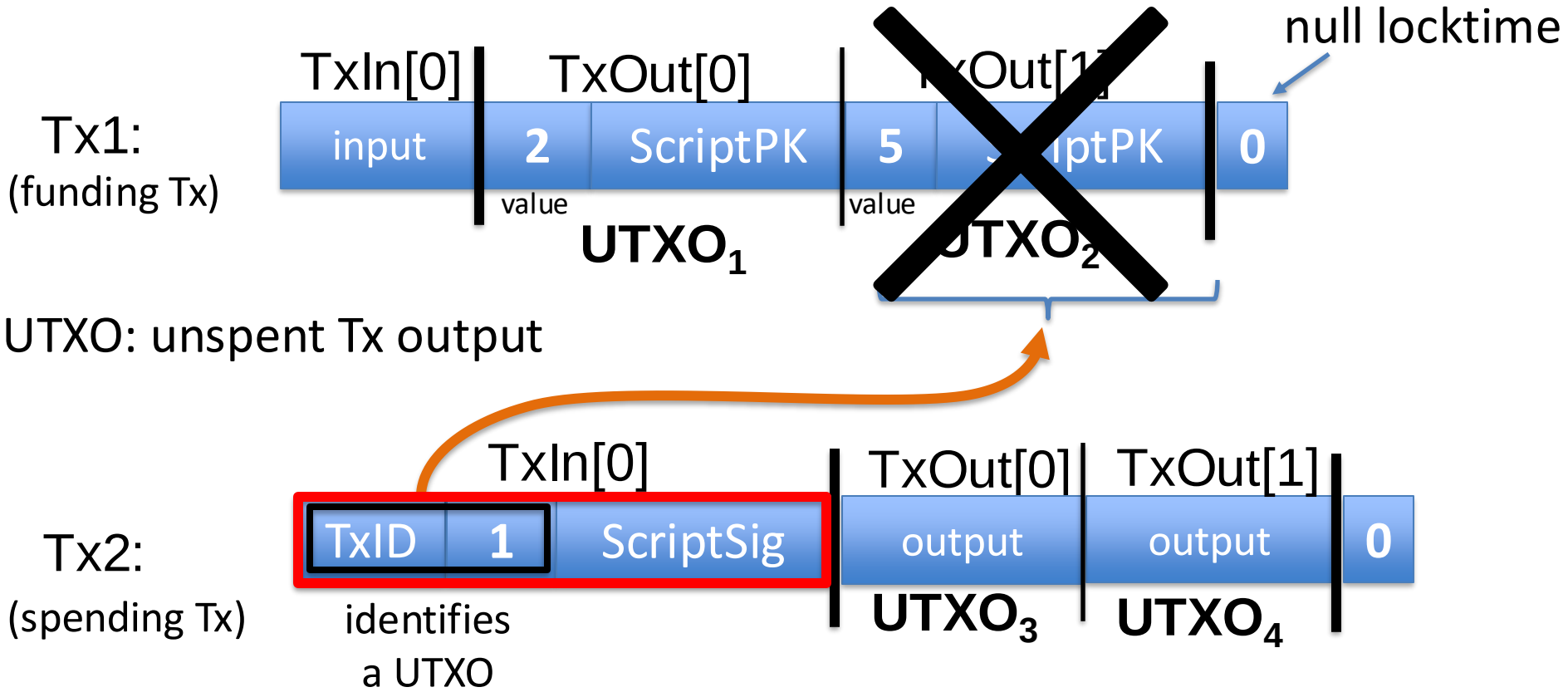
value	8 bytes
ScriptPK	program

#BTC = value/10^8

Example


Tx1:
(funding Tx)
TxIn[0]
TxOut[0]
TxOut[1]
null locktime
input
2
ScriptPK
5
ScriptPK
0
value
value
UTXO1
UTXO2
UTXO: unspent Tx output
Tx2:
(spending Tx)
TxIn[0]
TxID
1
ScriptSig
identifies
a UTXO
TxOut[0]
TxOut[1]
output
output
0
UTXO3
UTXO4

Example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UTXO: unspent Tx output
Tx2:
(spending Tx)
TxIn[0]
TxID
1
ScriptSig
identifies
a UTXO
TxOut[0]
TxOut[1]
output
output
0
UTXO3
UTXO4

Validating Tx2

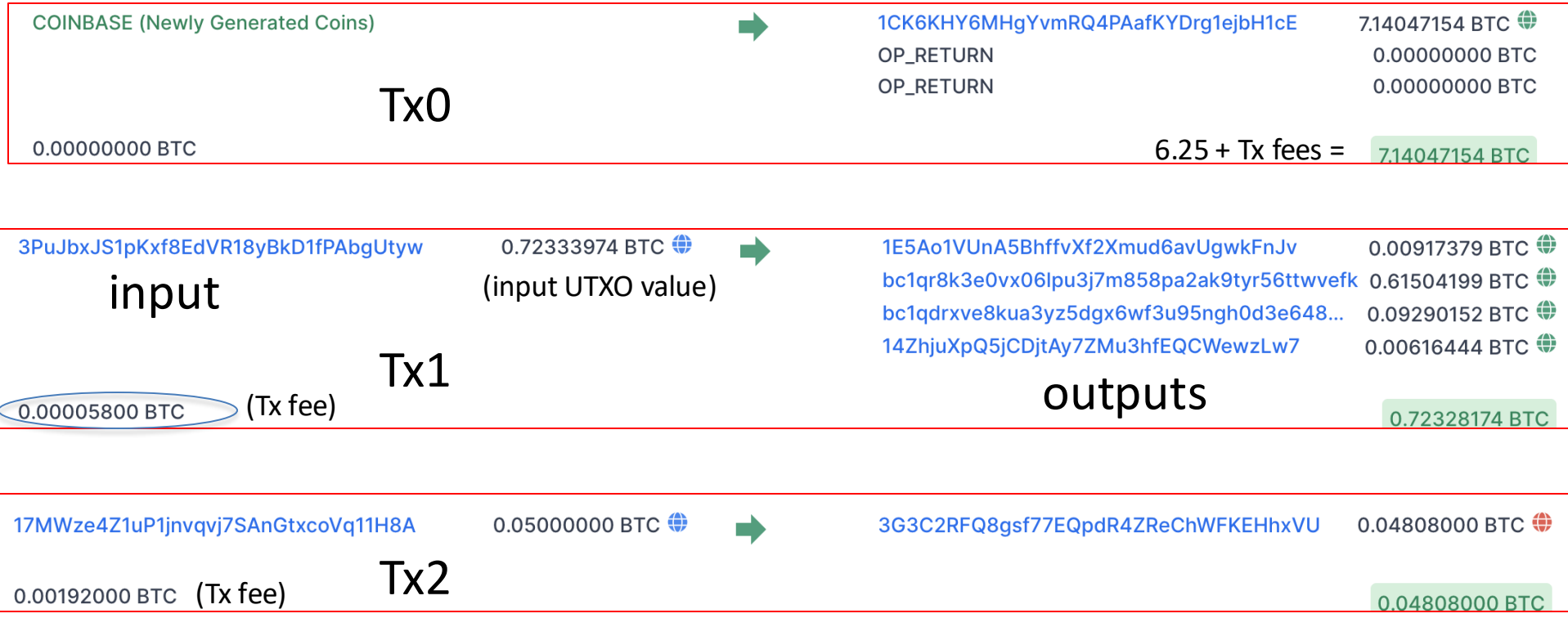
Miners check (for each input):

program from funding Tx: under what conditions can UTXO be spent

1. The program ScriptSig | ScriptPK returns true
2. TxID | index is in the current UTXO set
3. sum input values ≥ sum output values

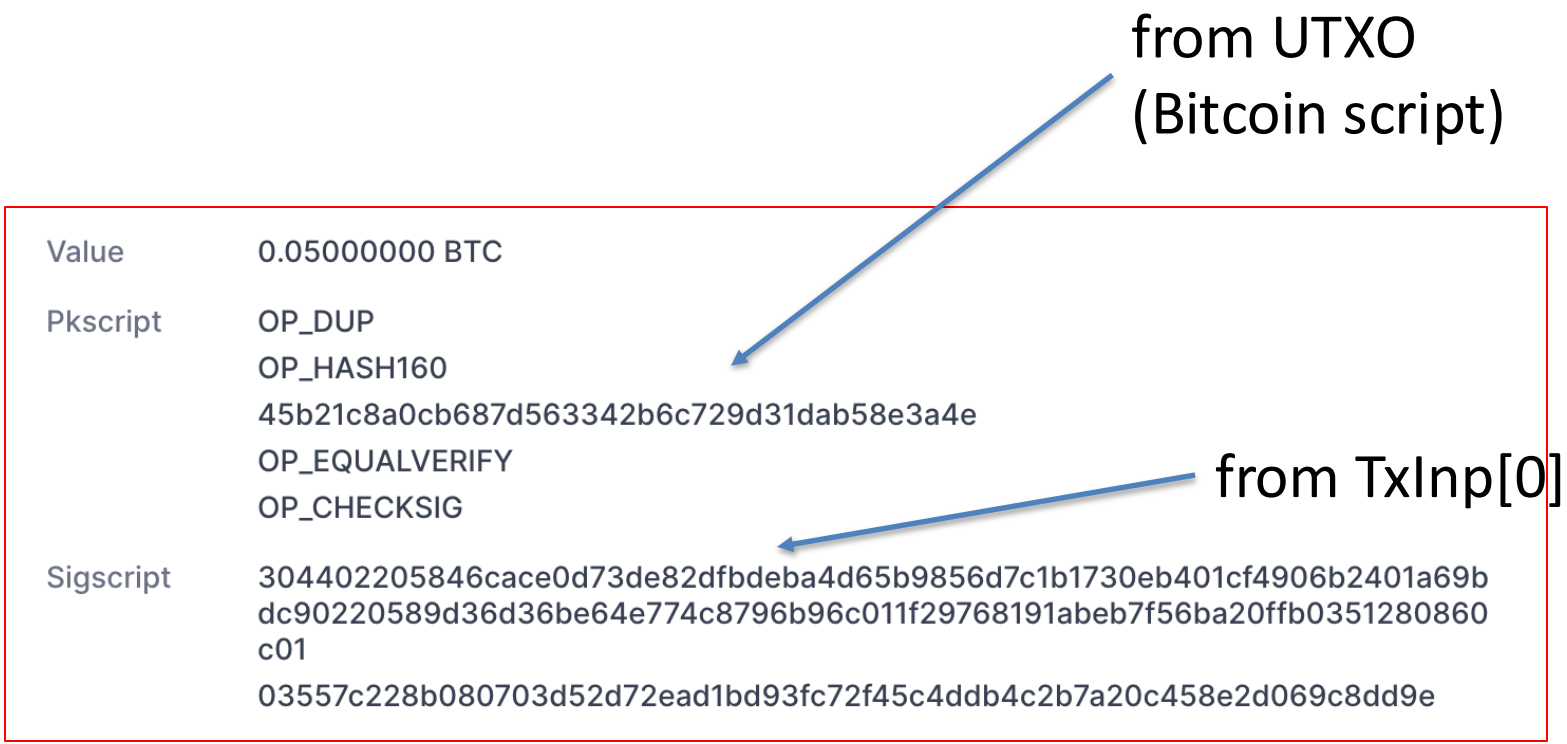
After Tx2 is posted, miners remove $UTXO_2$ from UTXO set

An example (block 648493) [2826 Tx]



sum of fees in block added to coinbase Tx

Focusing on Tx2: TxInp[0]



Transaction Script

What is Script?

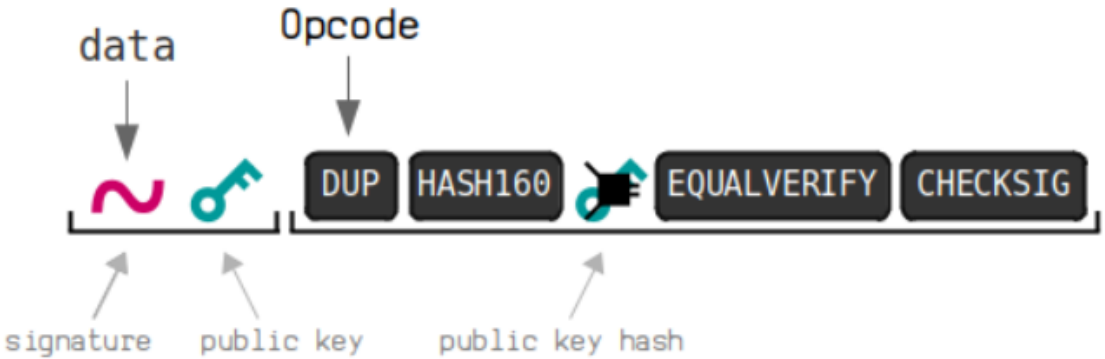
- Script is a mini programming language used as a locking mechanism for outputs in bitcoin transactions.
  - A locking script (ScriptPubKey) is placed on every transaction output.
  - An unlocking script (ScriptSig or Witness) must be provided to unlock an output (i.e. when used as an input to a transaction).
- If a full script (unlocking + locking) is valid, the output is "unlocked" and can be spent.

Script Language

Script is a very basic programming language. It consists of two things:

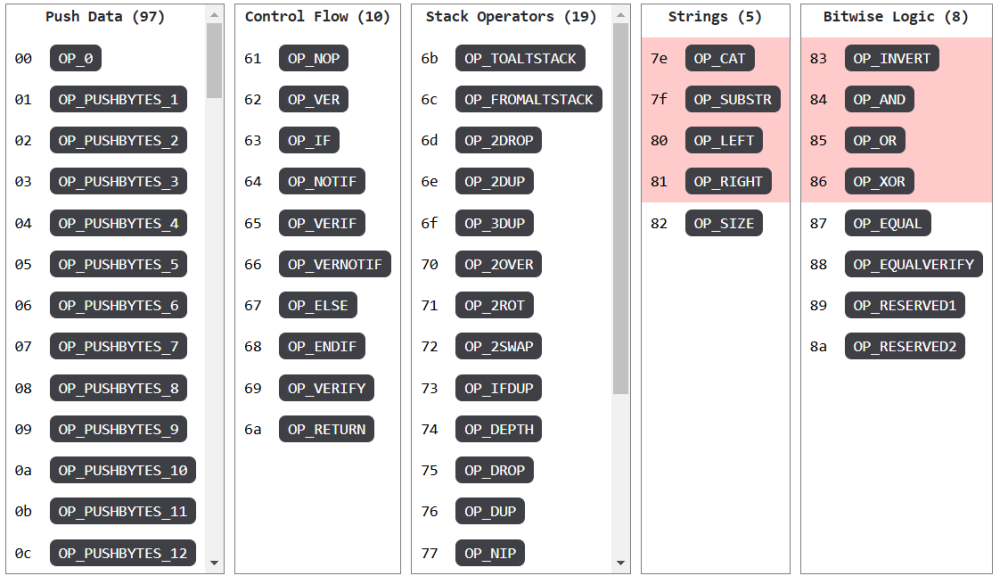
1. **Opcodes** – Simple functions that *operate* on data.
2. **Data** – Such as public keys and signatures.

Here's a simple diagram of a typical P2PKH script used in Bitcoin:



Opcodes

- Here's a quick list of all the opcodes available in the Script language (along with the corresponding hexadecimal byte used to represent each one).



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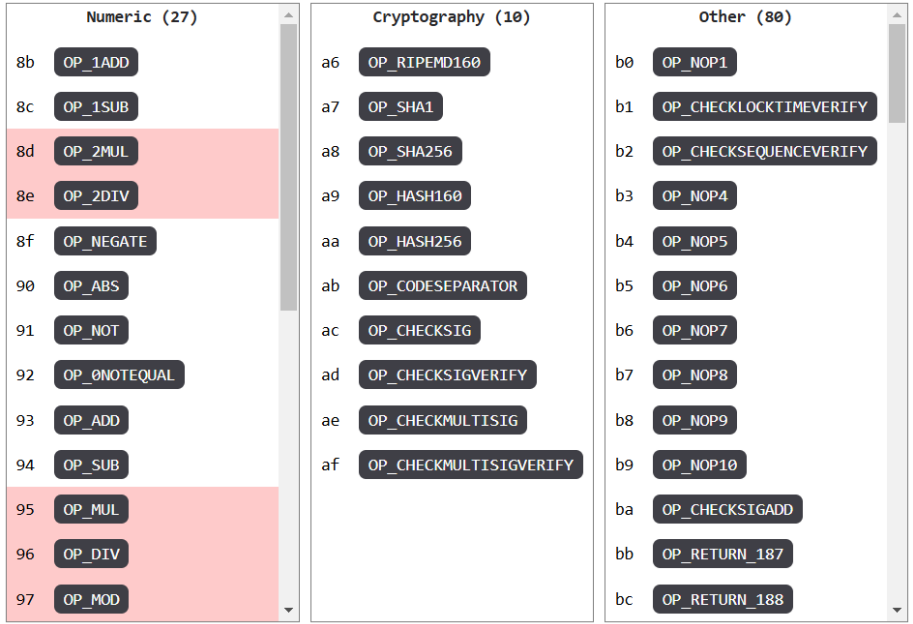


Numeric (27)

8b	OP_1ADD
8c	OP_1SUB
8d	OP_2MUL
8e	OP_2DIV
8f	OP_NEGATE
90	OP_ABS
91	OP_NOT
92	OP_0NOTEQUAL
93	OP_ADD
94	OP_SUB
95	OP_MUL
96	OP_DIV
97	OP_MOD

Cryptography (10)

a6	OP_RIPEMD160
a7	OP_SHA1
a8	OP_SHA256
a9	OP_HASH160
aa	OP_HASH256
ab	OP_CODESEPARATOR
ac	OP_CHECKSIG
ad	OP_CHECKSIGVERIFY
ae	OP_CHECKMULTISIG
af	OP_CHECKMULTISIGVERIFY

Other (80)

b0	OP_NOP1
b1	OP_CHECKLOCKTIMEVERIFY
b2	OP_CHECKSEQUENCEVERIFY
b3	OP_NOP4
b4	OP_NOP5
b5	OP_NOP6
b6	OP_NOP7
b7	OP_NOP8
b8	OP_NOP9
b9	OP_NOP10
ba	OP_CHECKSIGADD
bb	OP_RETURN_187
bc	OP_RETURN_188

Data

The data elements inside a Script (e.g. public keys, signatures) have to be **manually pushed on to the stack** using an opcode.

There are a few specific opcodes you can choose from to do this, and the one you use depends on *how many bytes* you want to push on to the stack.

`OP_0` to `OP_16`: (single byte representing numbers 0 to 16) [show]

`OP_PUSHBYTES_X`: 1 to 75 bytes [show]

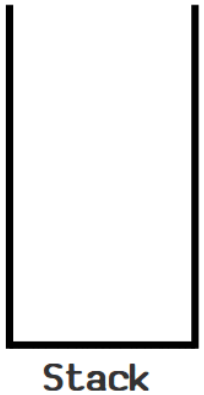
`OP_PUSHDATA1`: 76 to 255 bytes [show]

`OP_PUSHDATA2`: 256 to 65535 bytes [show]

`OP_PUSHDATA4`: 65536 to 4294967295 bytes [show]

Execution

- A complete script is run from left-to-right. As it runs, it makes use of a data structure called a stack.
- Data is pushed on to the stack.



Bitcoin Script

A stack machine. Not Turing Complete: no loops.

Quick survey of op codes:

1. **OP_TRUE** (OP_1), **OP_2**, …, **OP_16**: push value onto stack

   81 82 96

2. **OP_DUP**: push top of stack onto stack

   118

Bitcoin Script

3. control:

99 **OP_IF** <statements> **OP_ELSE** <statements> **OP_ENDIF**

105 **OP_VERIFY**: abort fail if top = false

106 **OP_RETURN**: abort and fail

what is this for? ScriptPK = [OP_RETURN, <data>]

136 **OP_EQVERIFY**: pop, pop, abort fail if not equal

Bitcoin Script

4. arithmetic:

   OP_ADD, **OP_SUB**, **OP_AND**, …: pop two items, add, push

5. crypto:

   OP_SHA256: pop, hash, push

   OP_CHECKSIG: pop pk, pop sig, verify sig. on Tx, push 0 or 1

6. Time: **OP_CheckLockTimeVerify** (CLTV):

   fail if value at the top of stack > Tx locktime value.

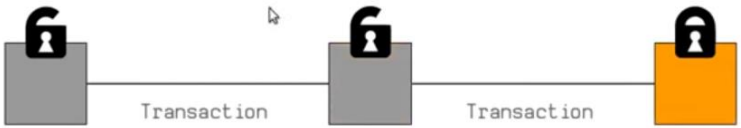
   usage: UTXO can specify min-time when it can be spent

Script

Script

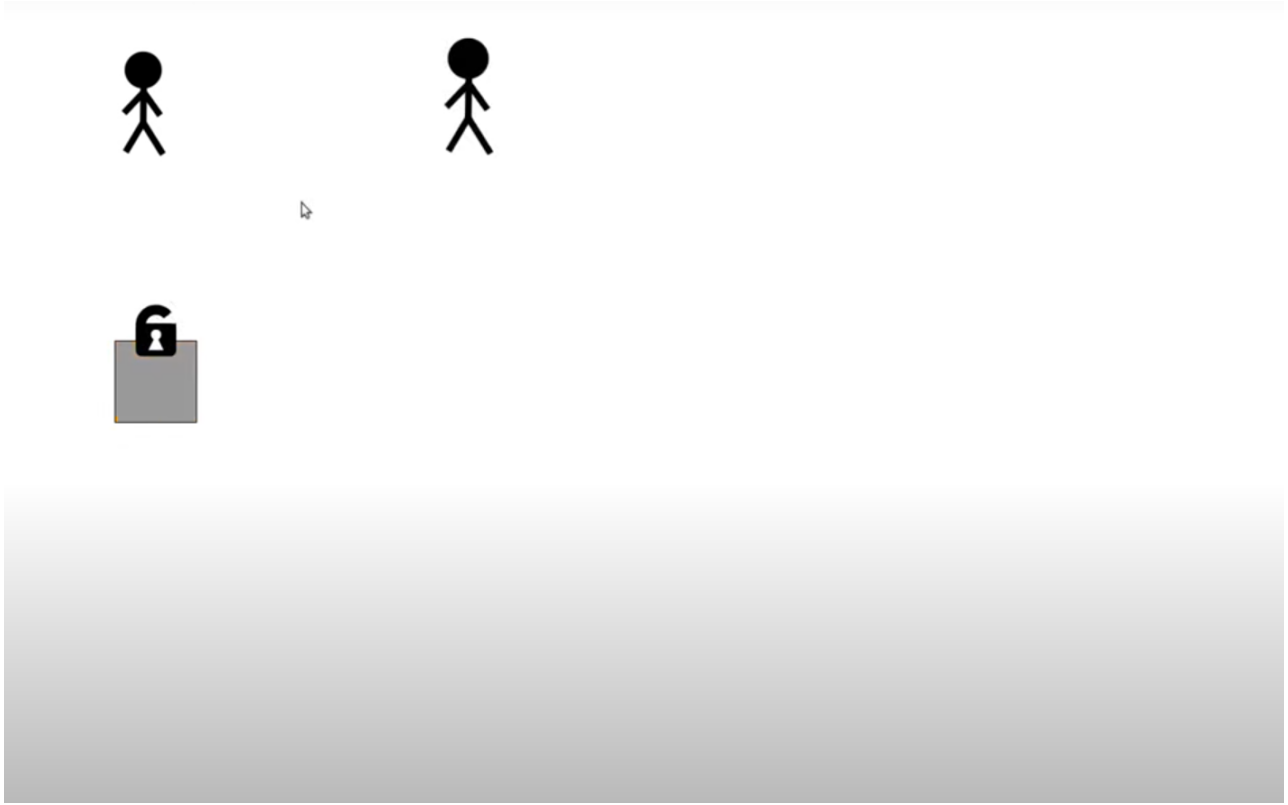
Script

Script



Script

Script



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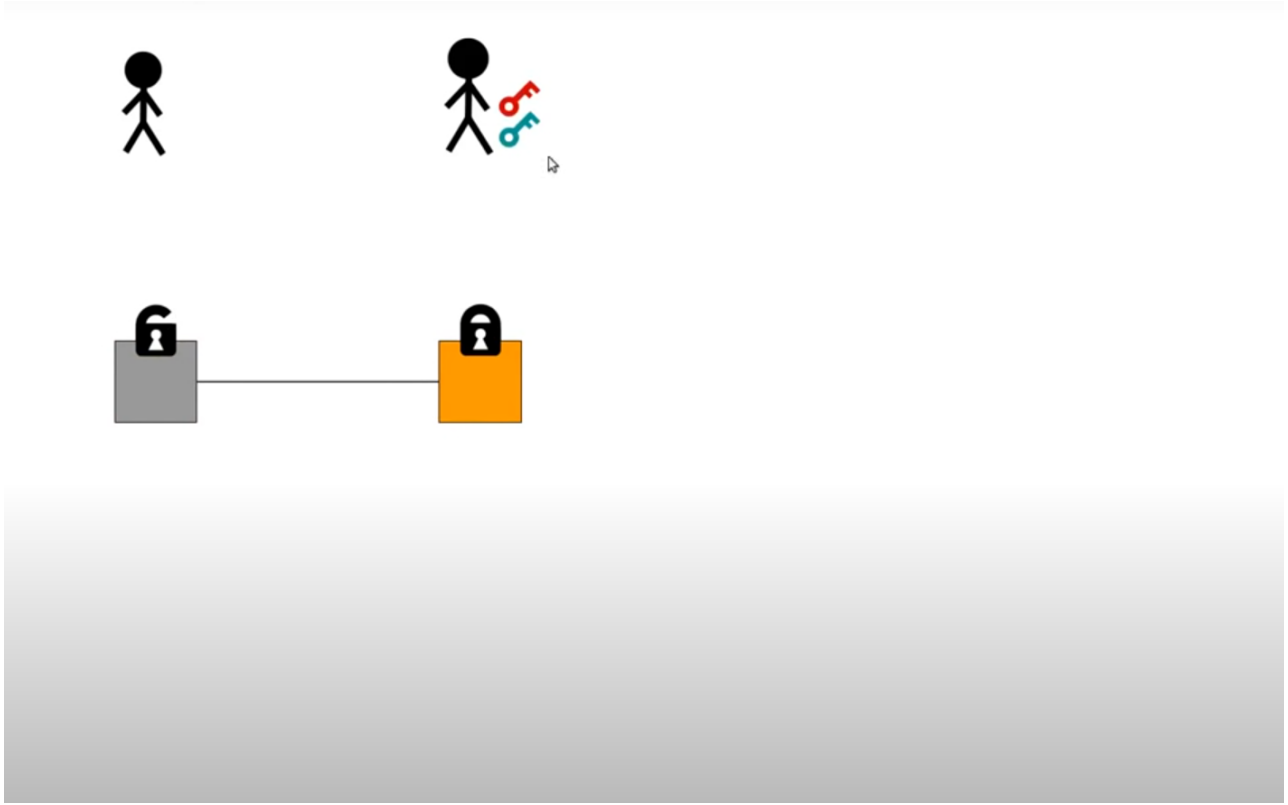

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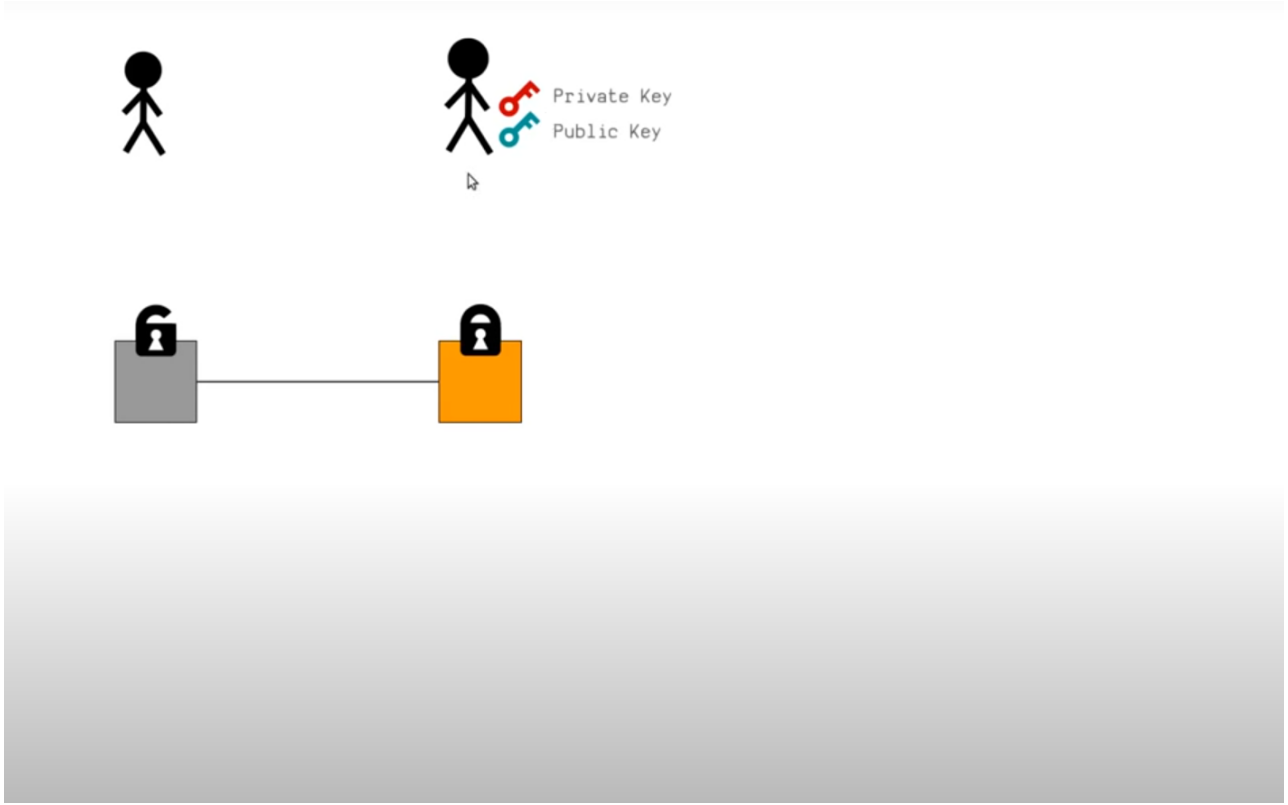

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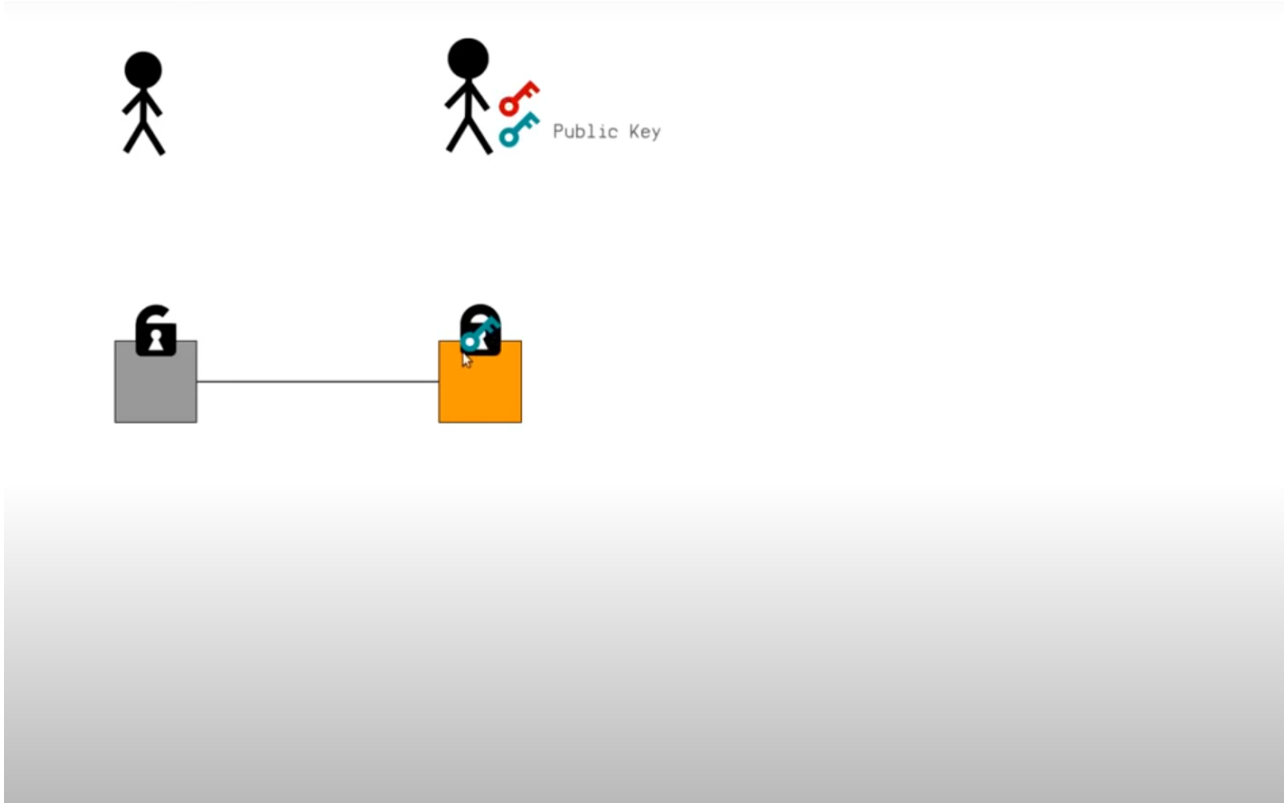

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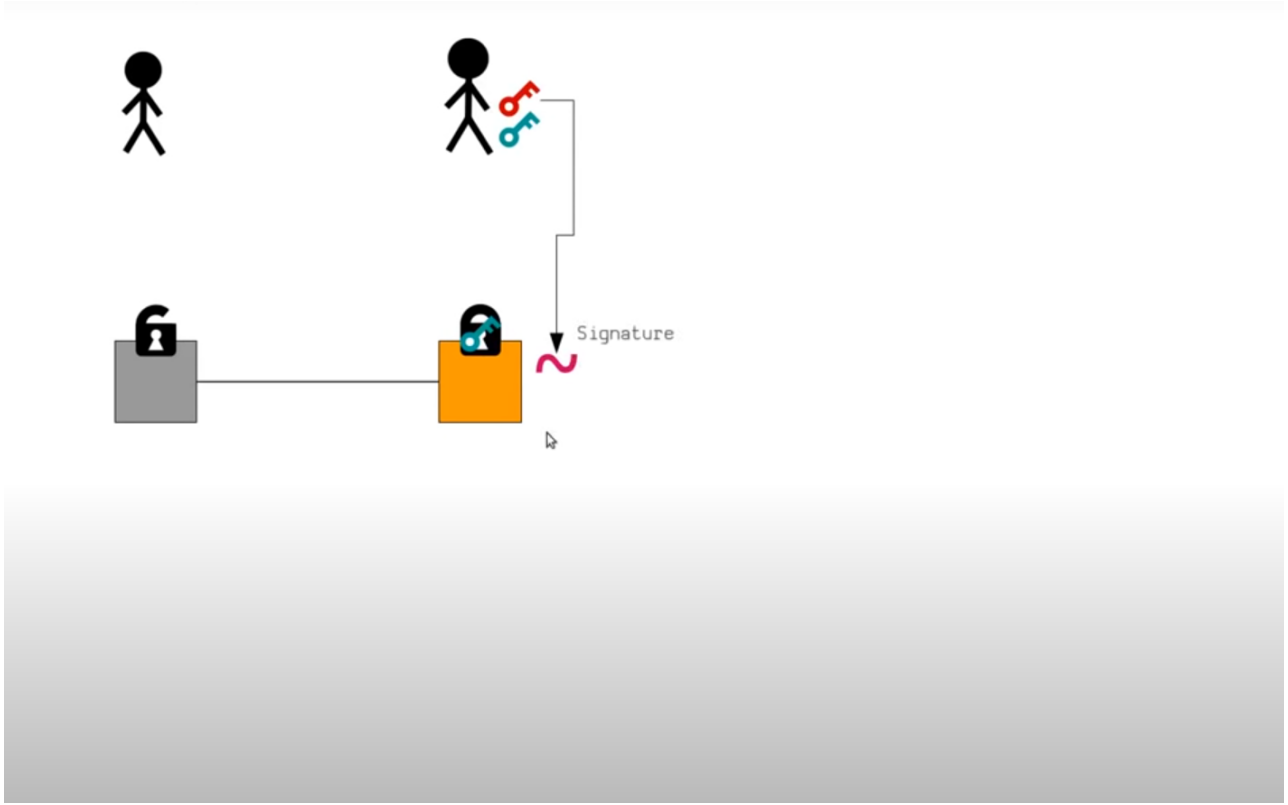

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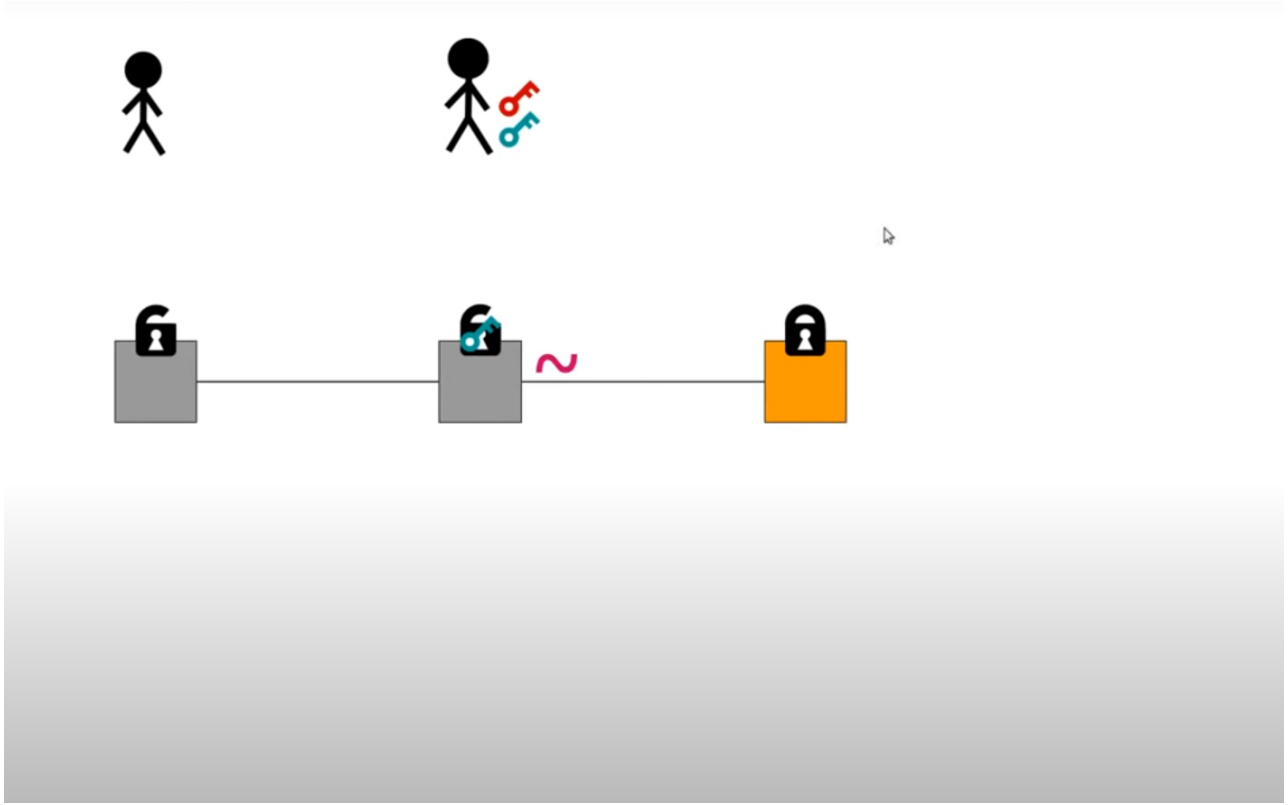

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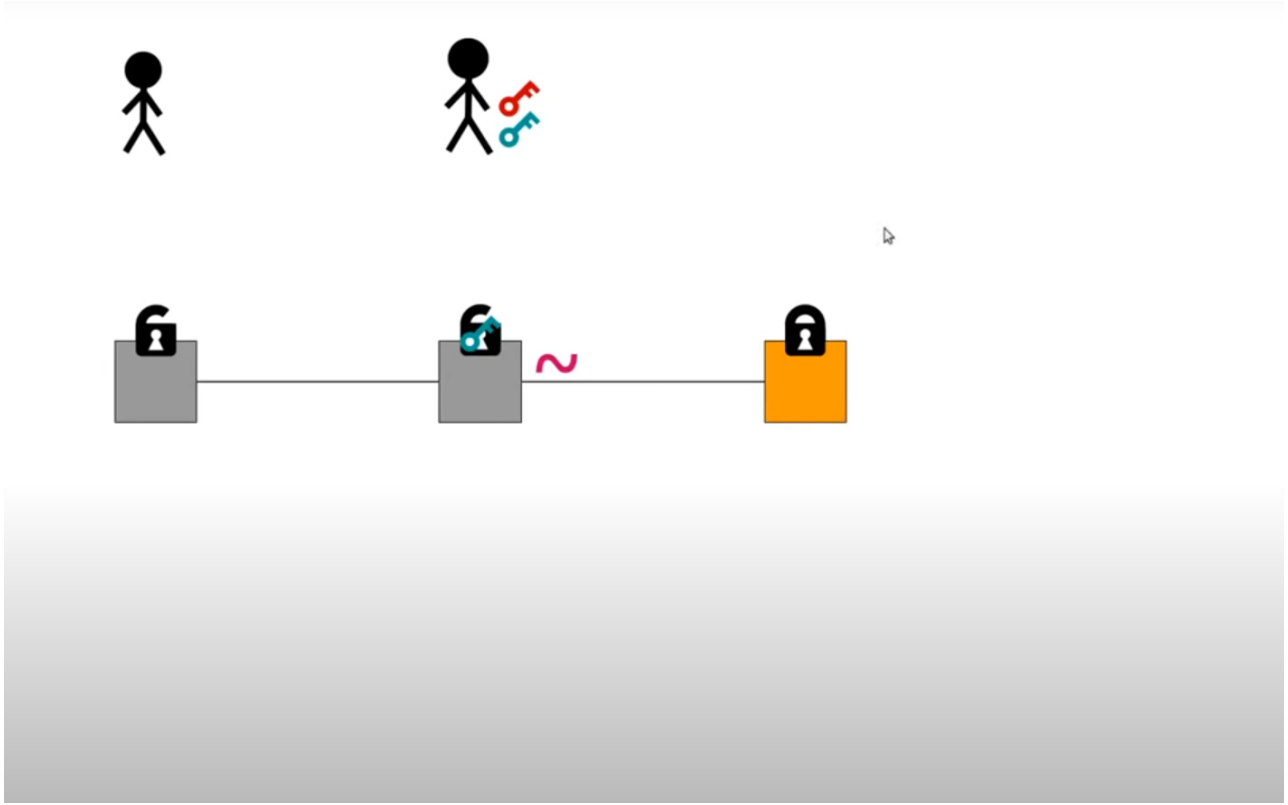

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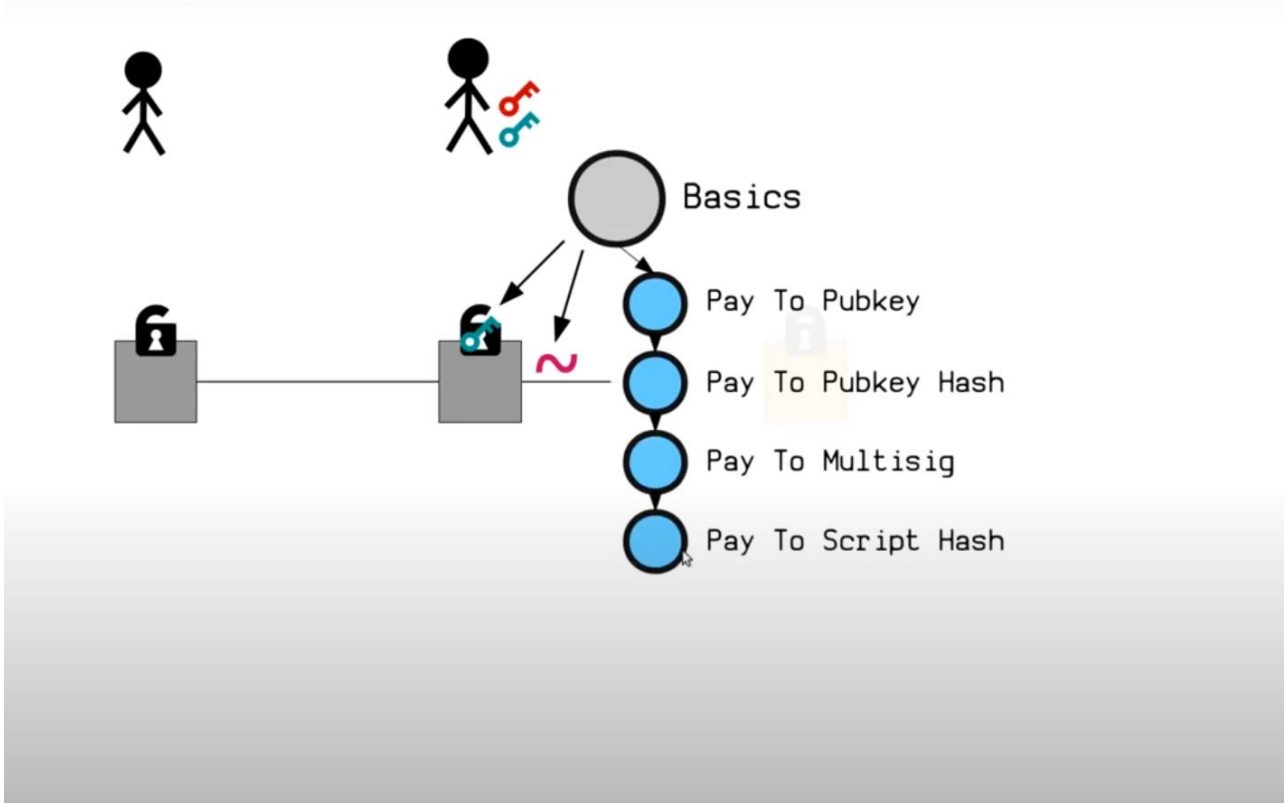
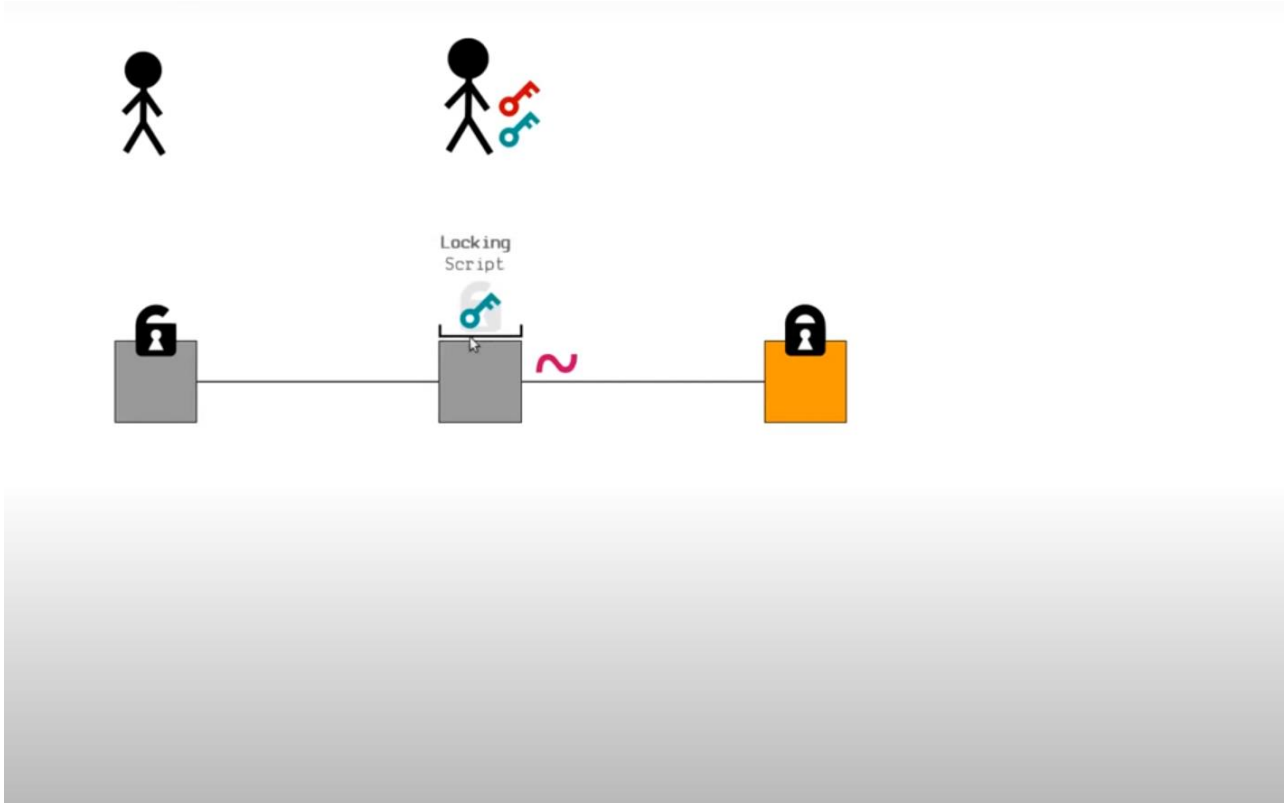

Basics
Pay To Pubkey
Pay To Pubkey Hash
Pay To Multisig
Pay To Script Hash

Script



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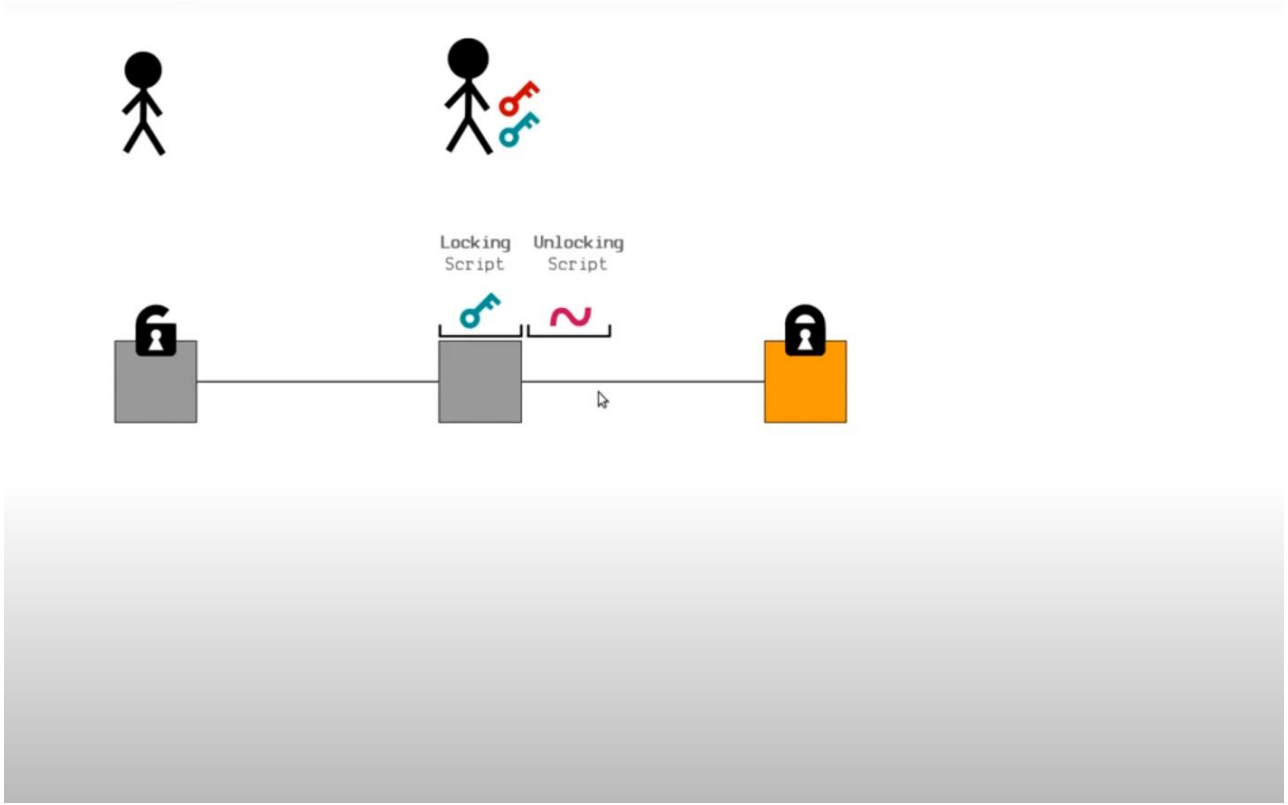

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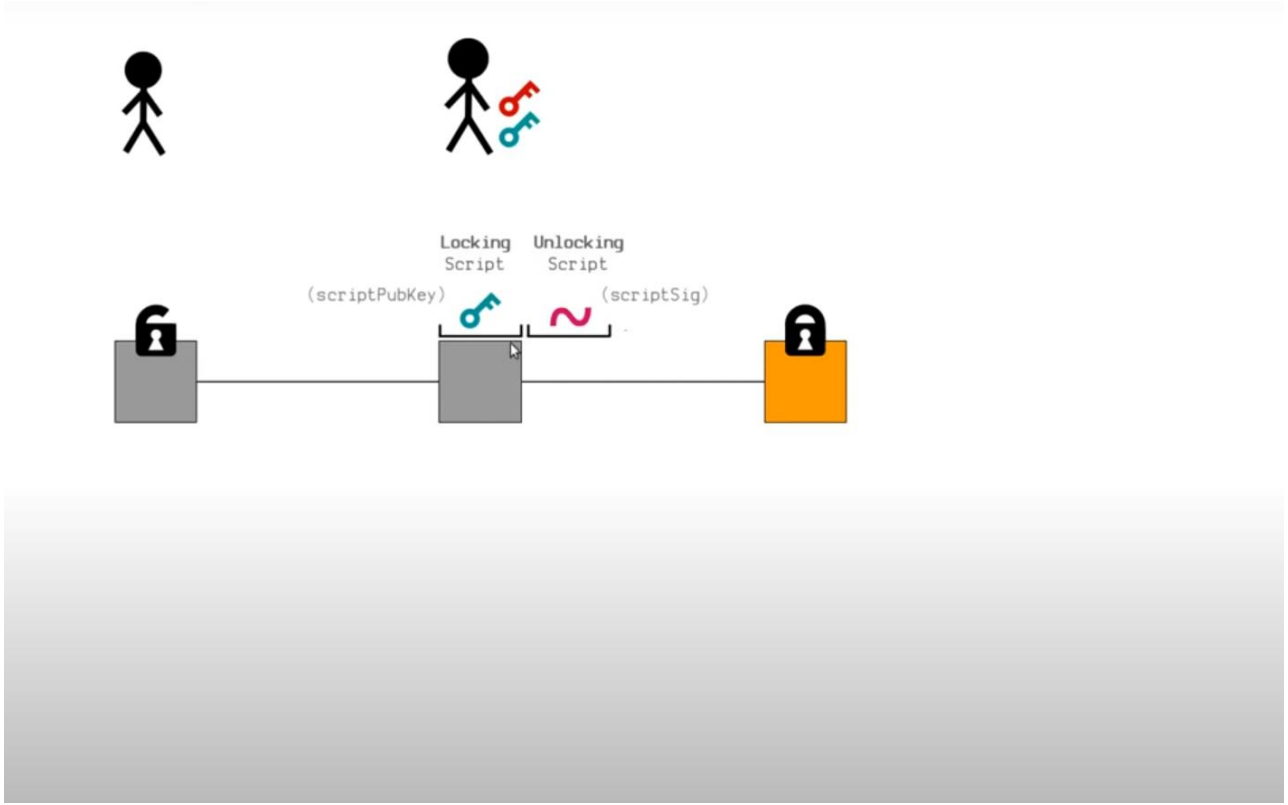

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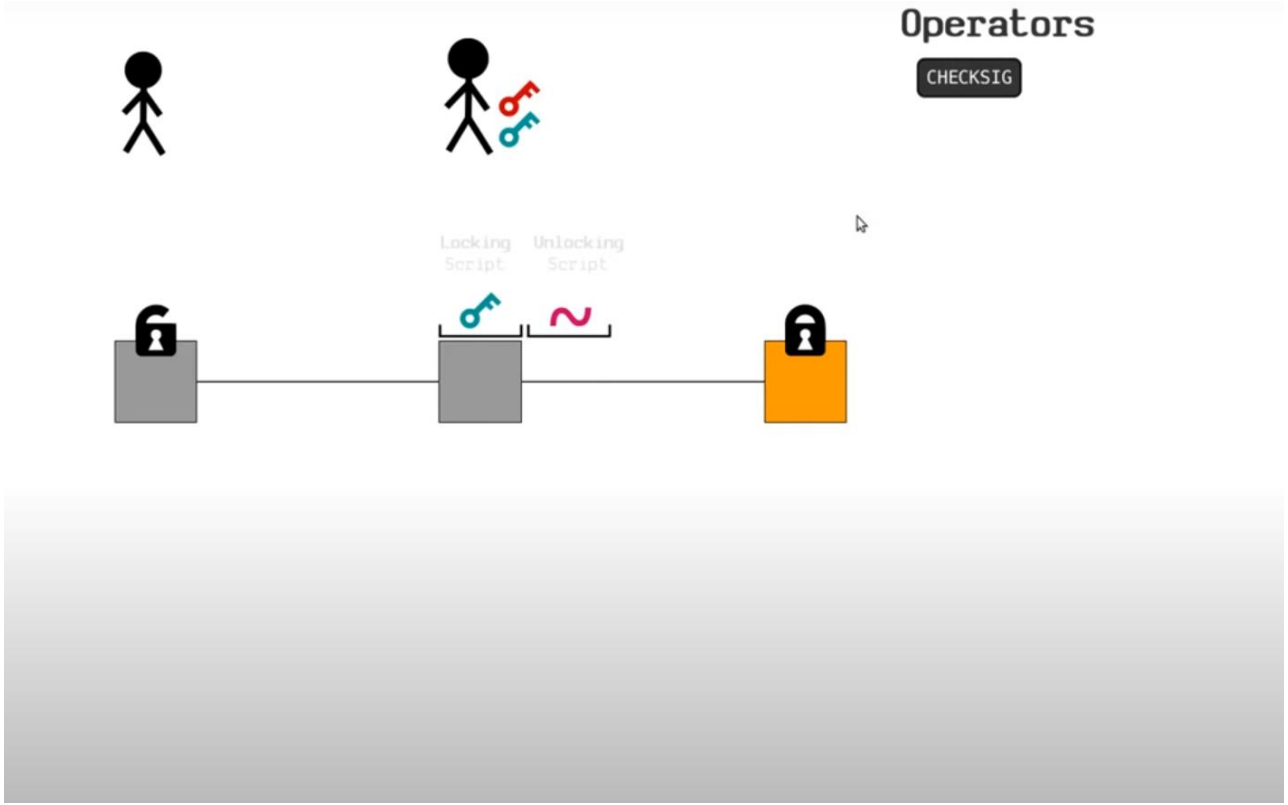

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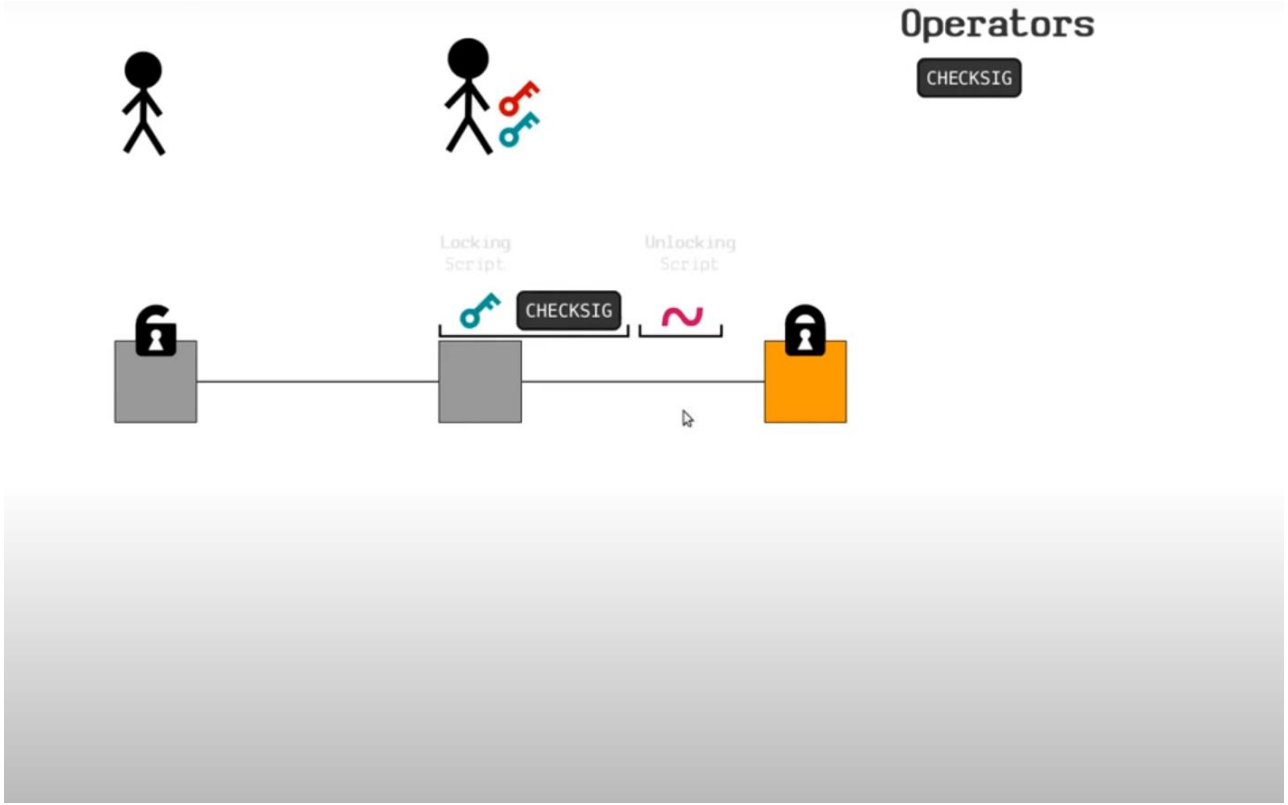
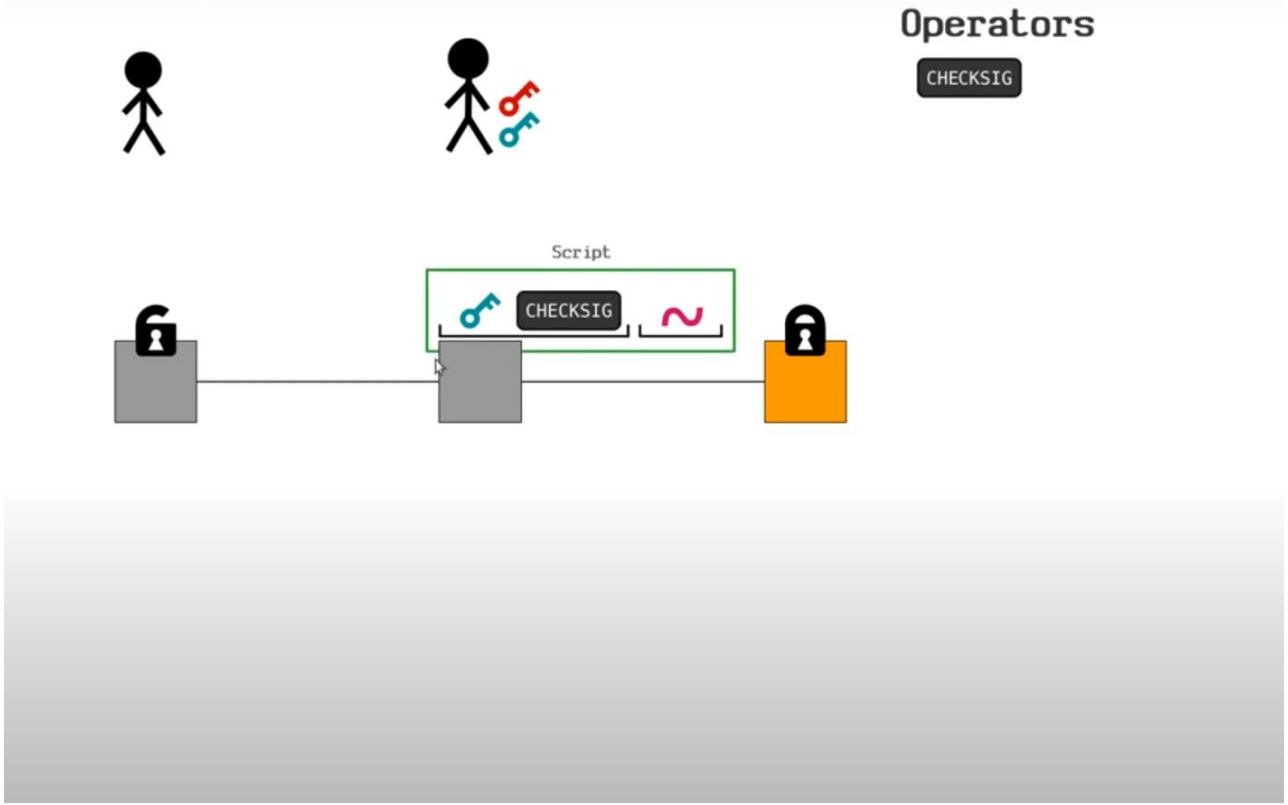

Operators
CHECKSIG
Locking Script
Unlocking Script
CHECKSIG

Script



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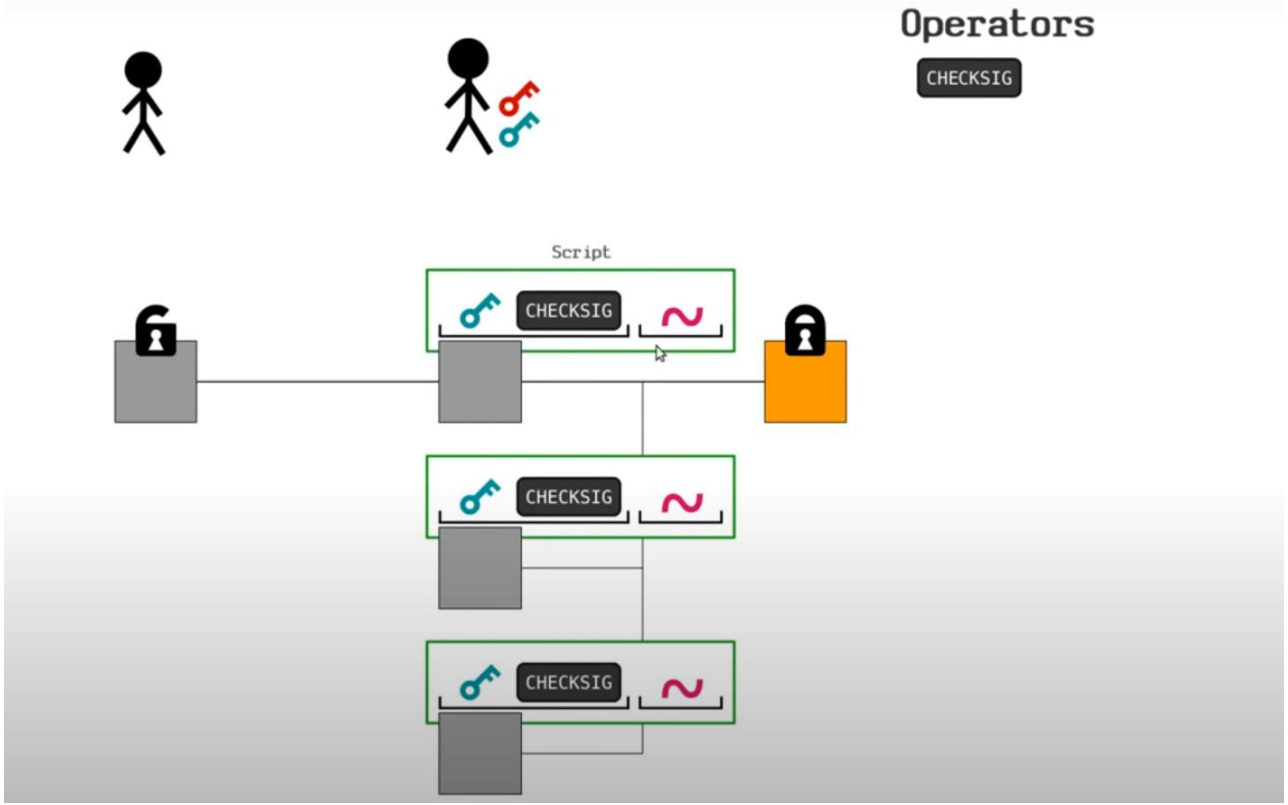

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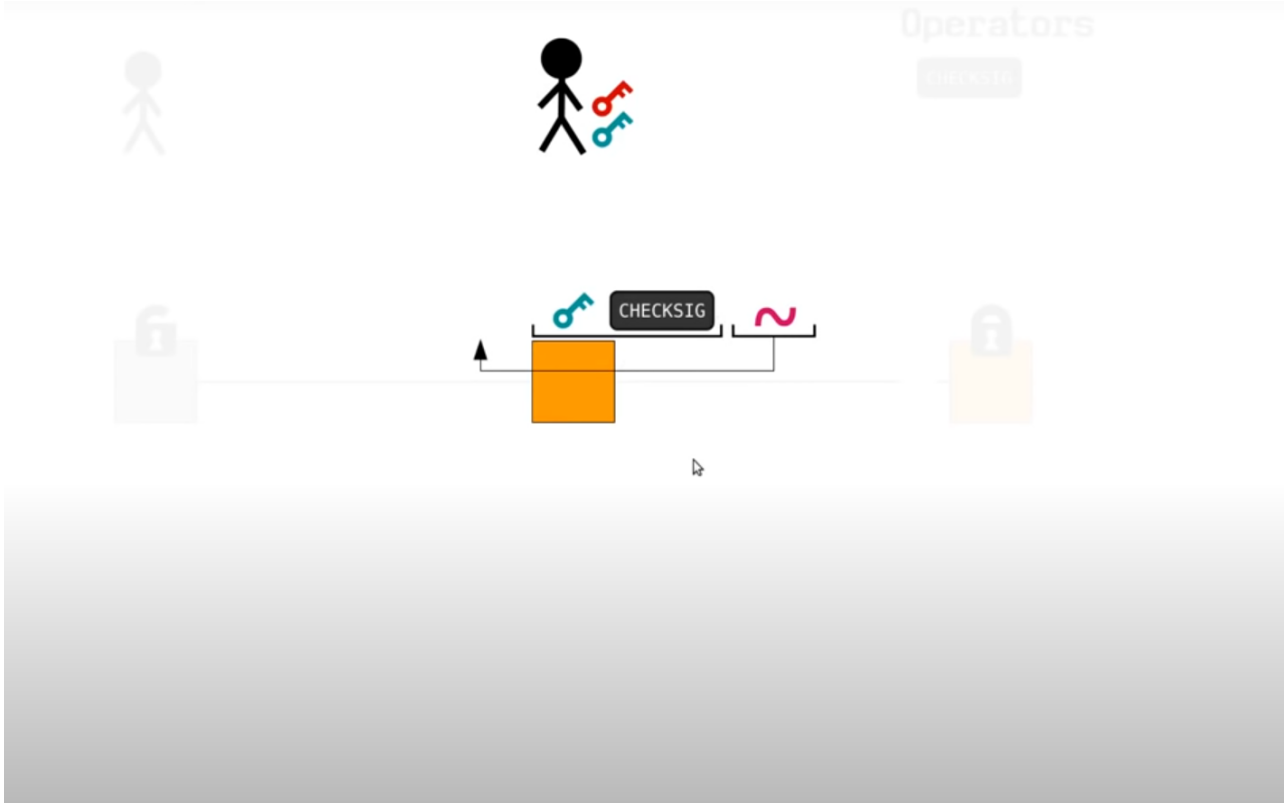

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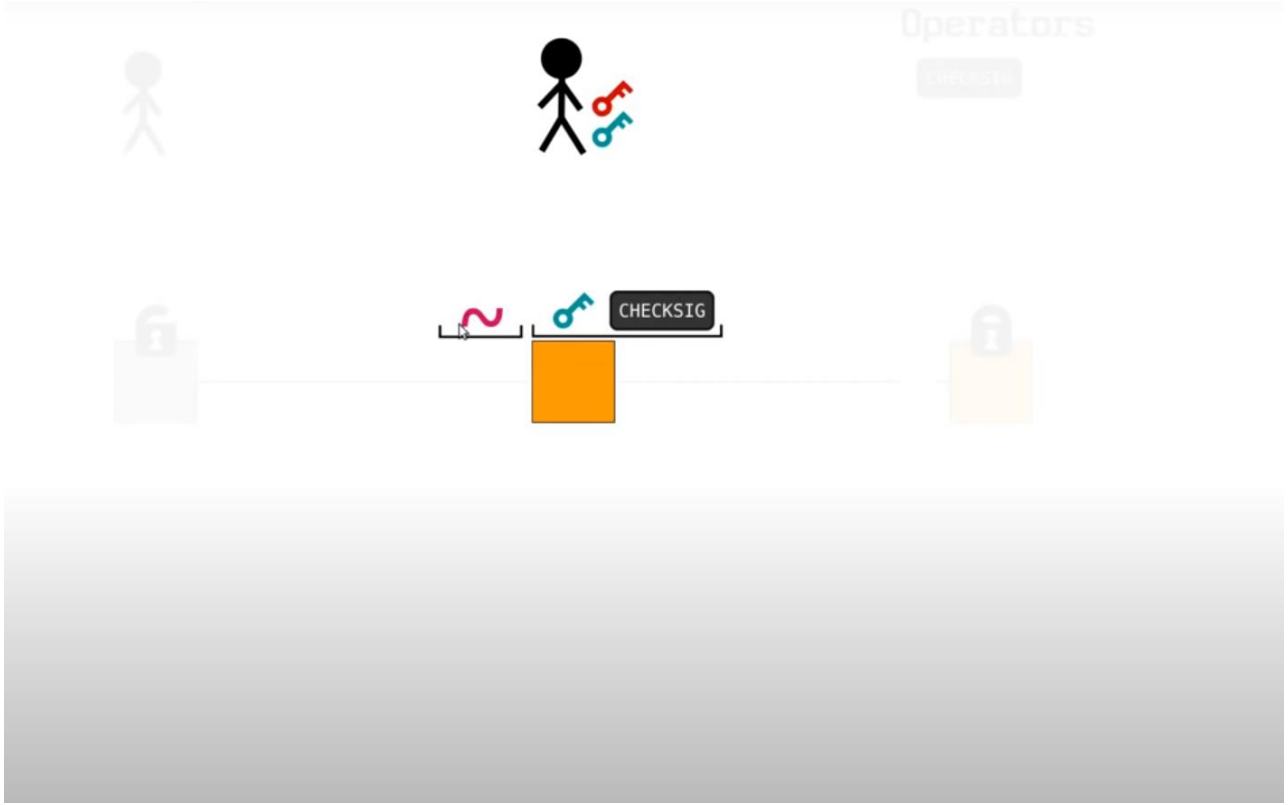

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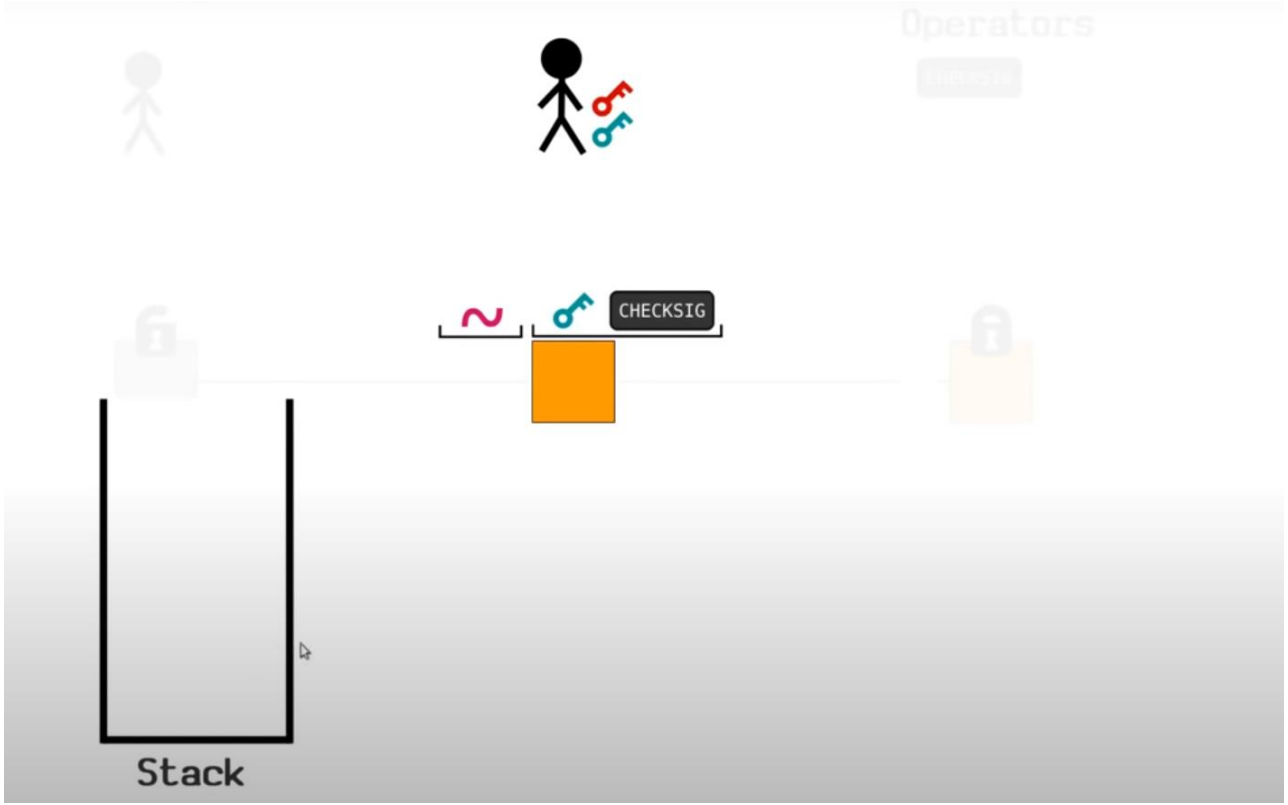

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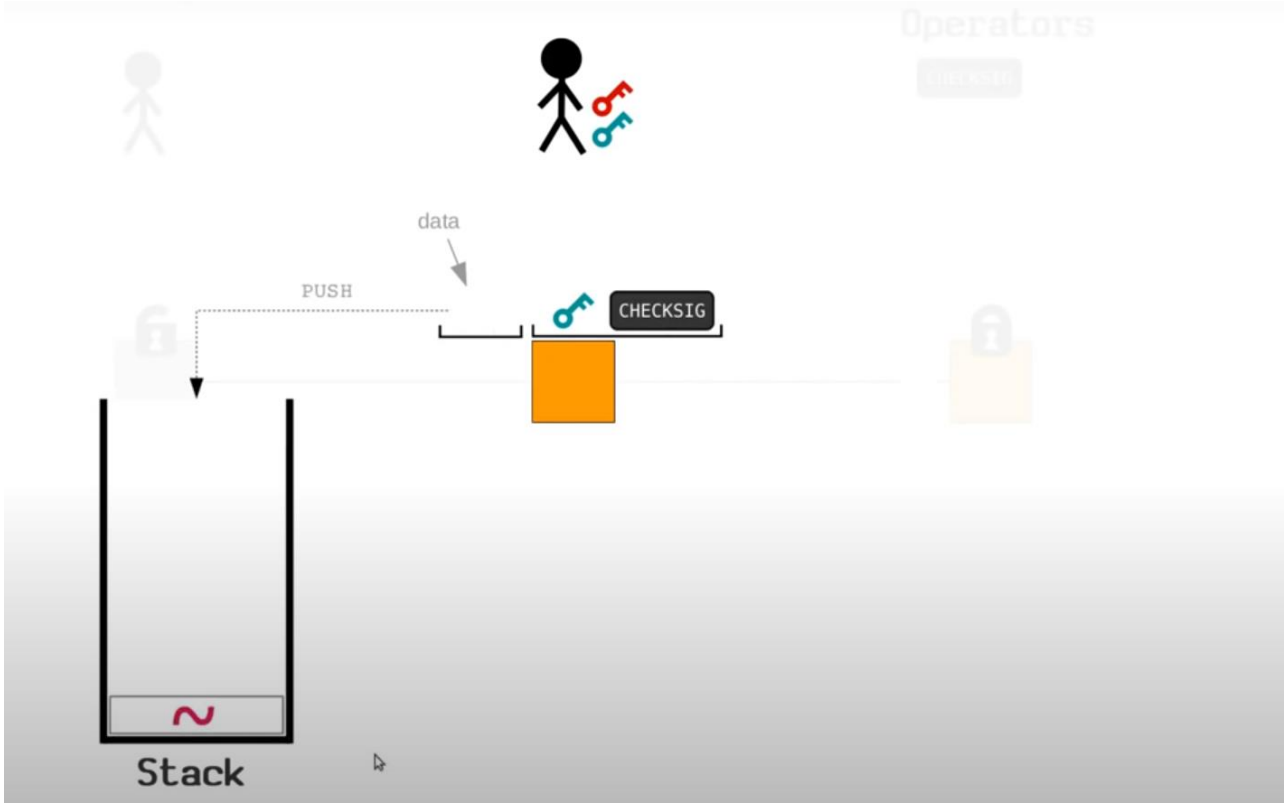

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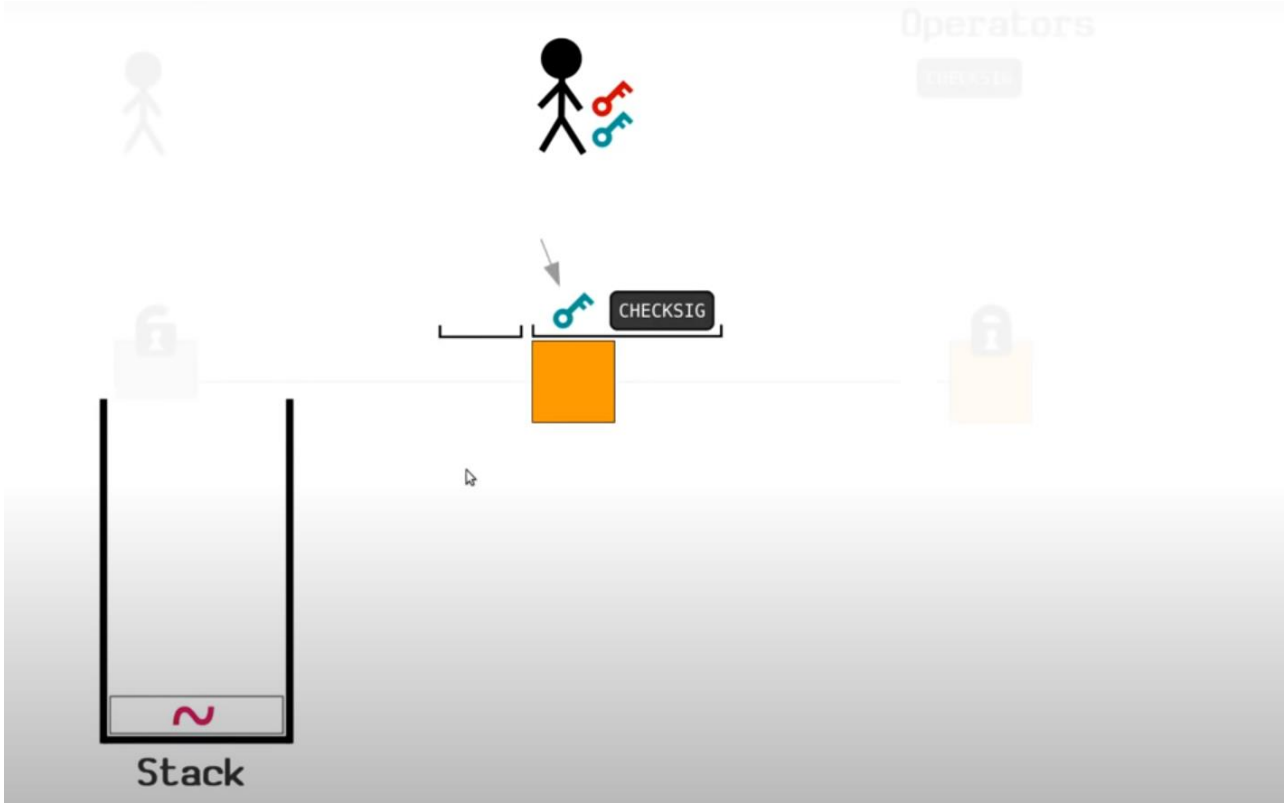

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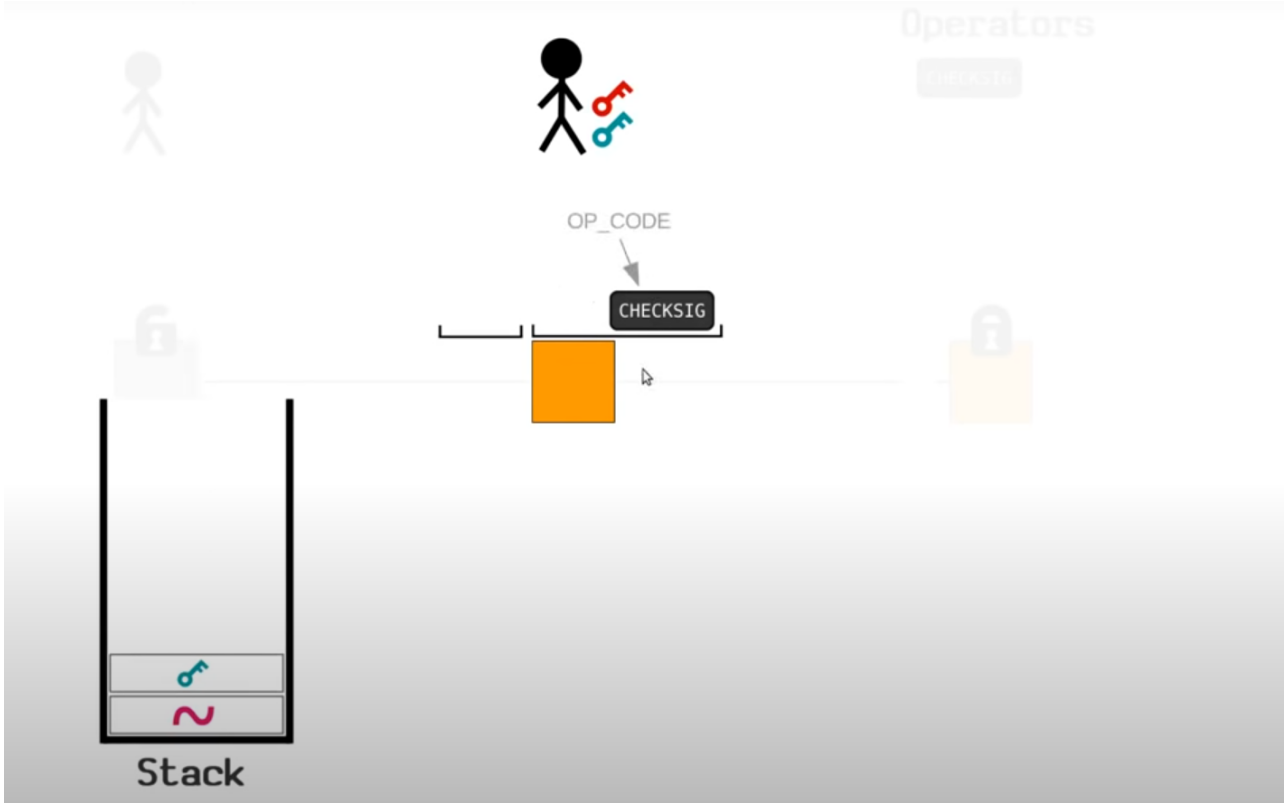

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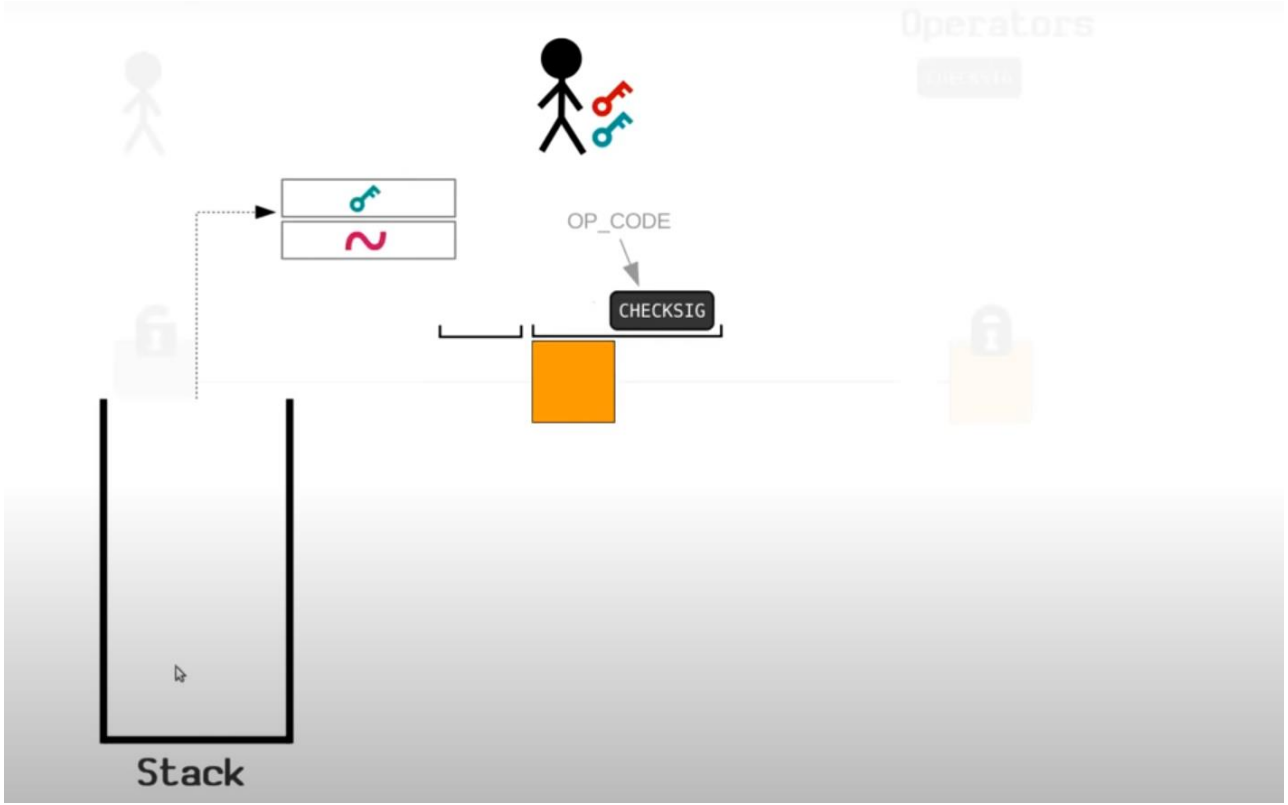

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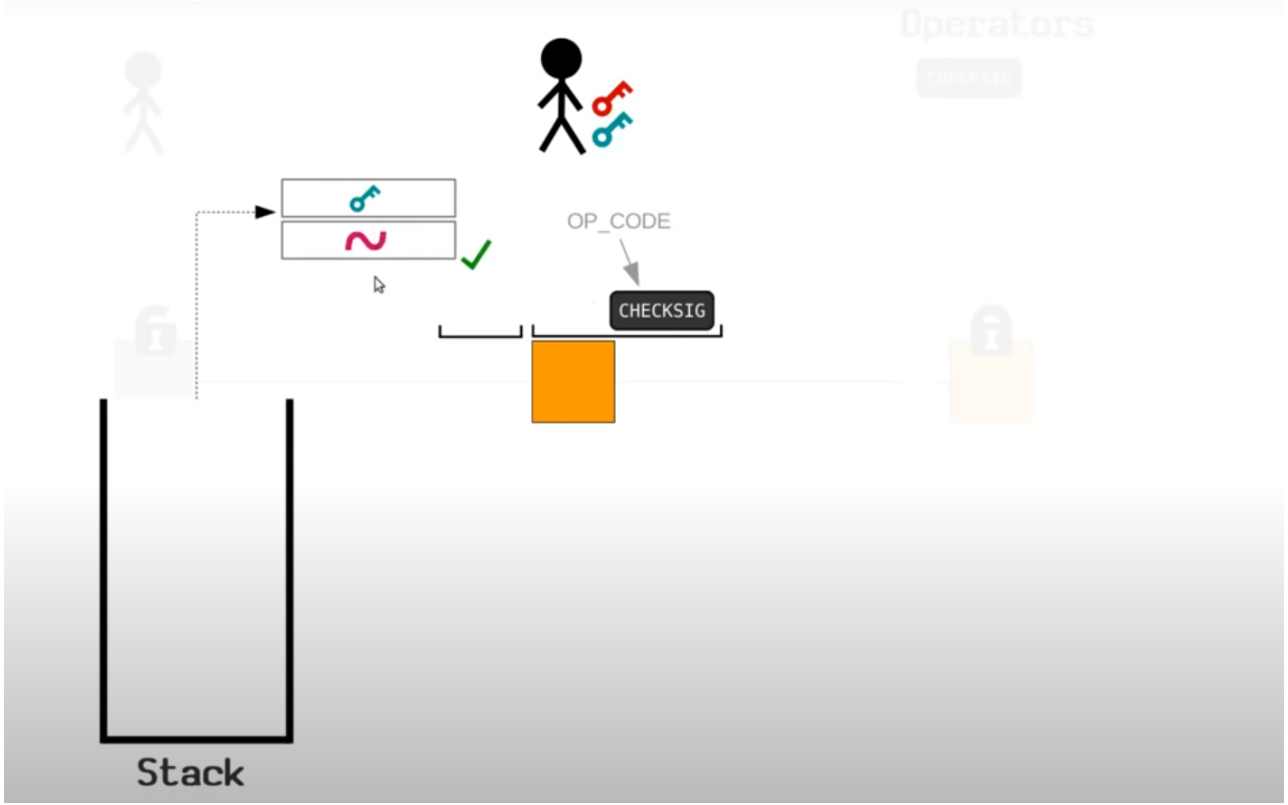

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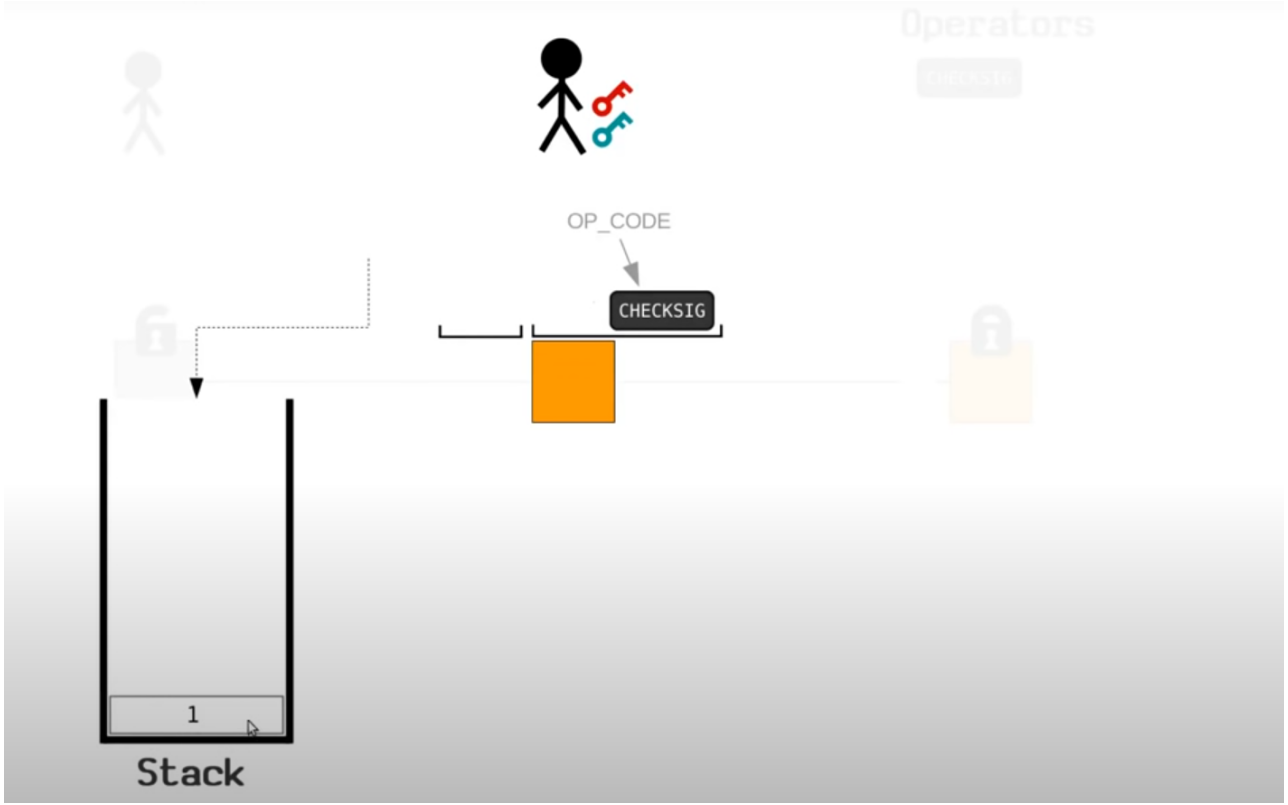

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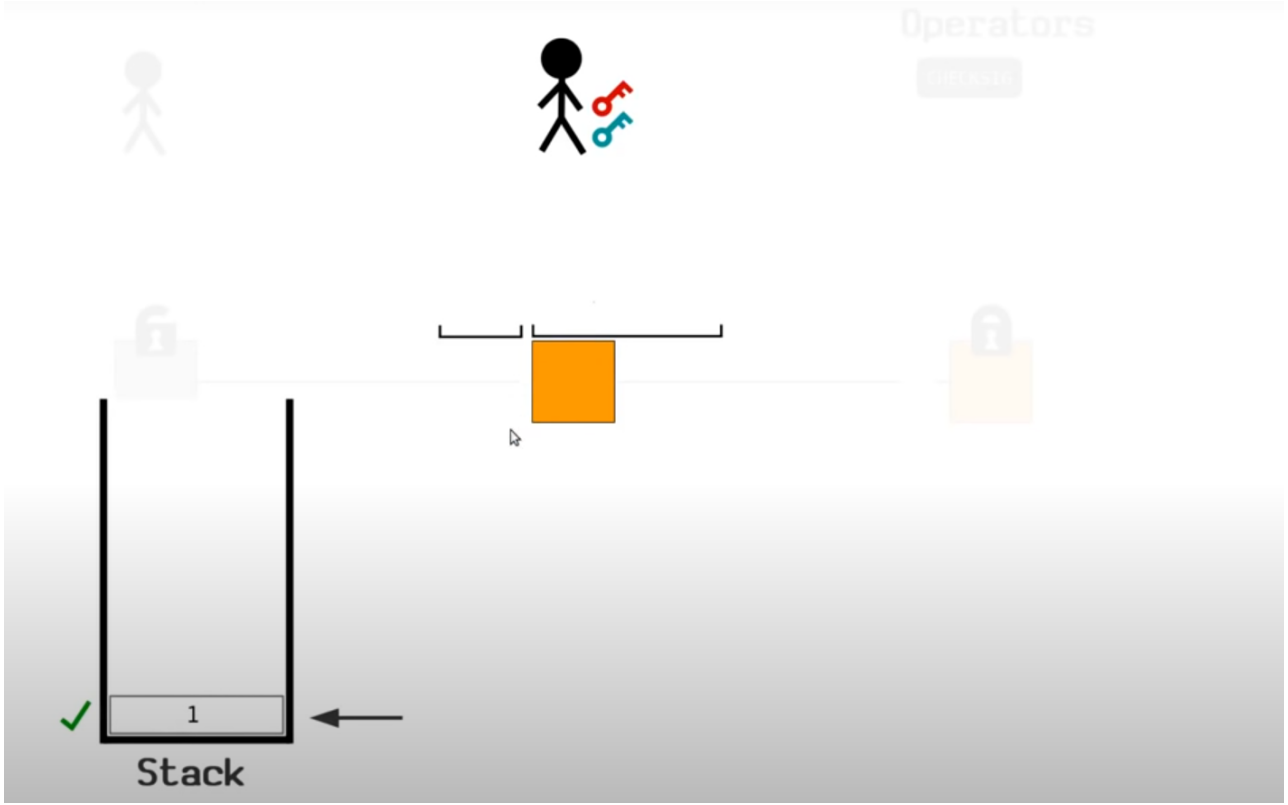

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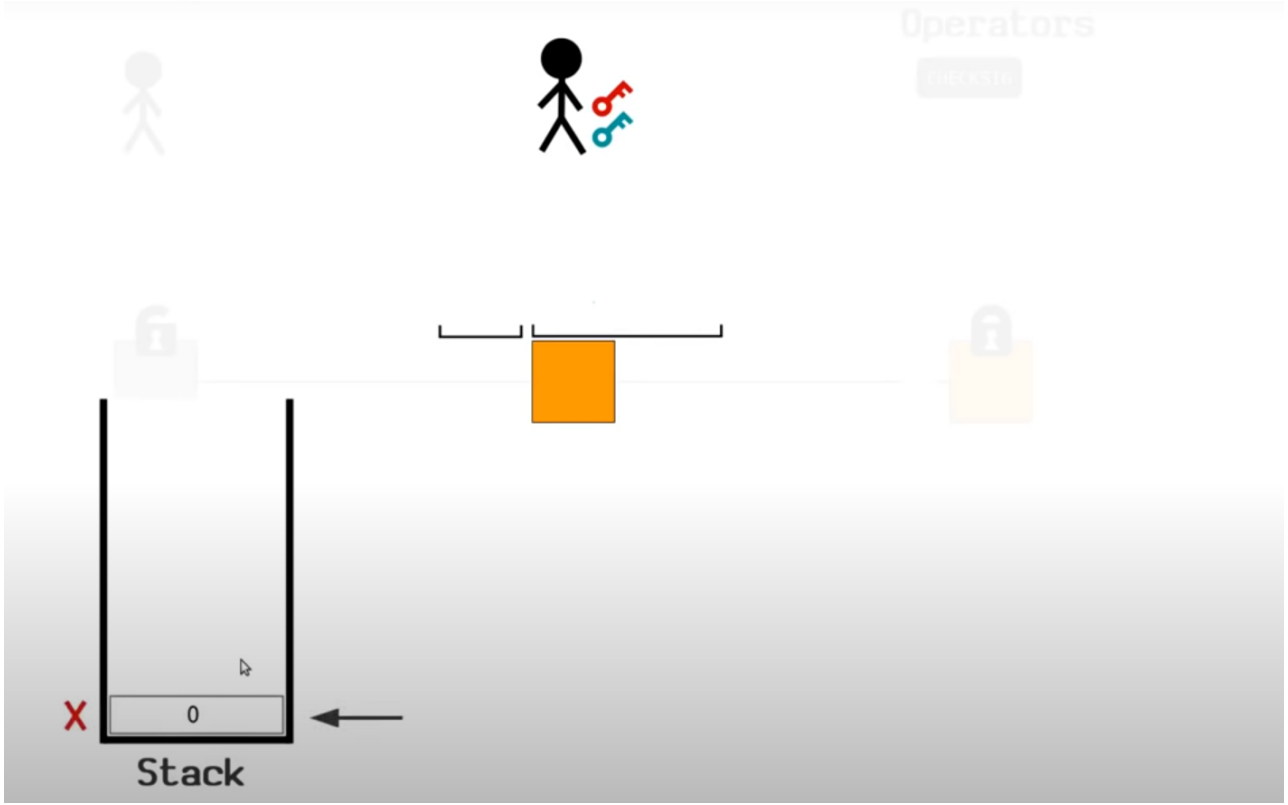
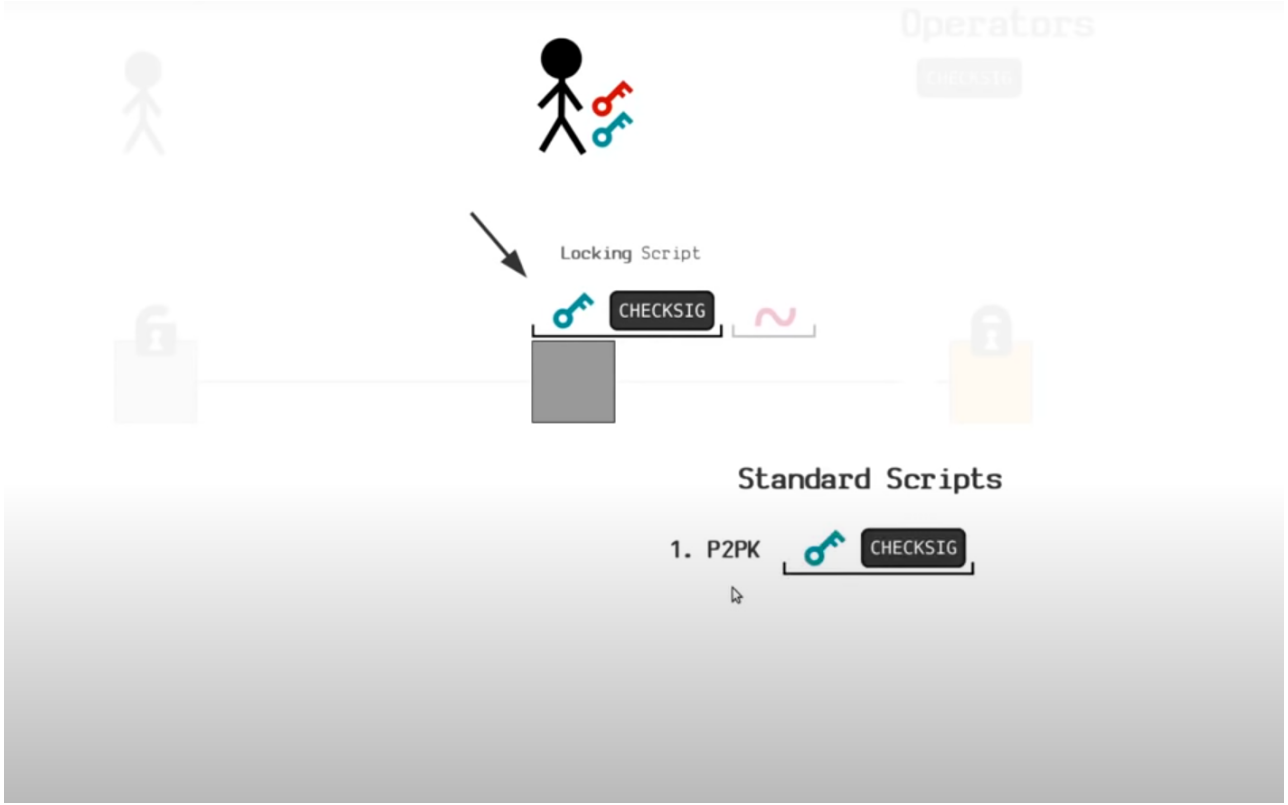


Pay to PublicKey (P2PK)



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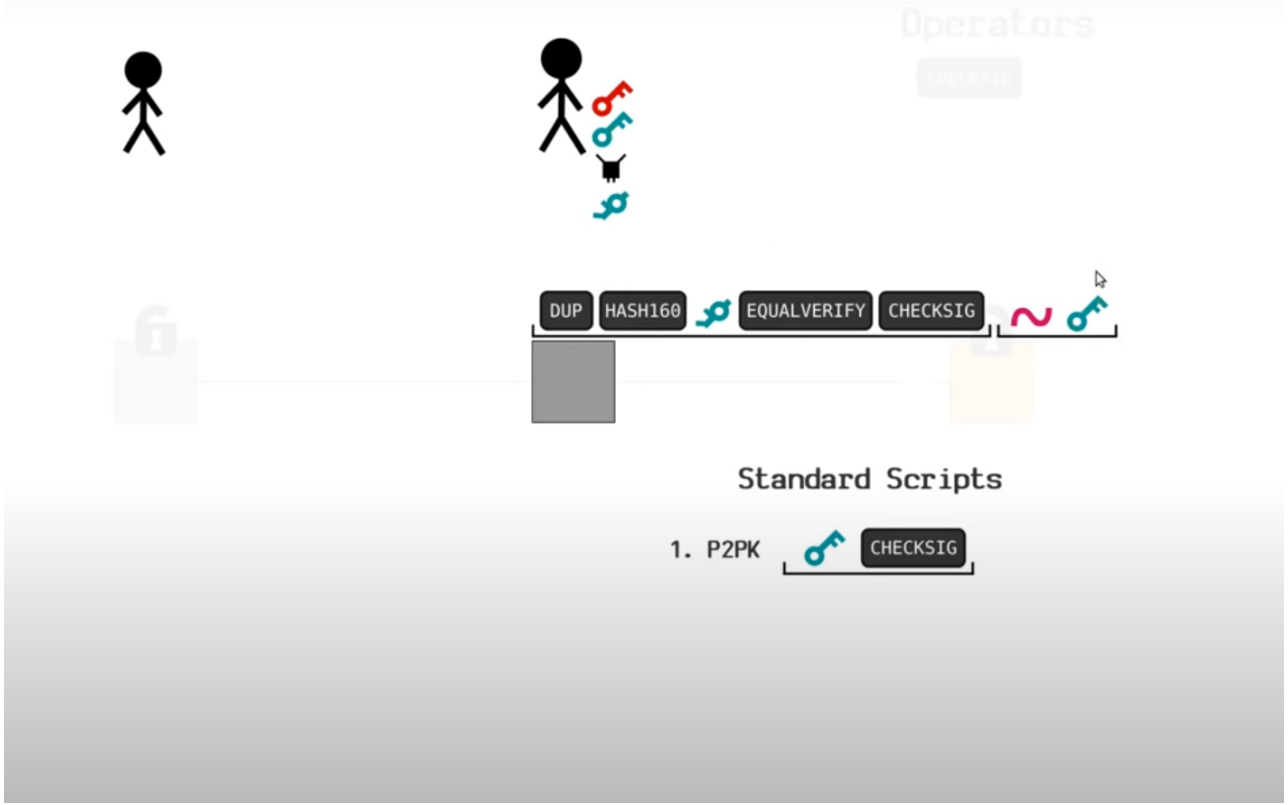

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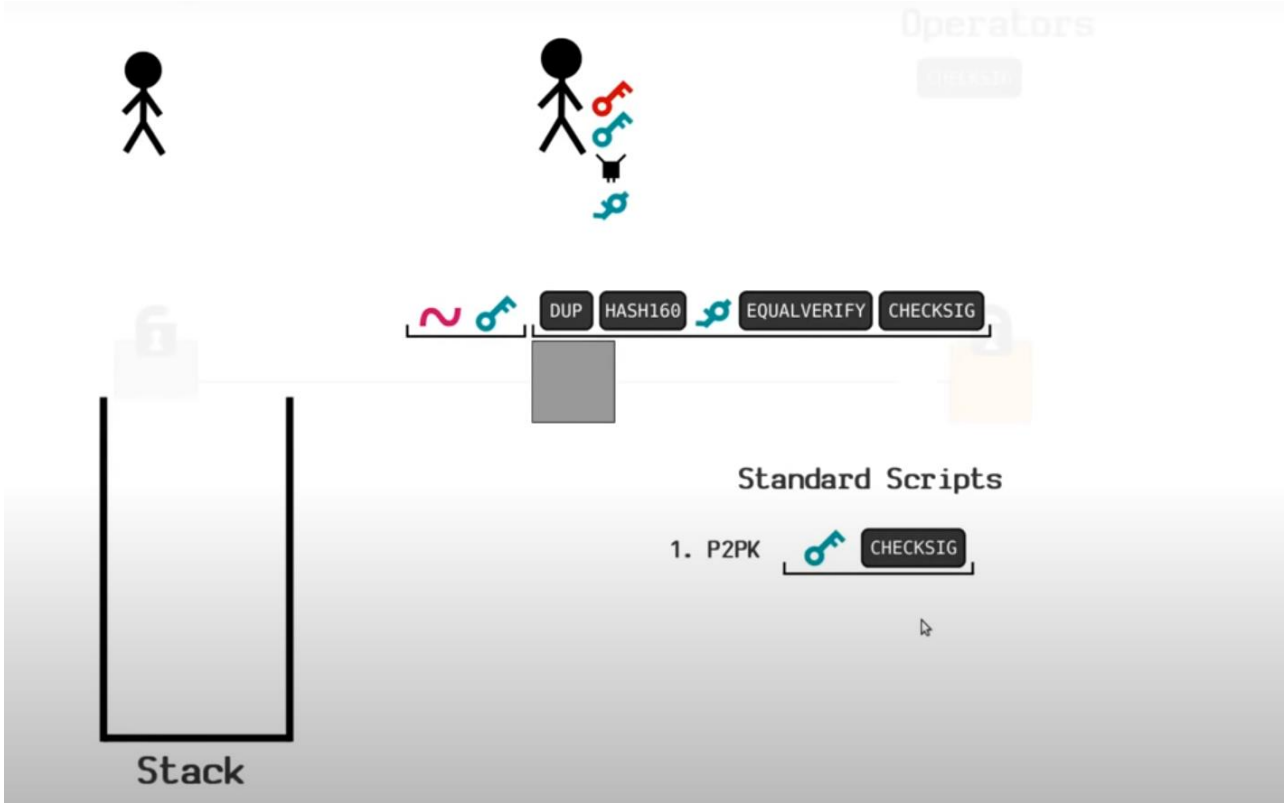

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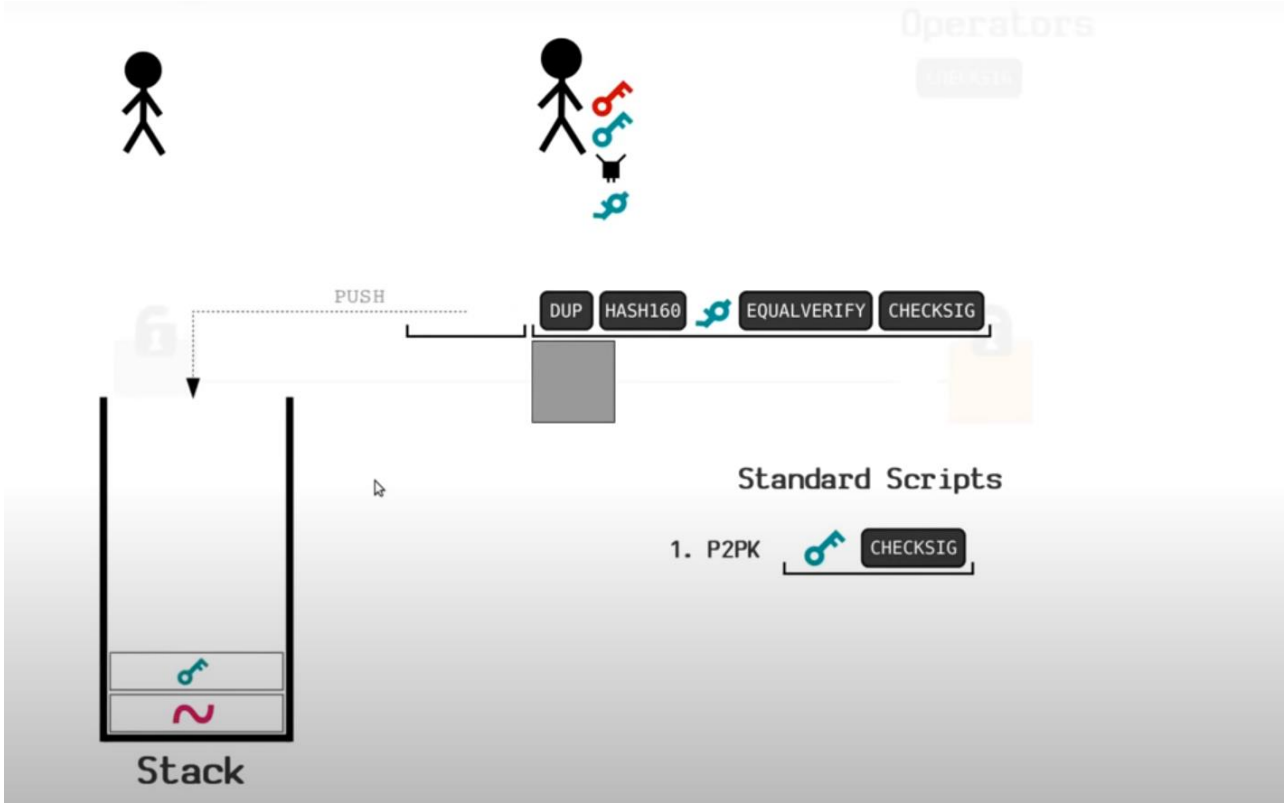

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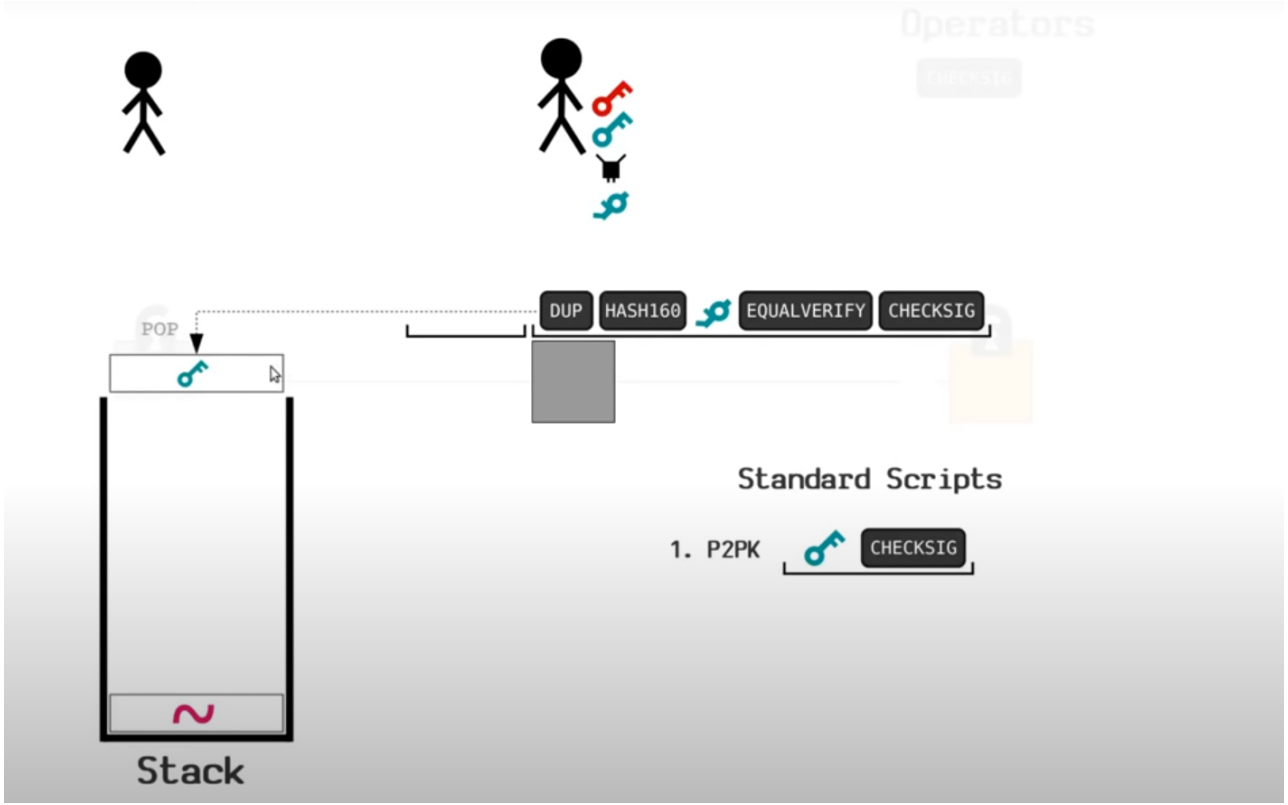

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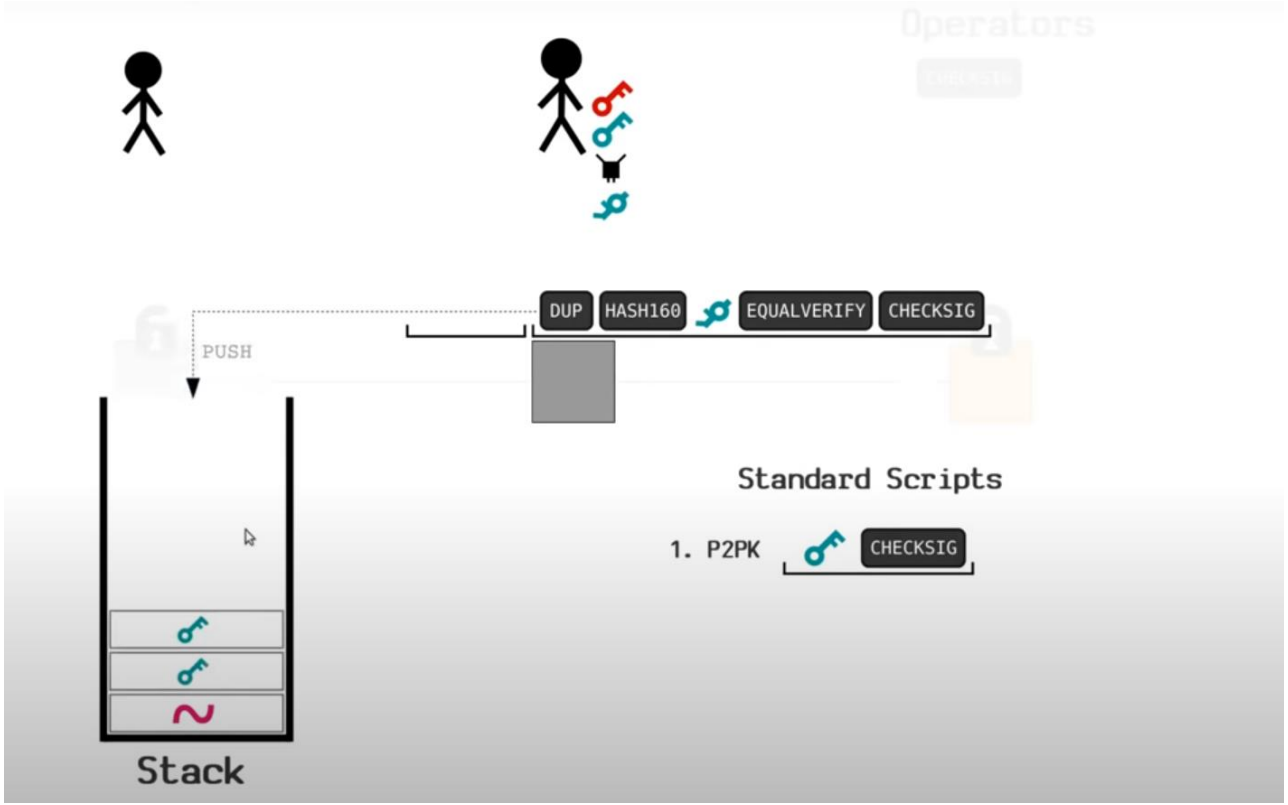

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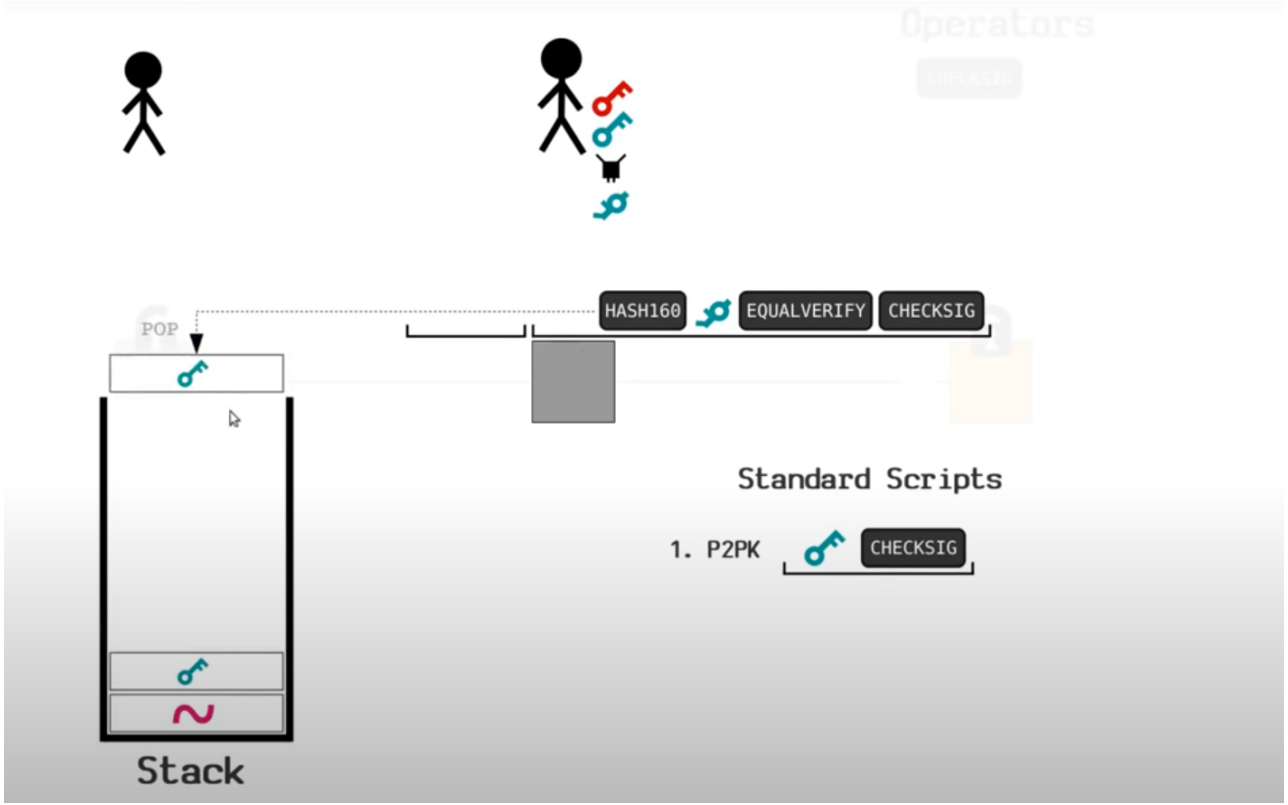

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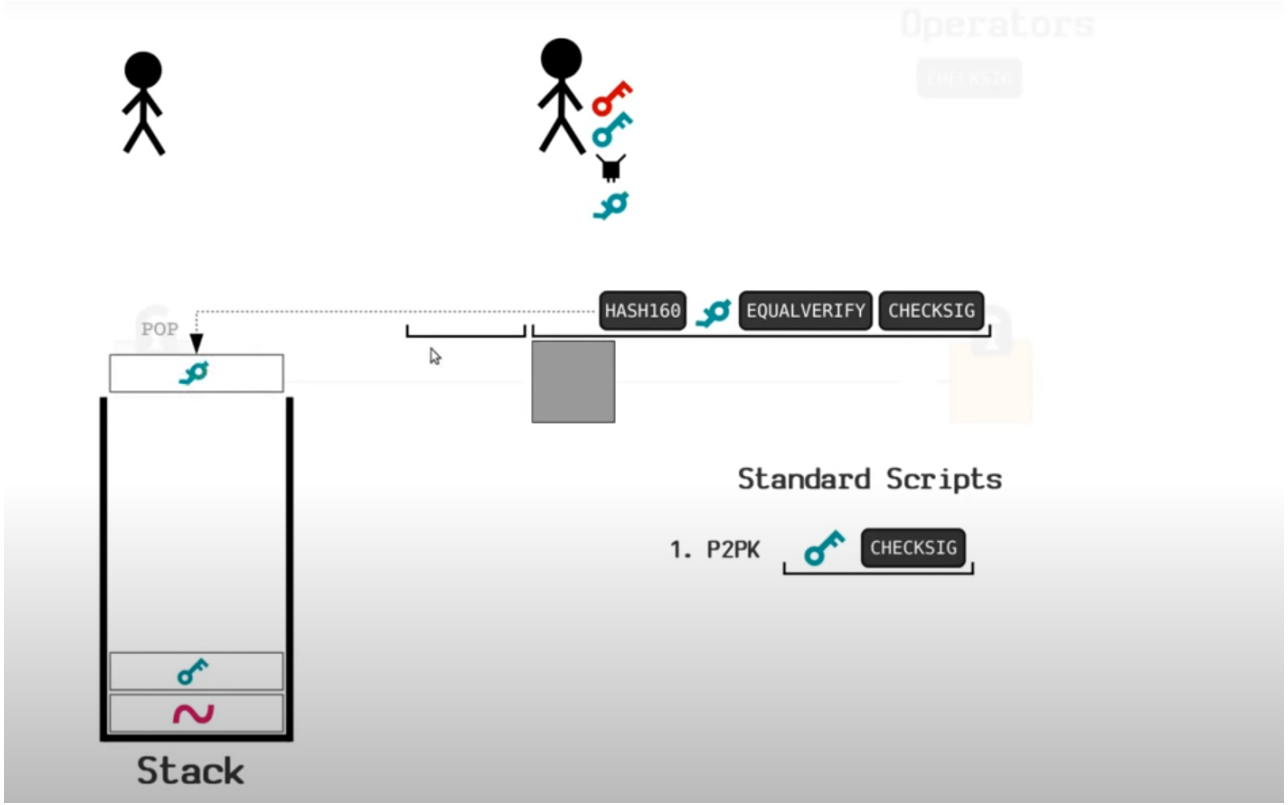

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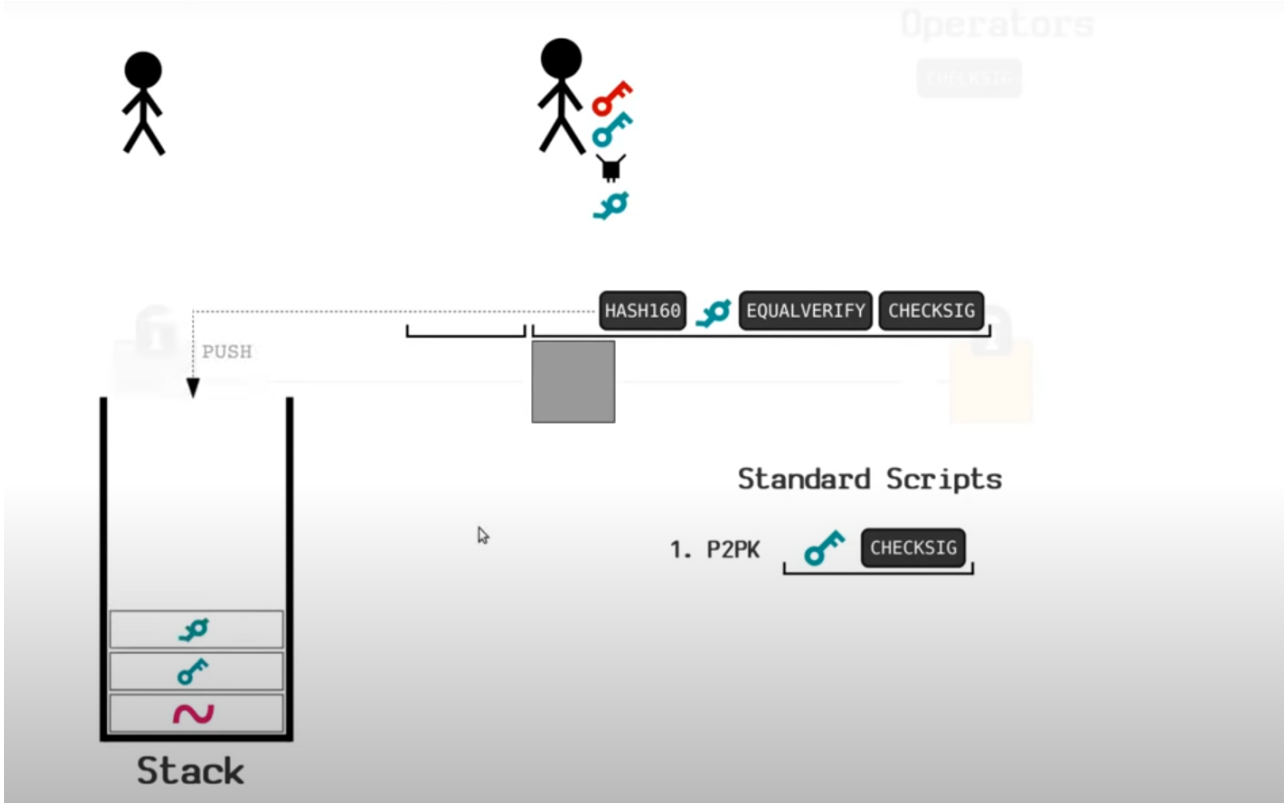

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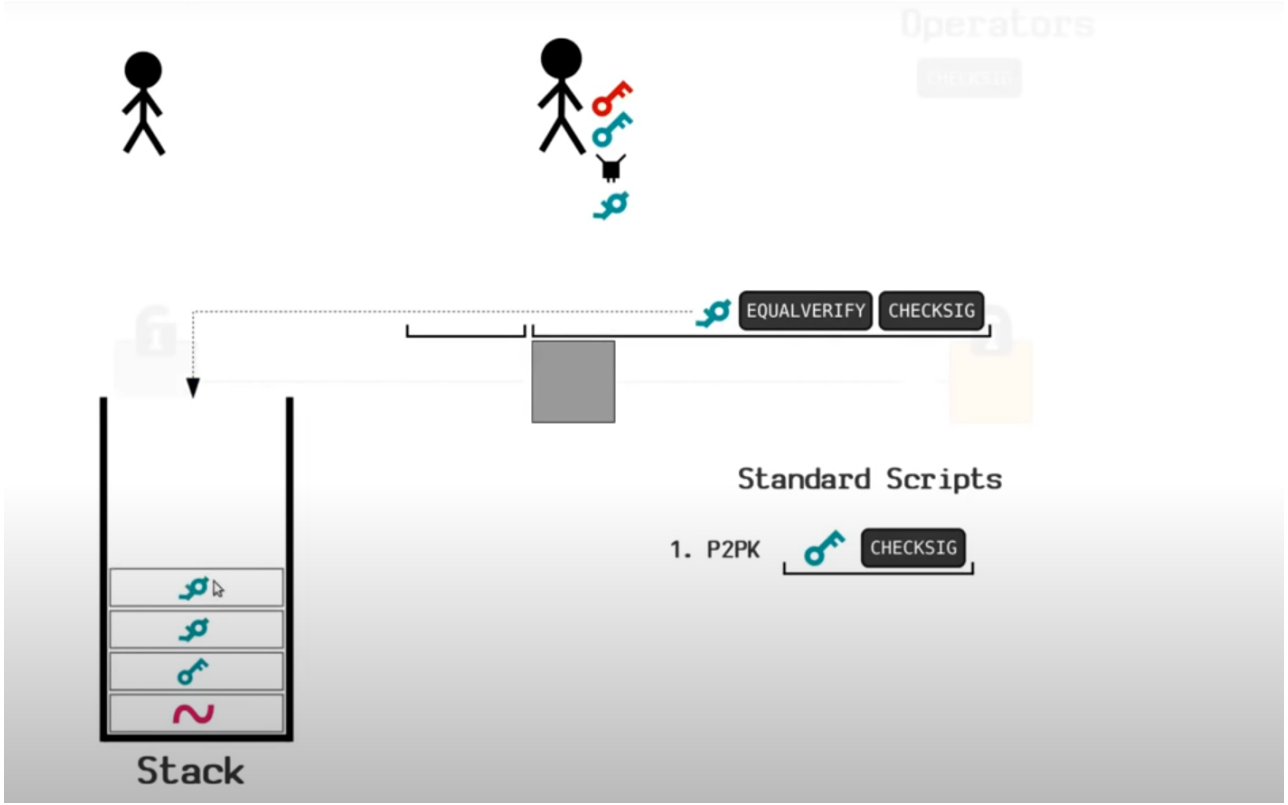

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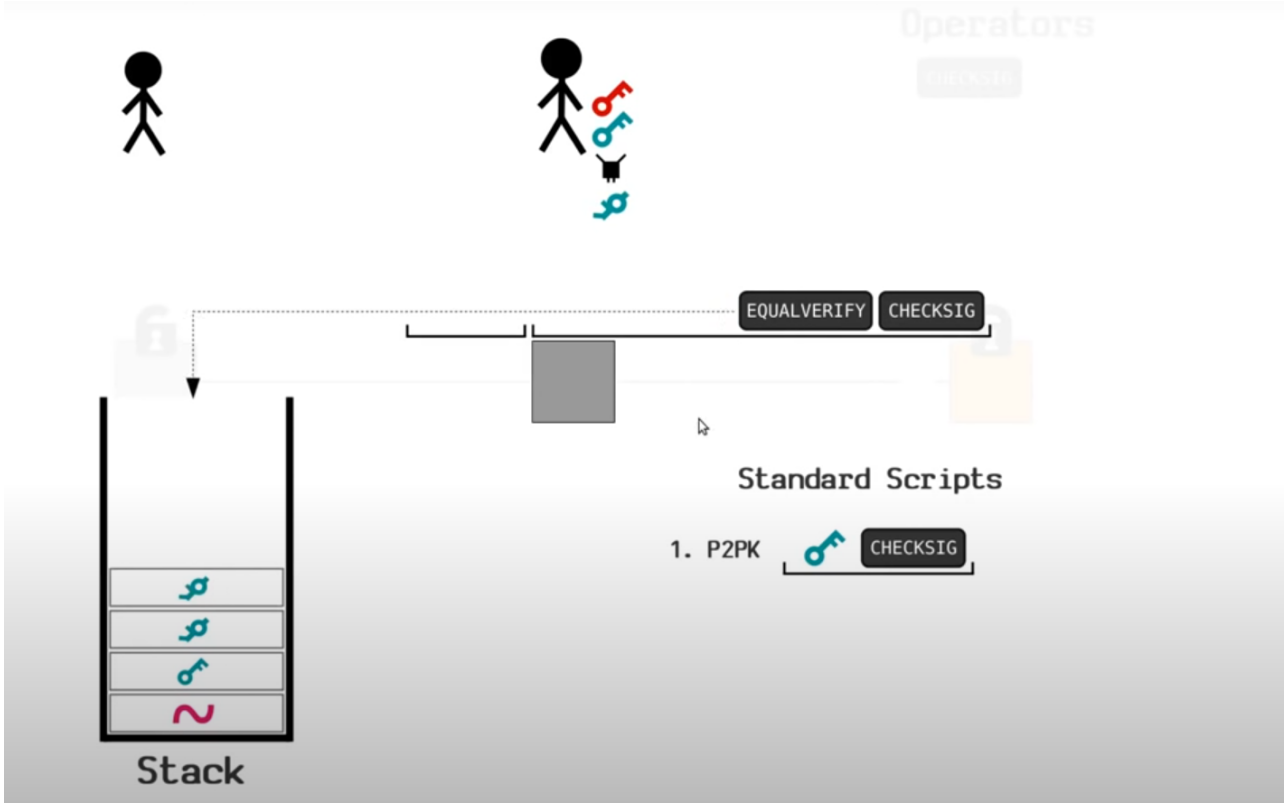

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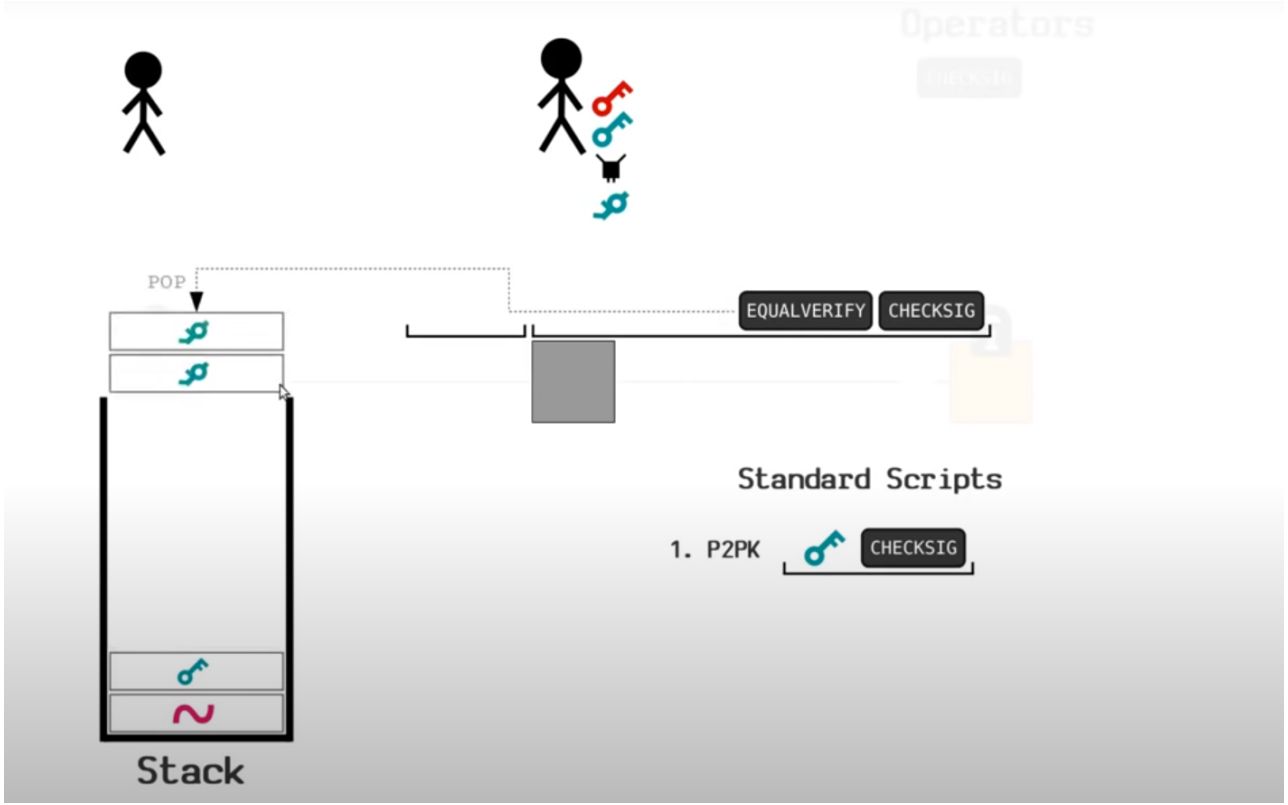

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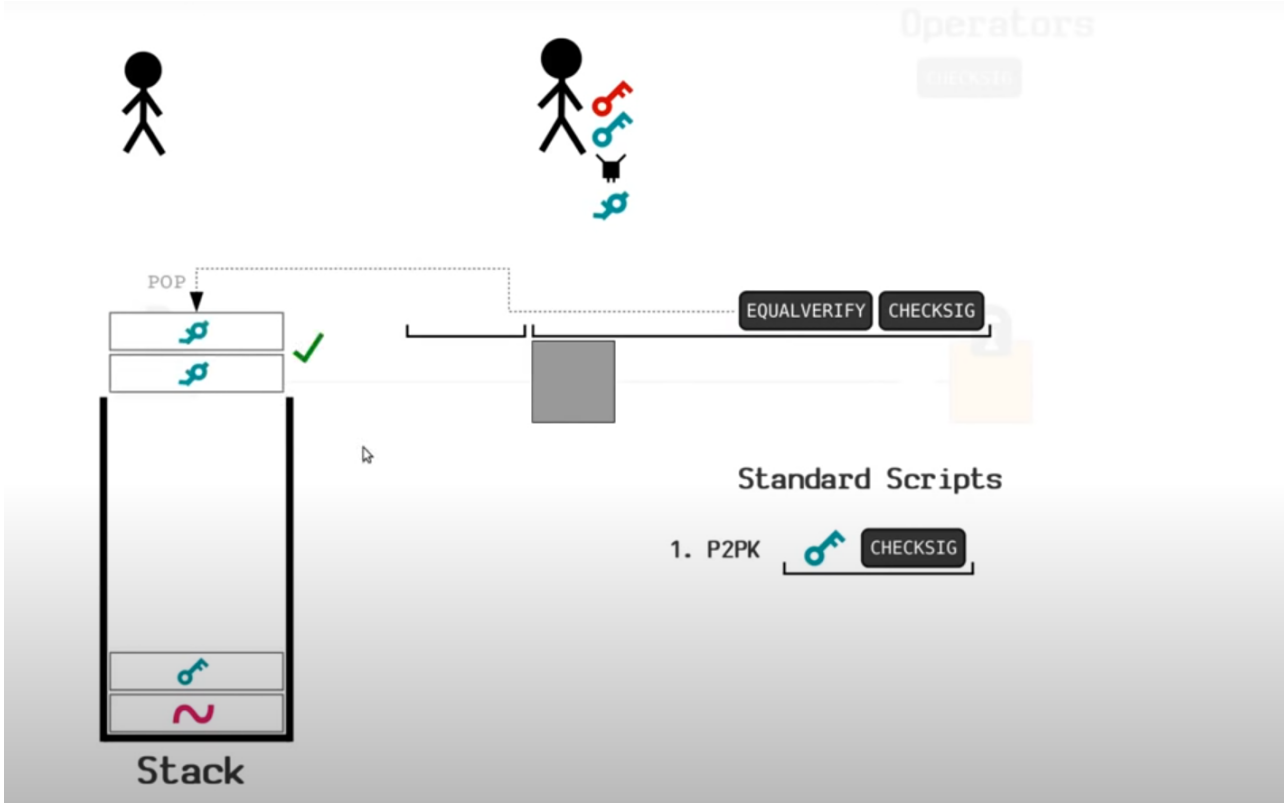

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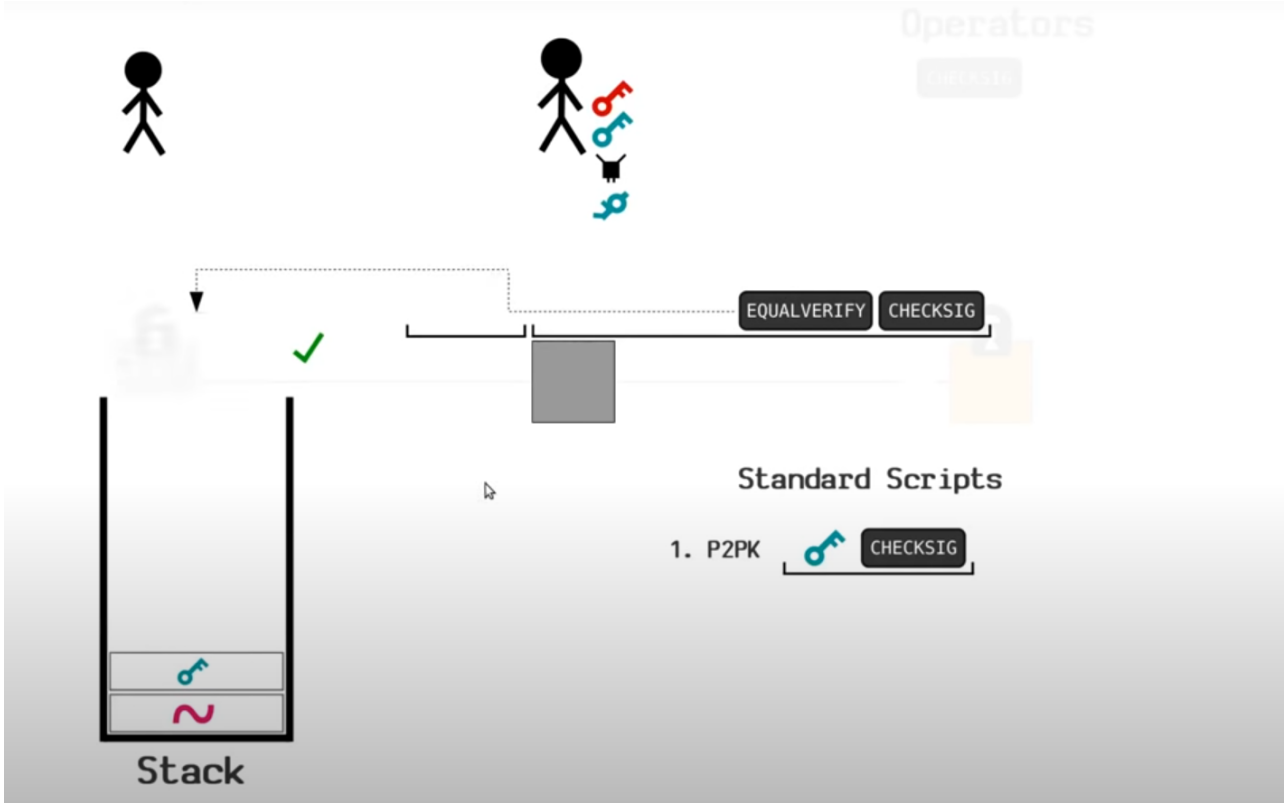

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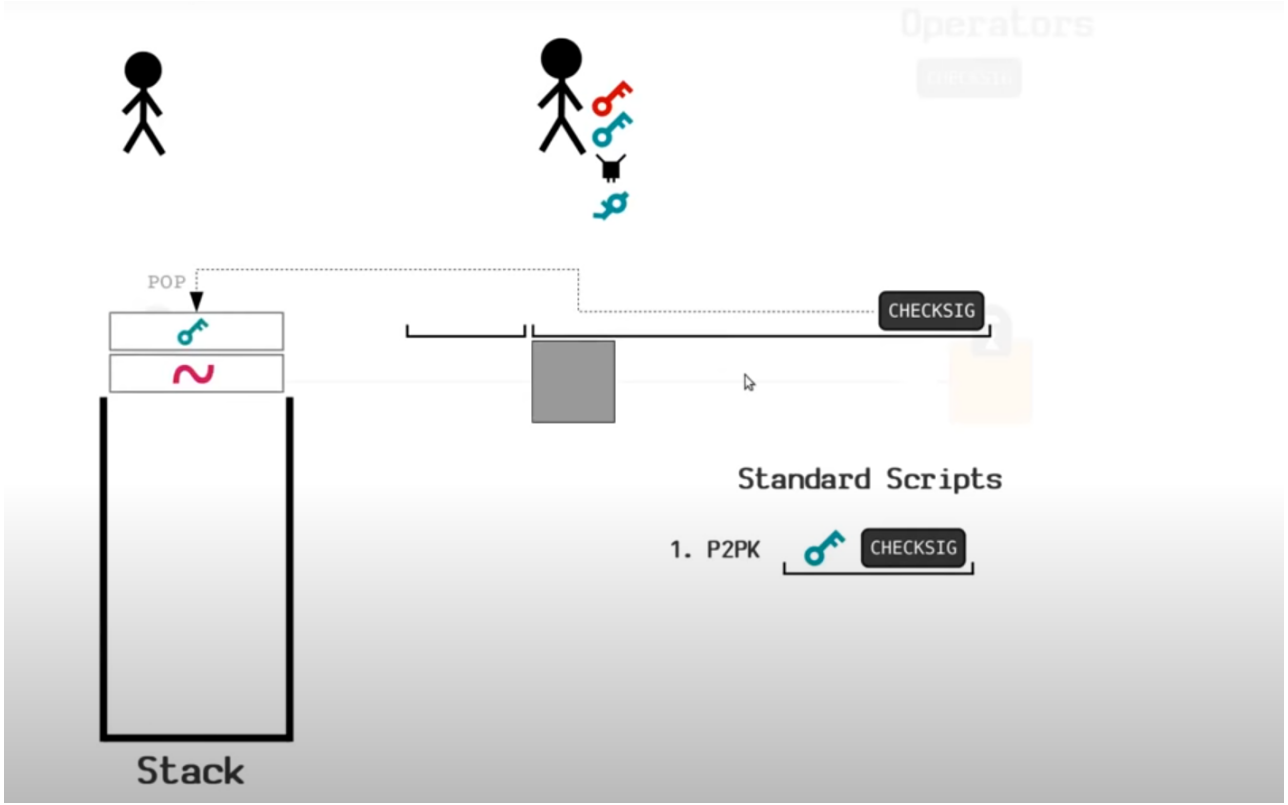

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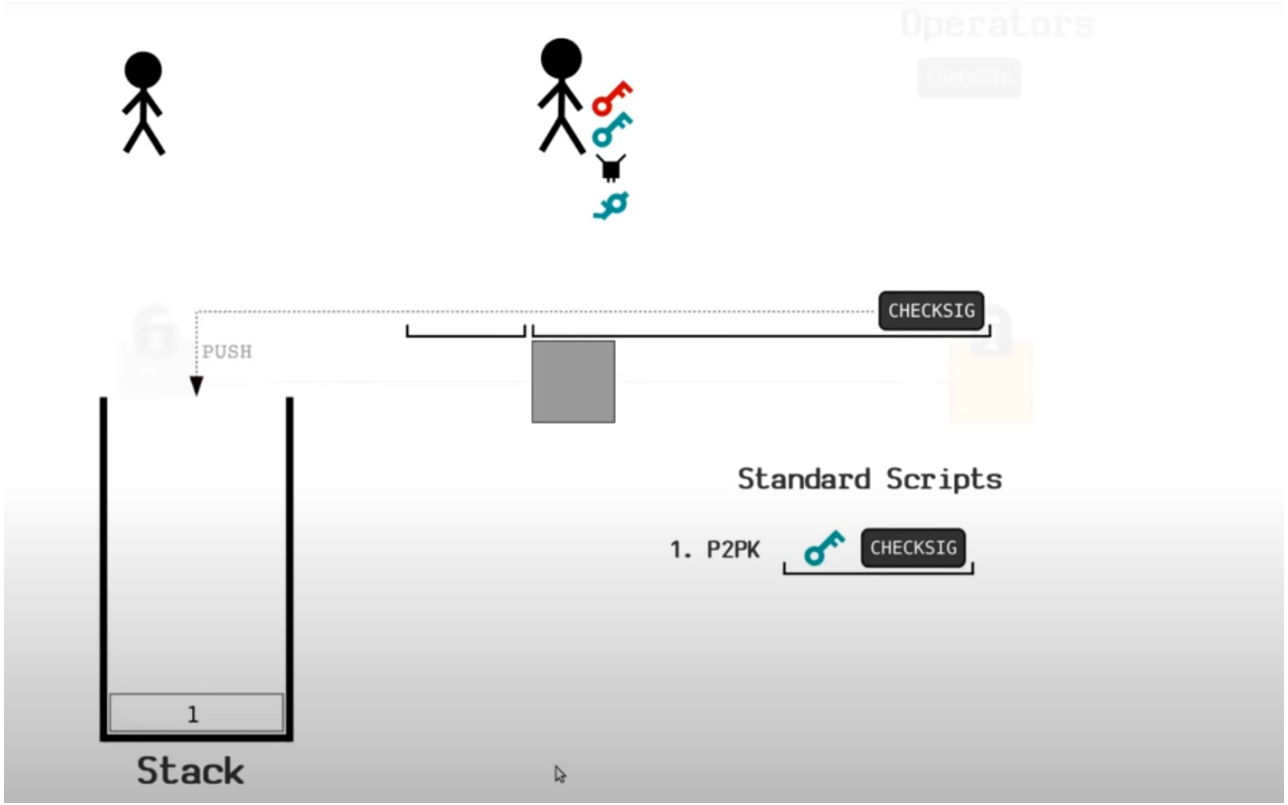

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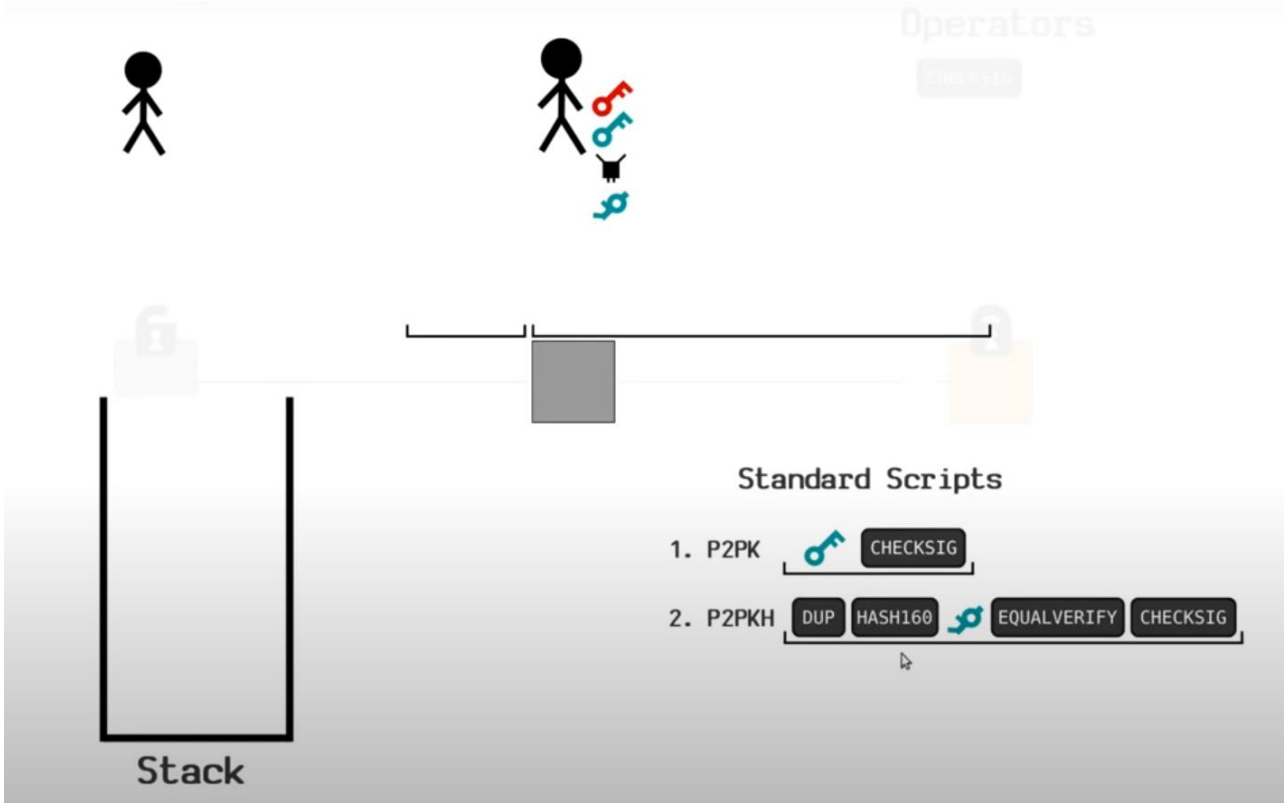

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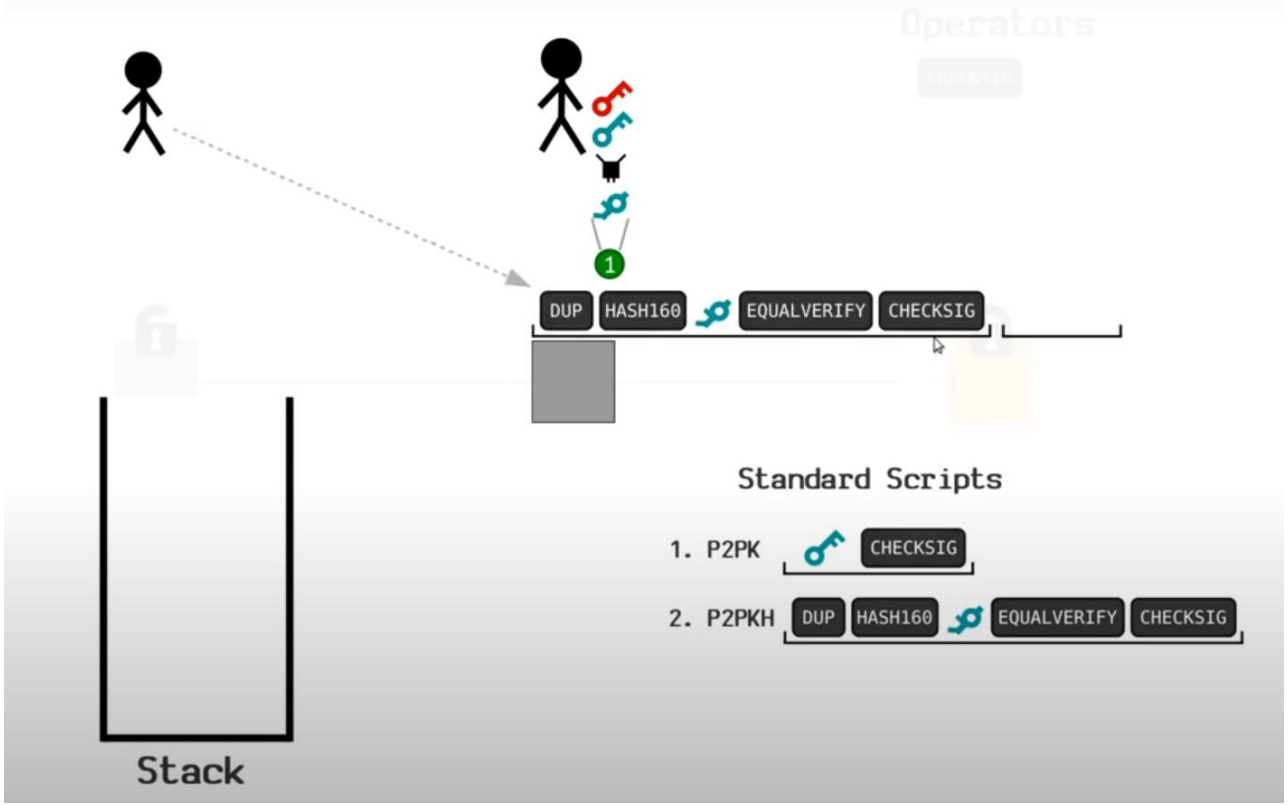

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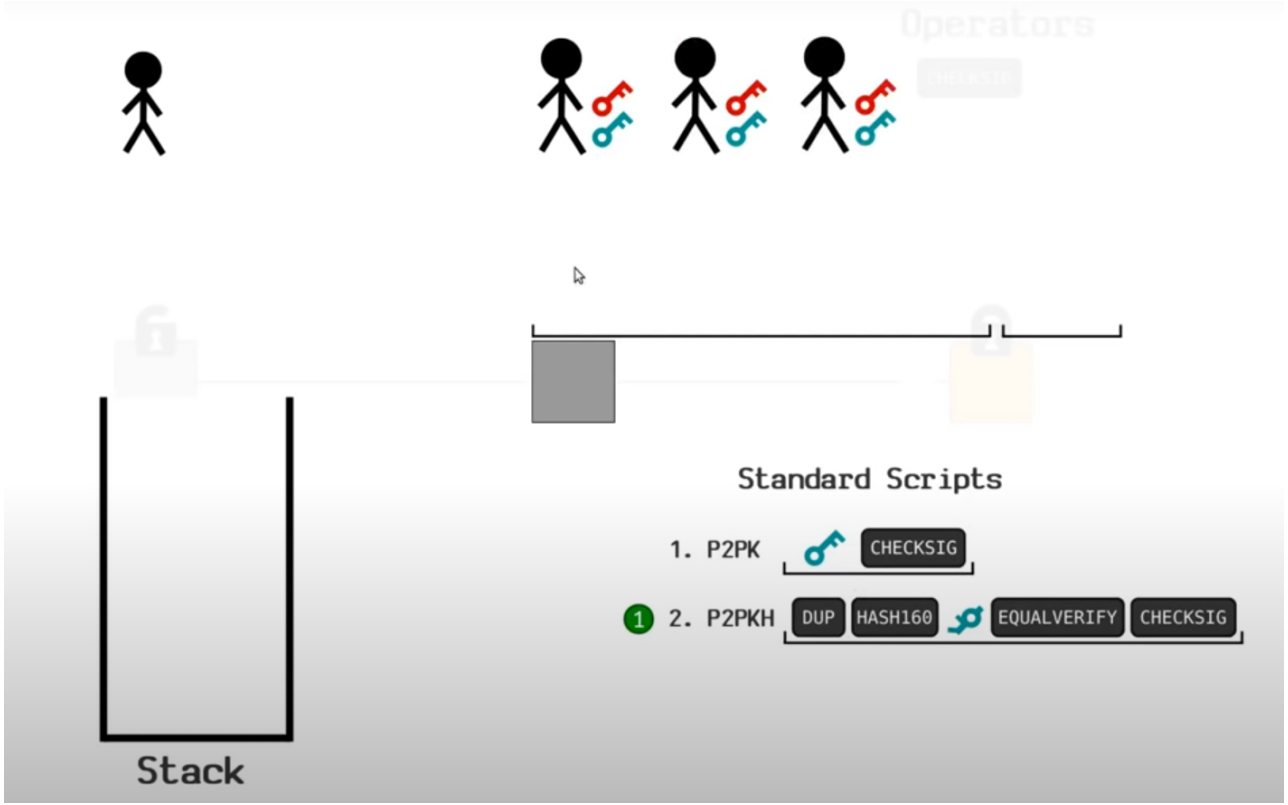

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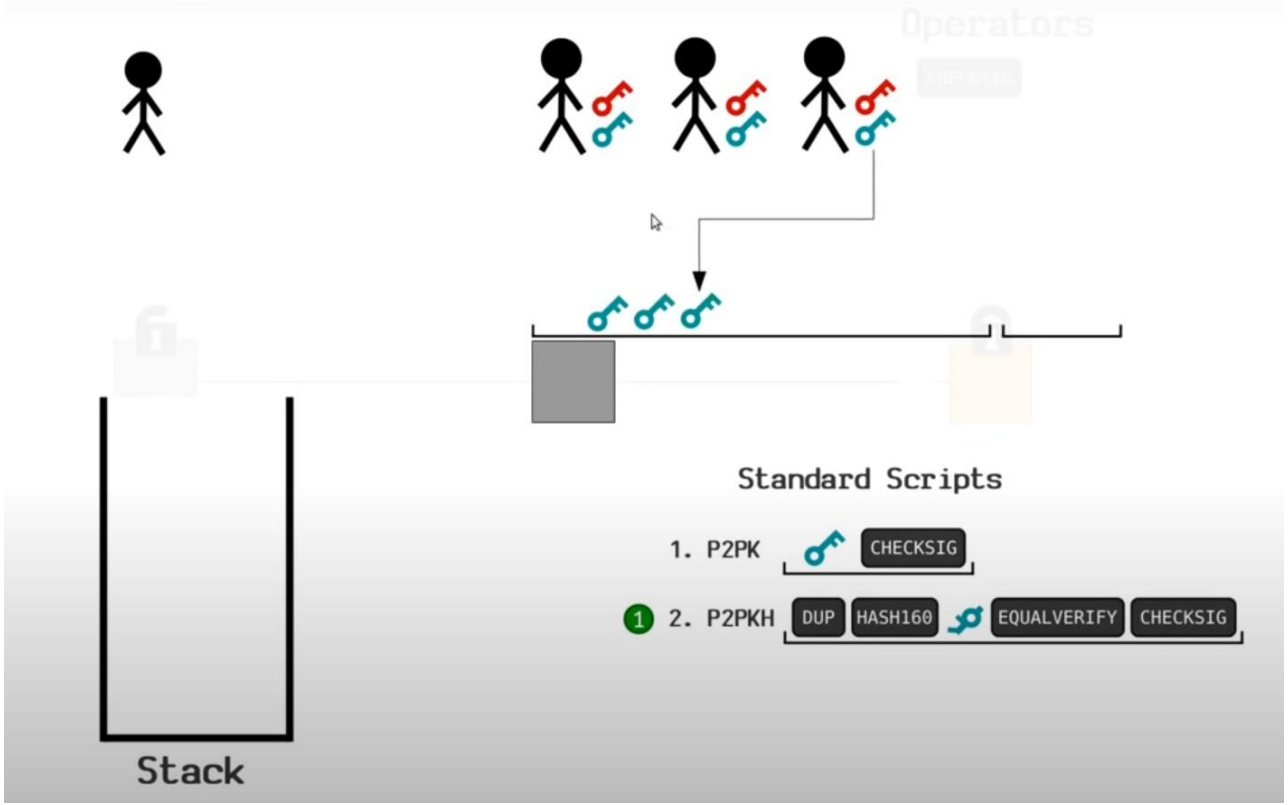

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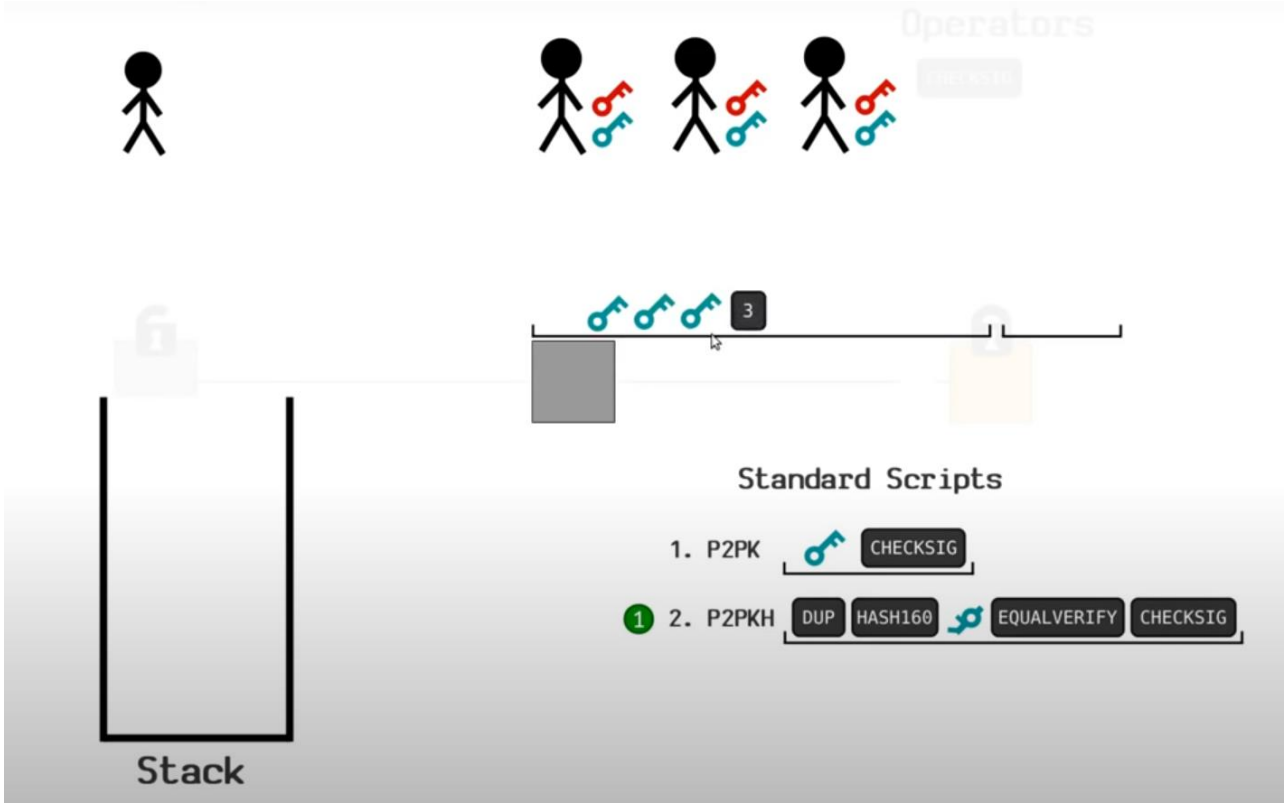

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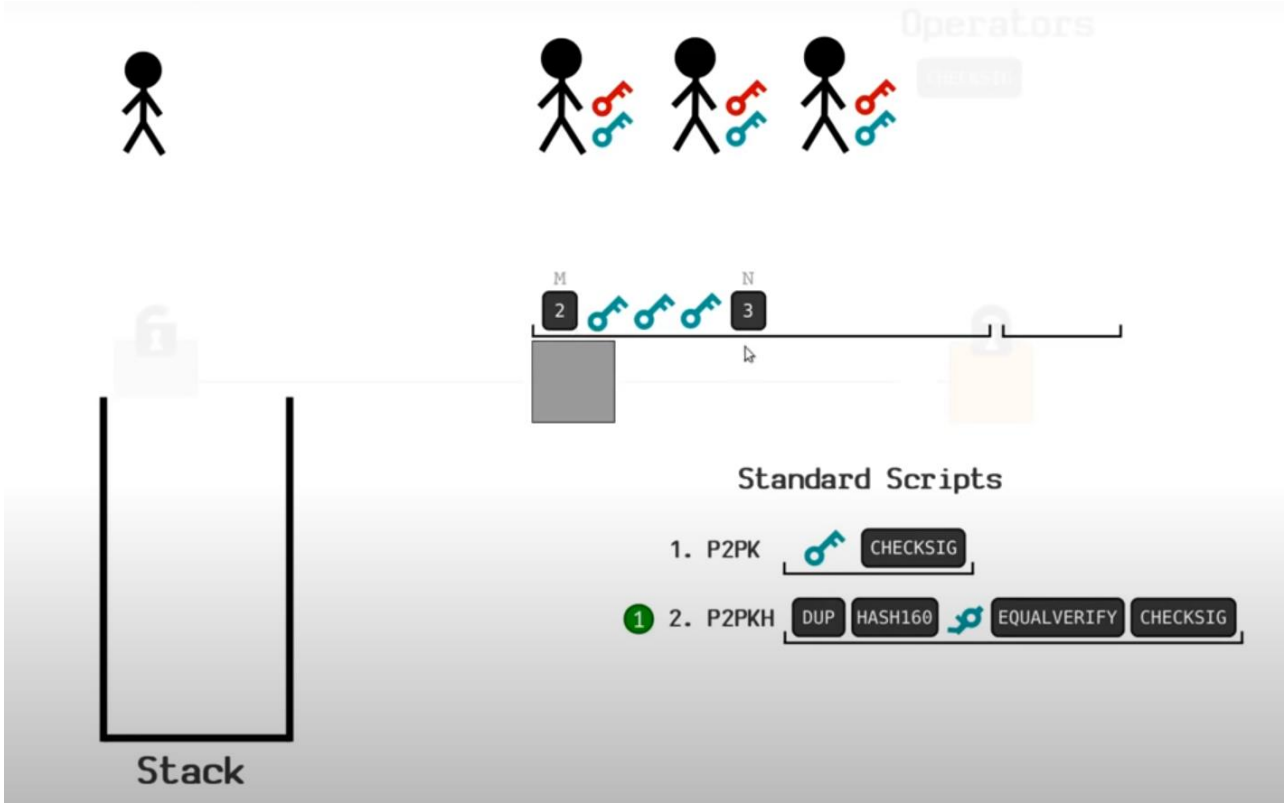

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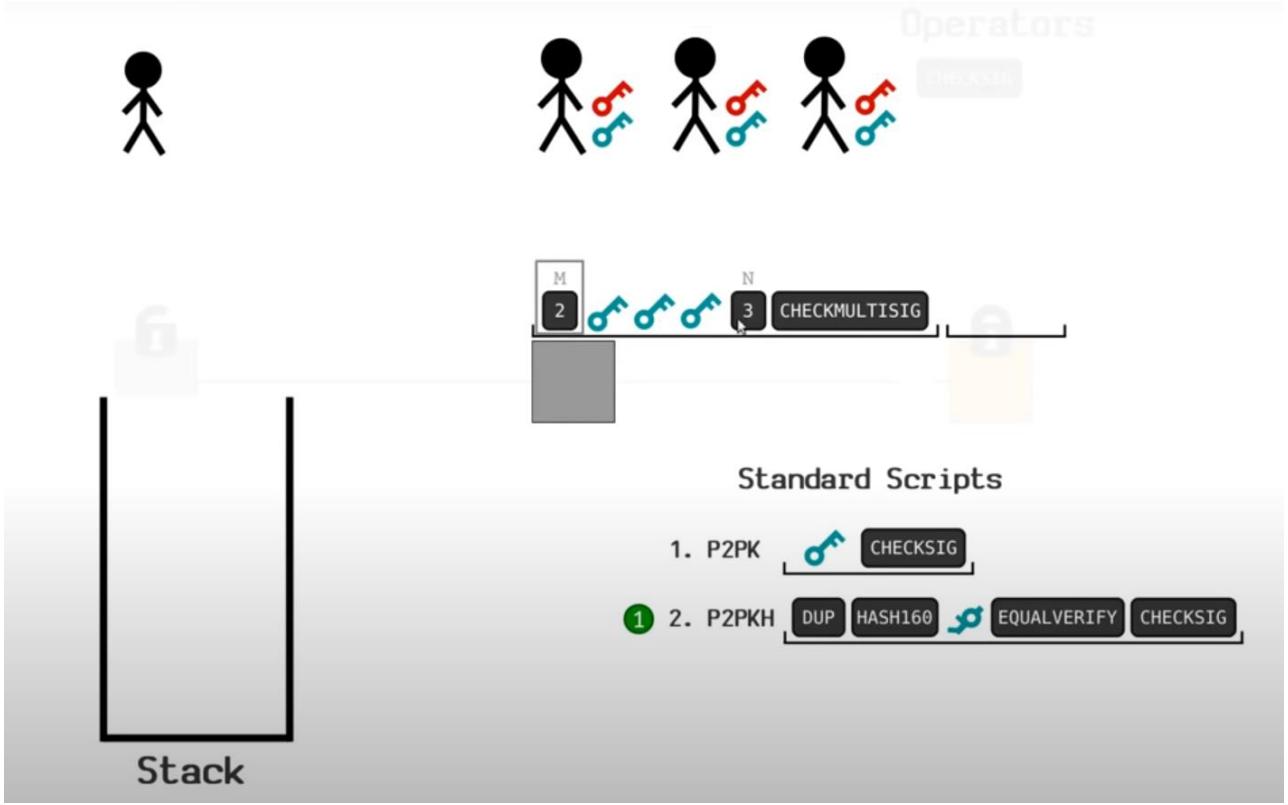

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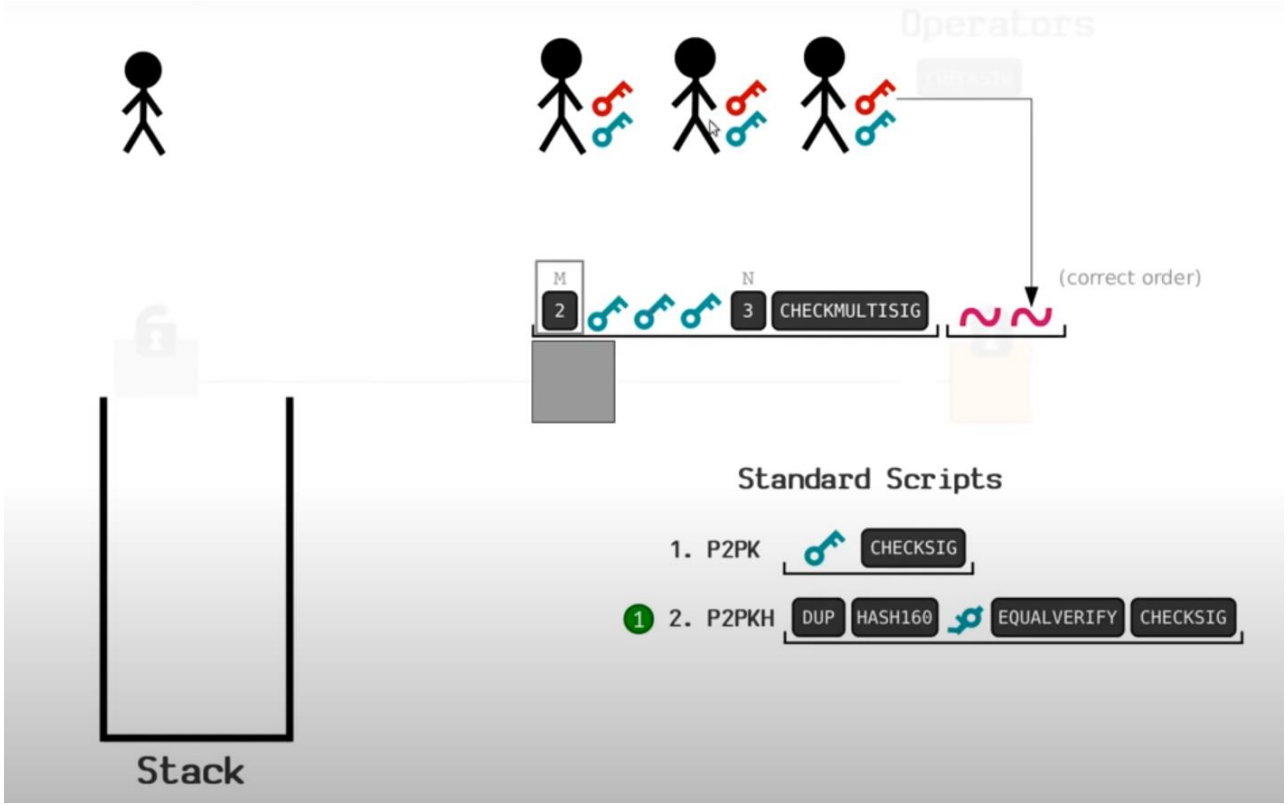

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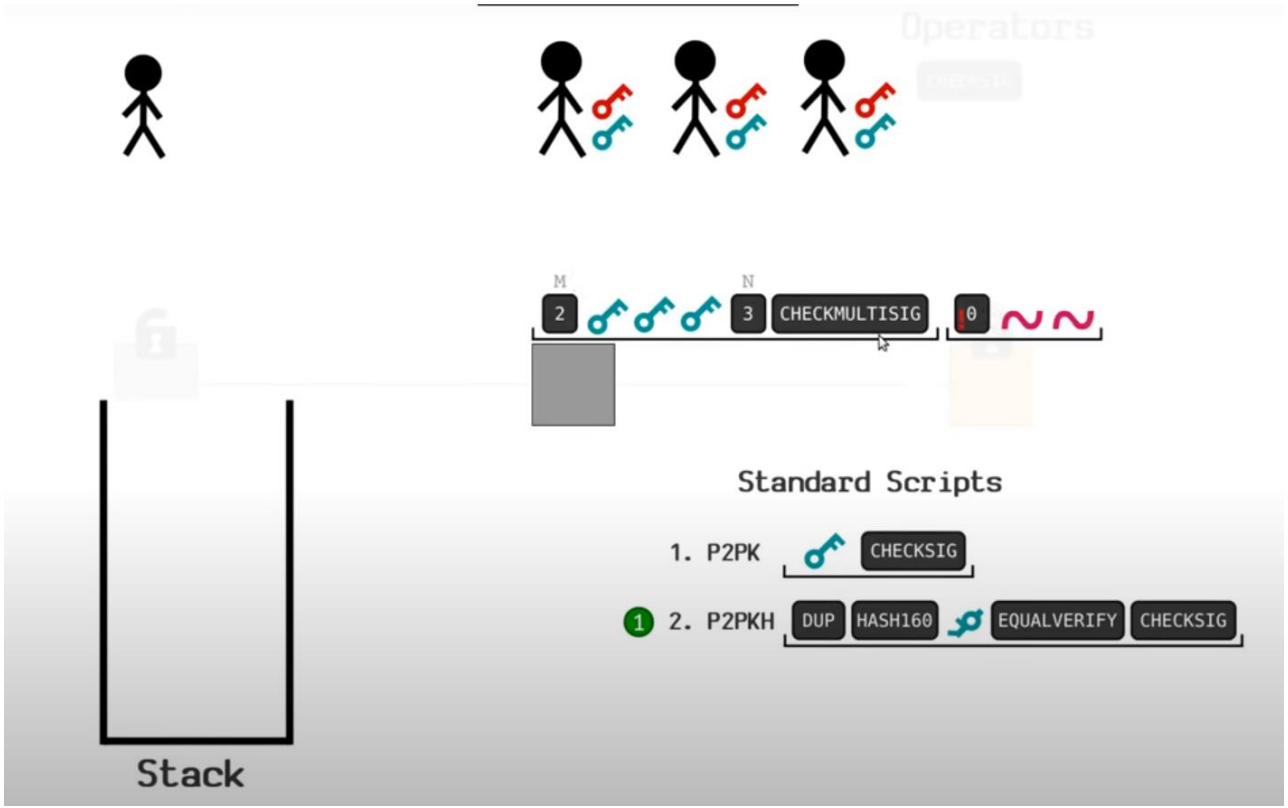

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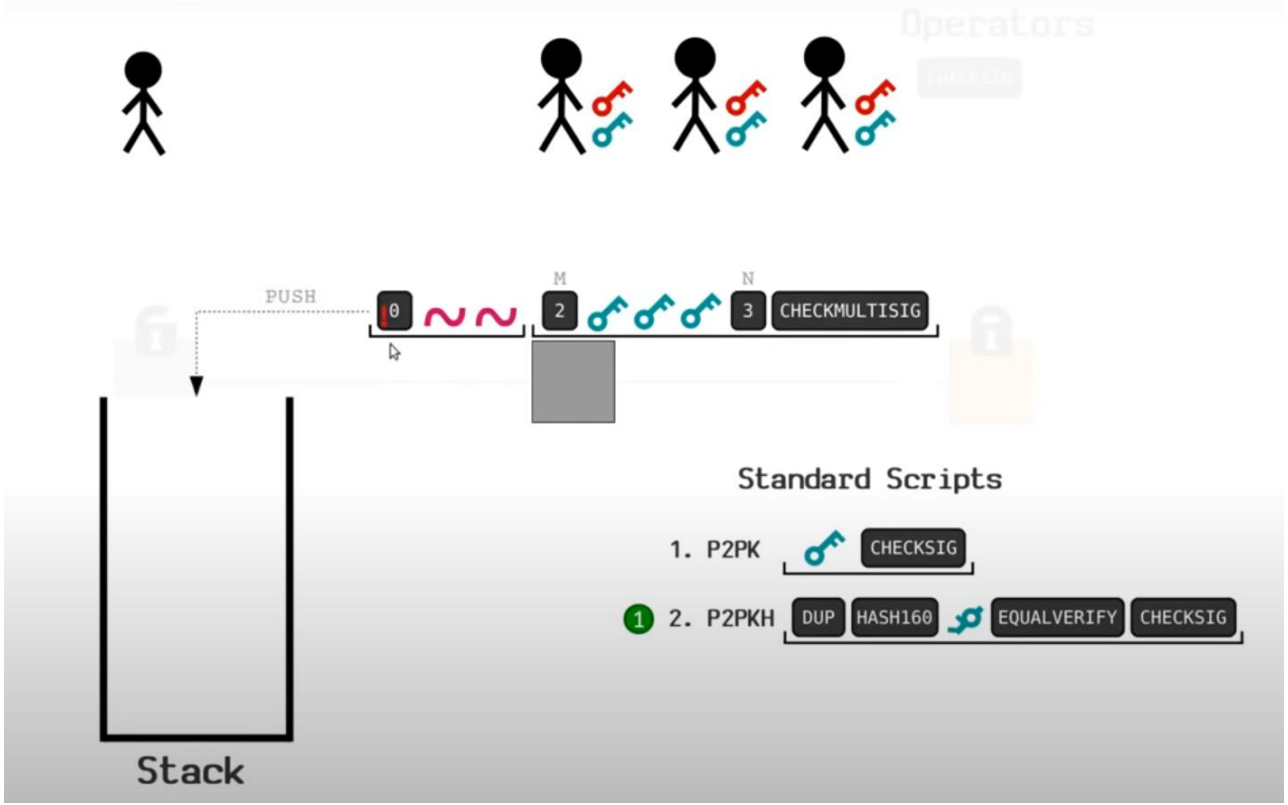

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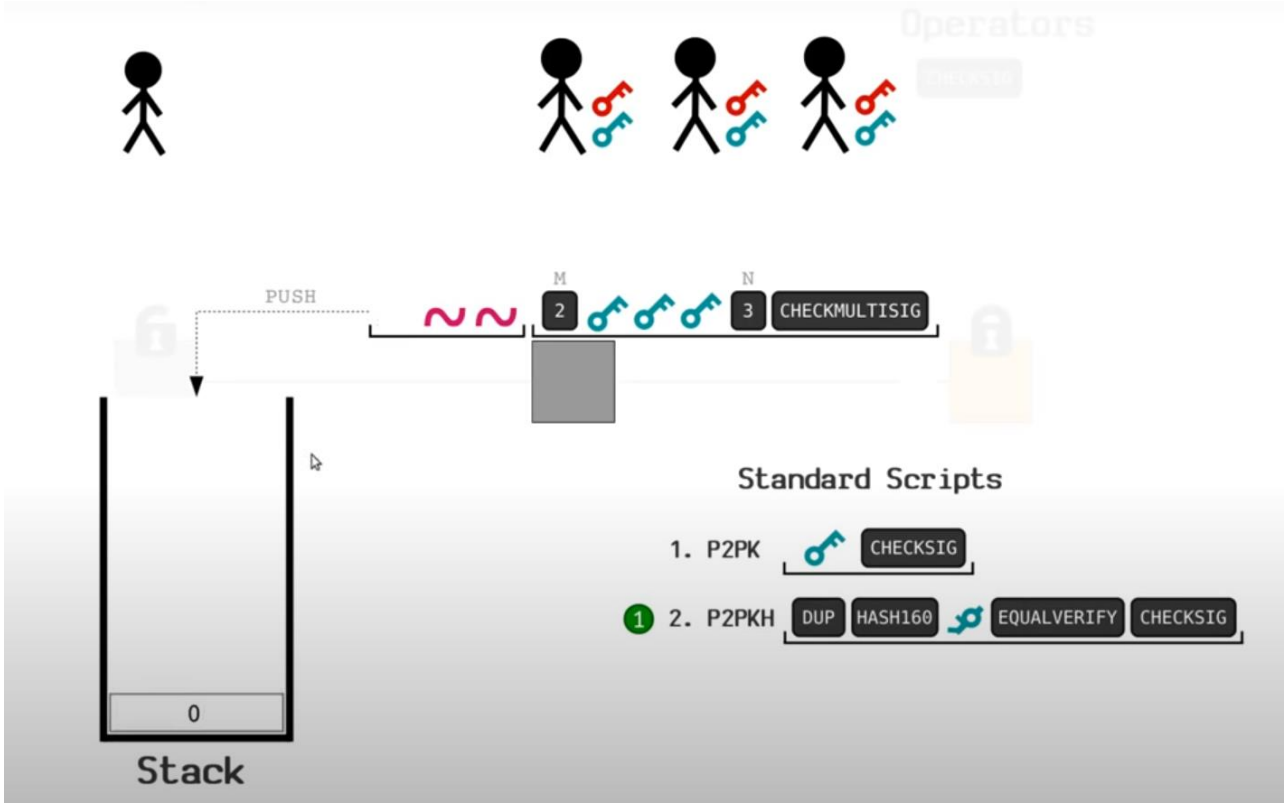

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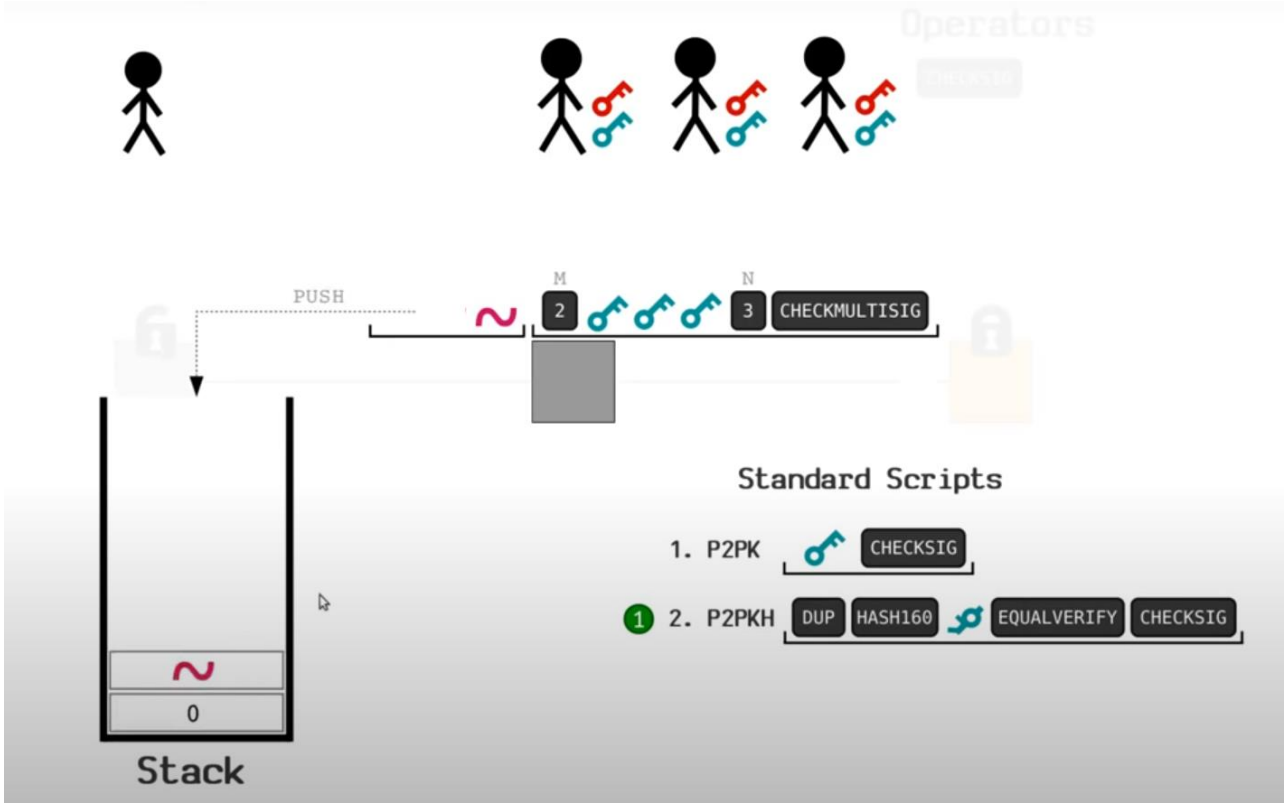

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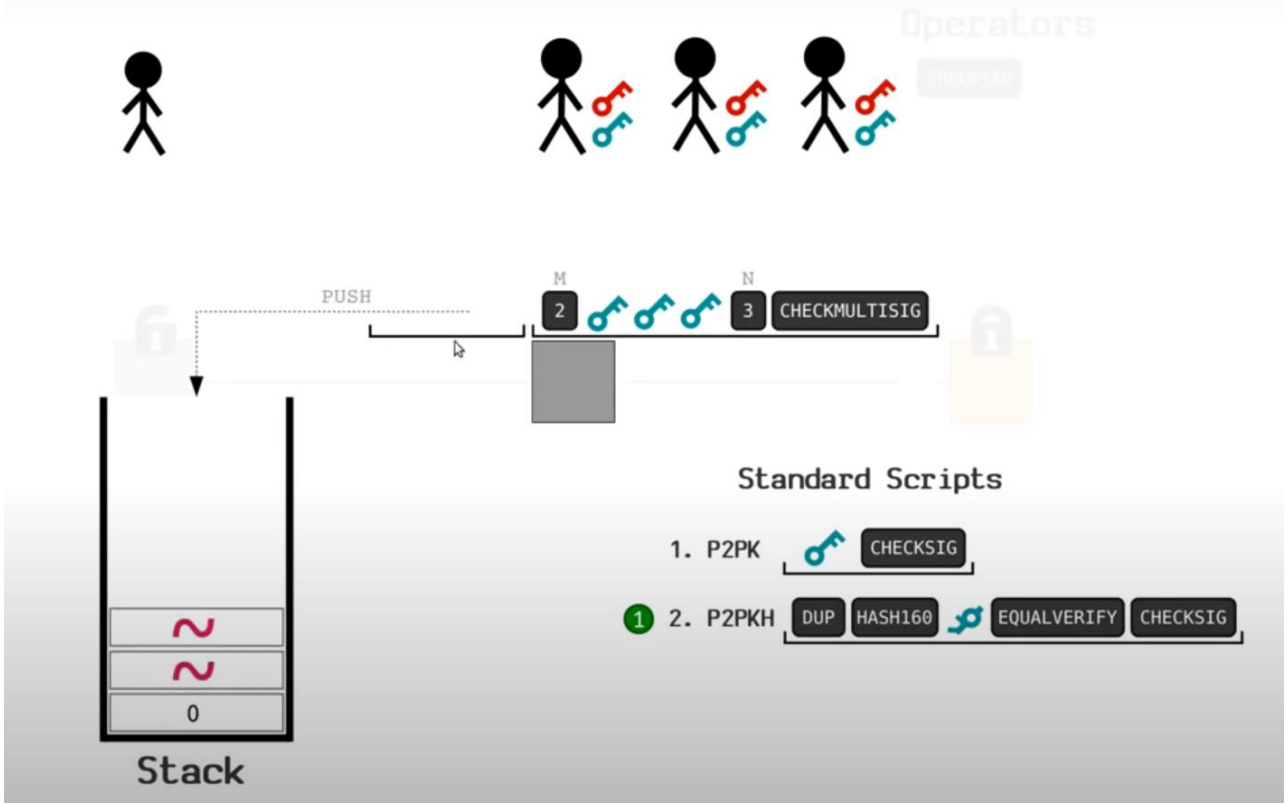

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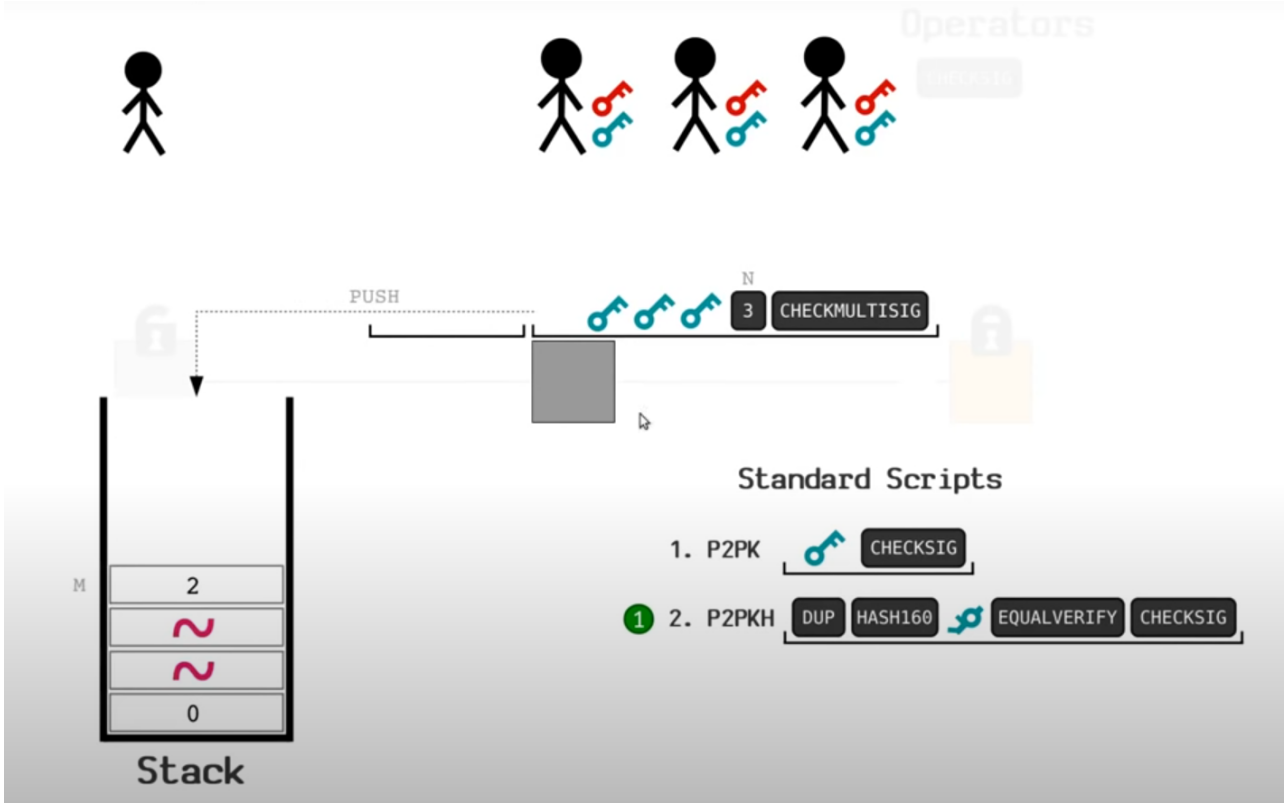

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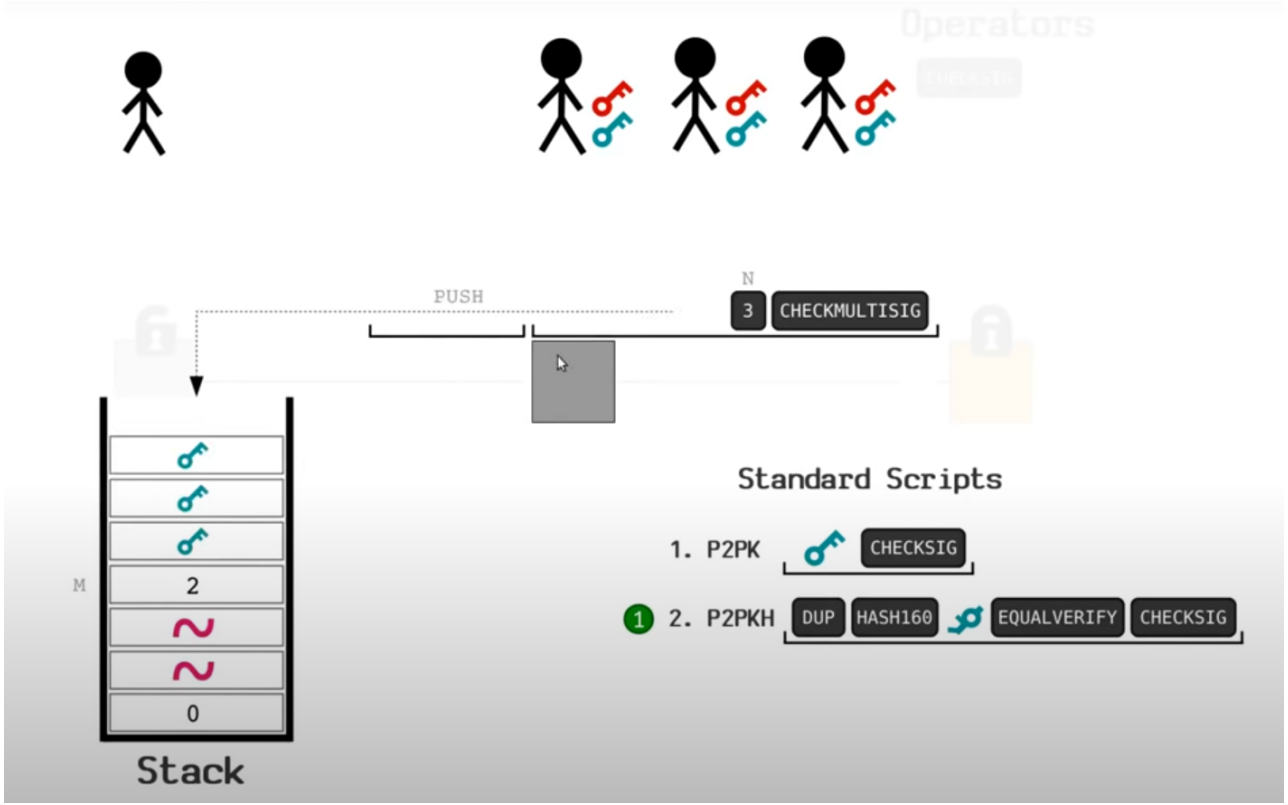

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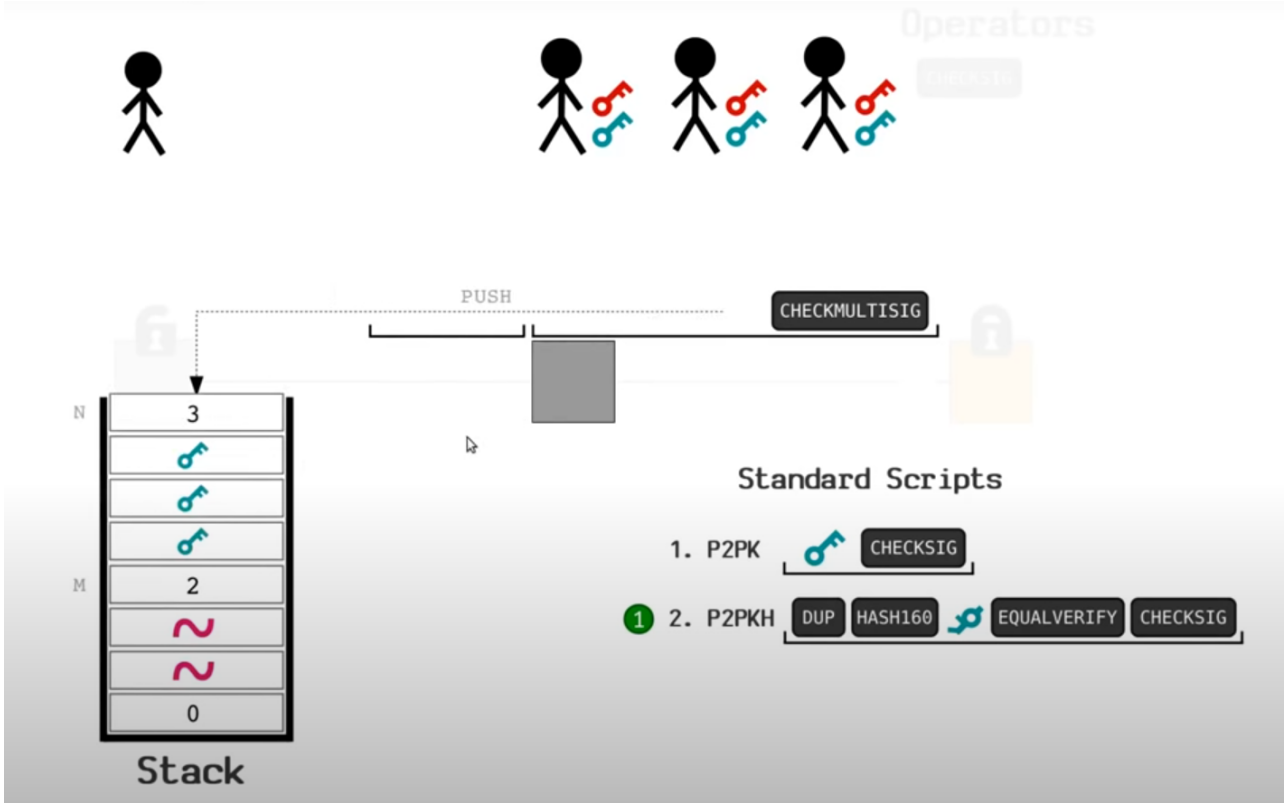

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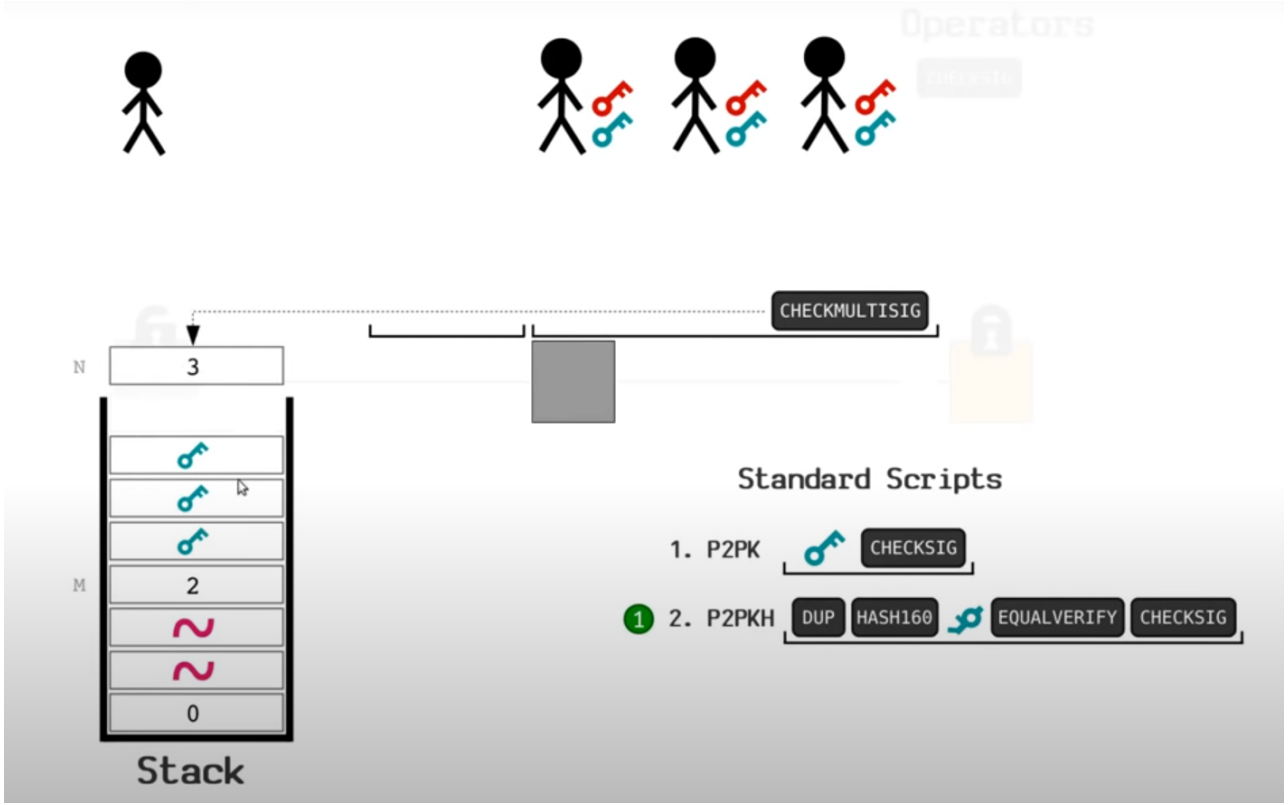

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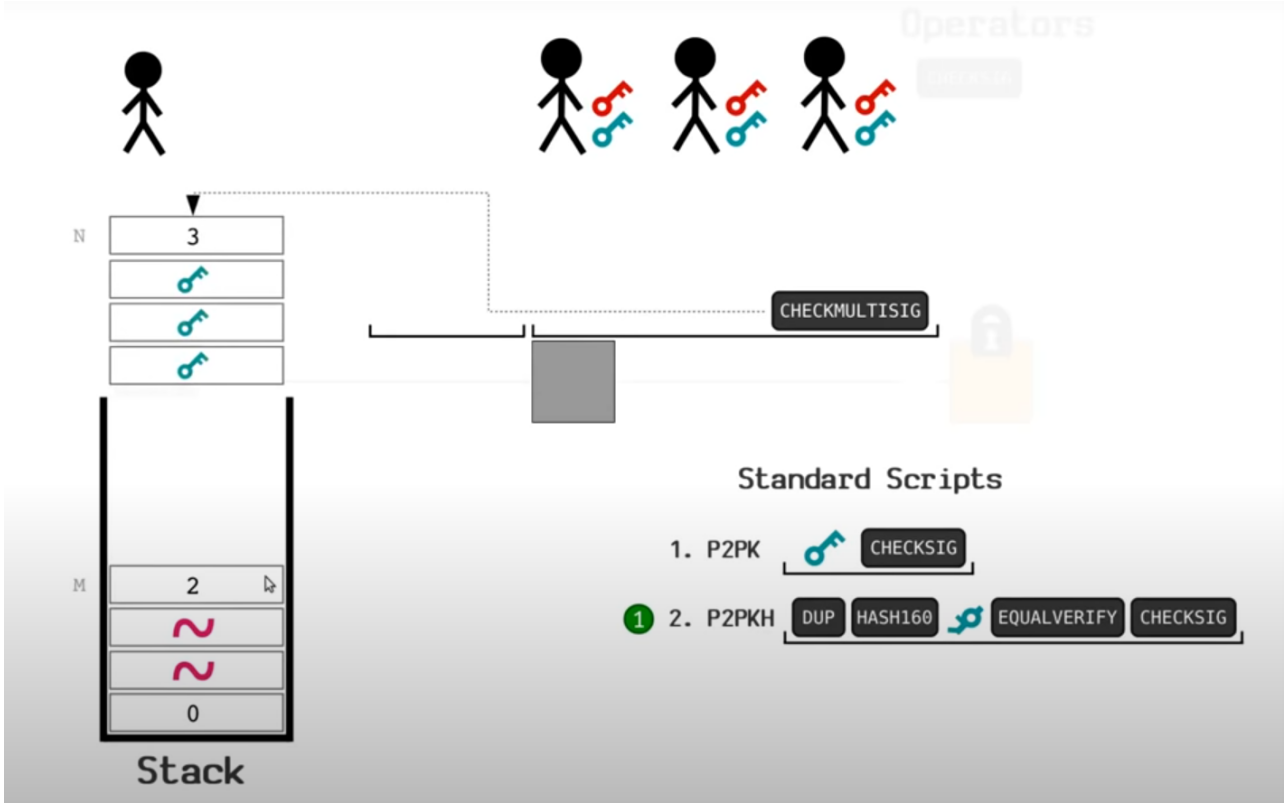

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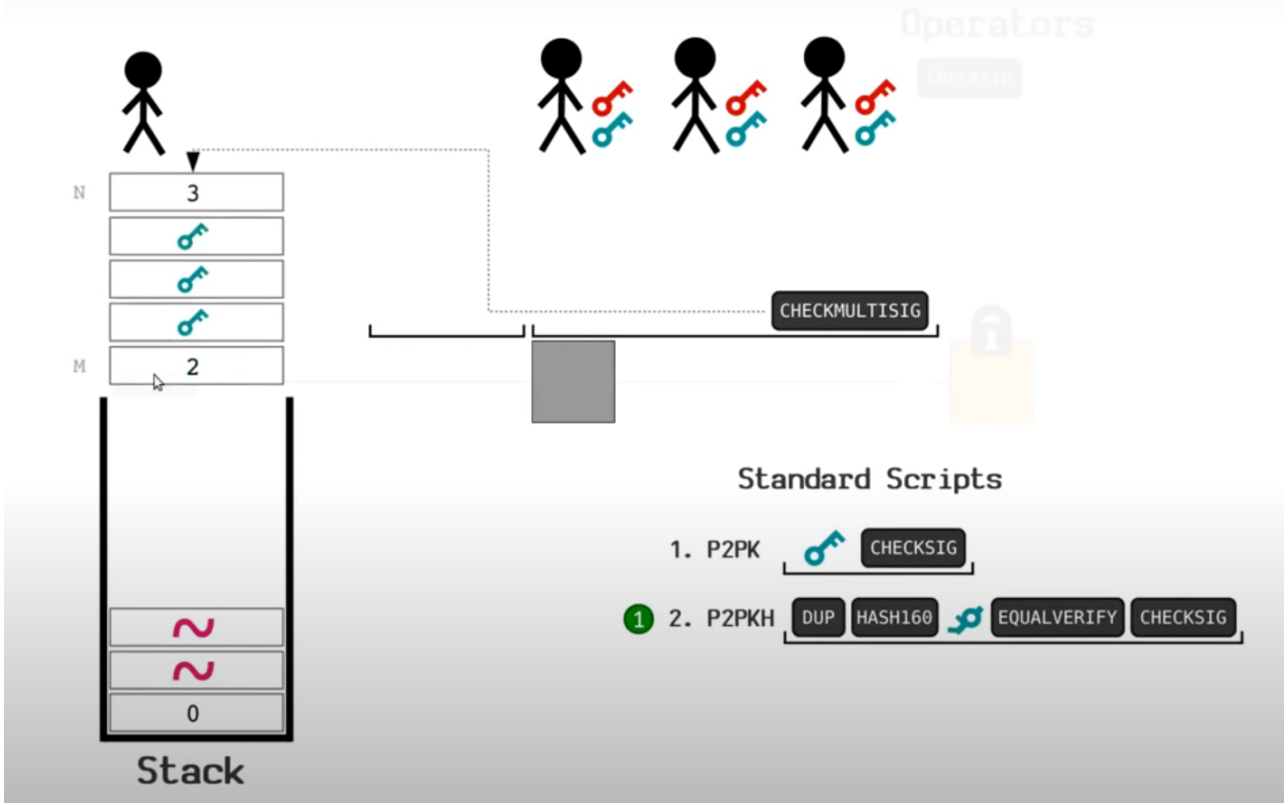

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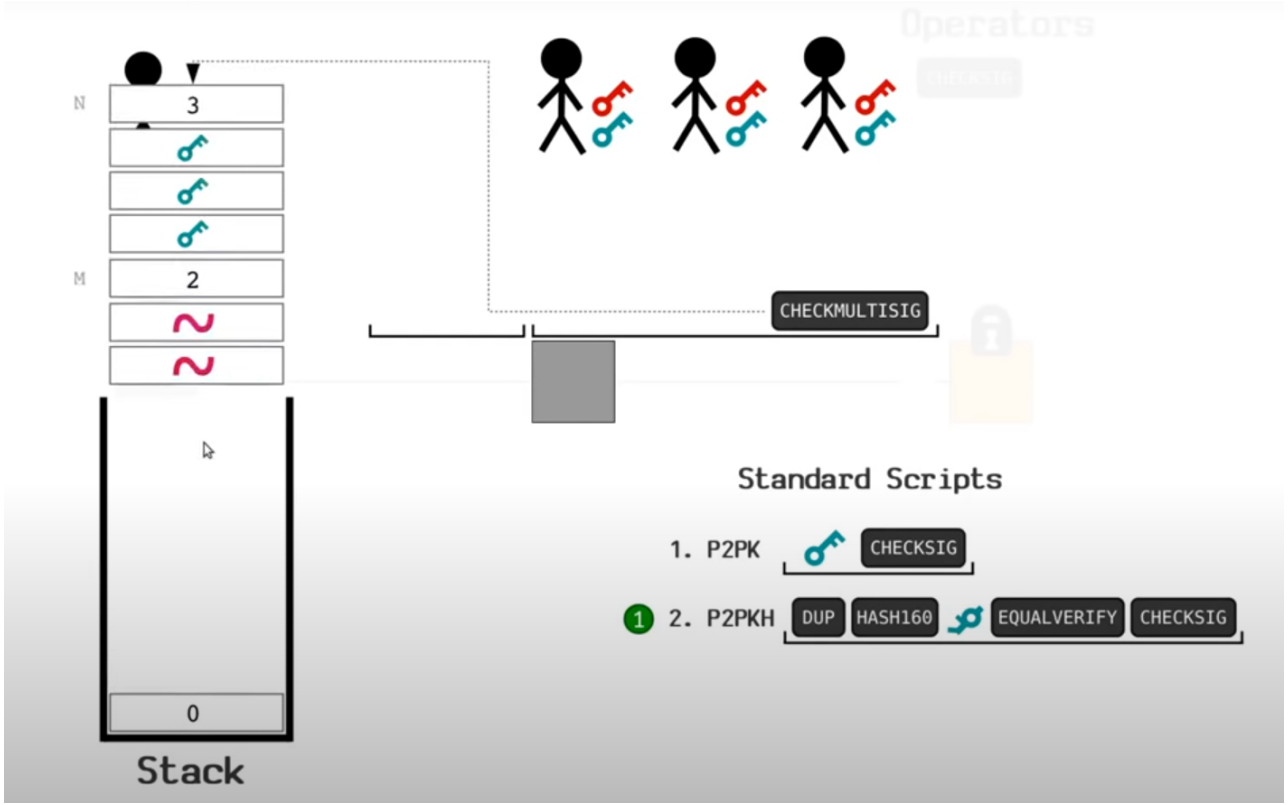

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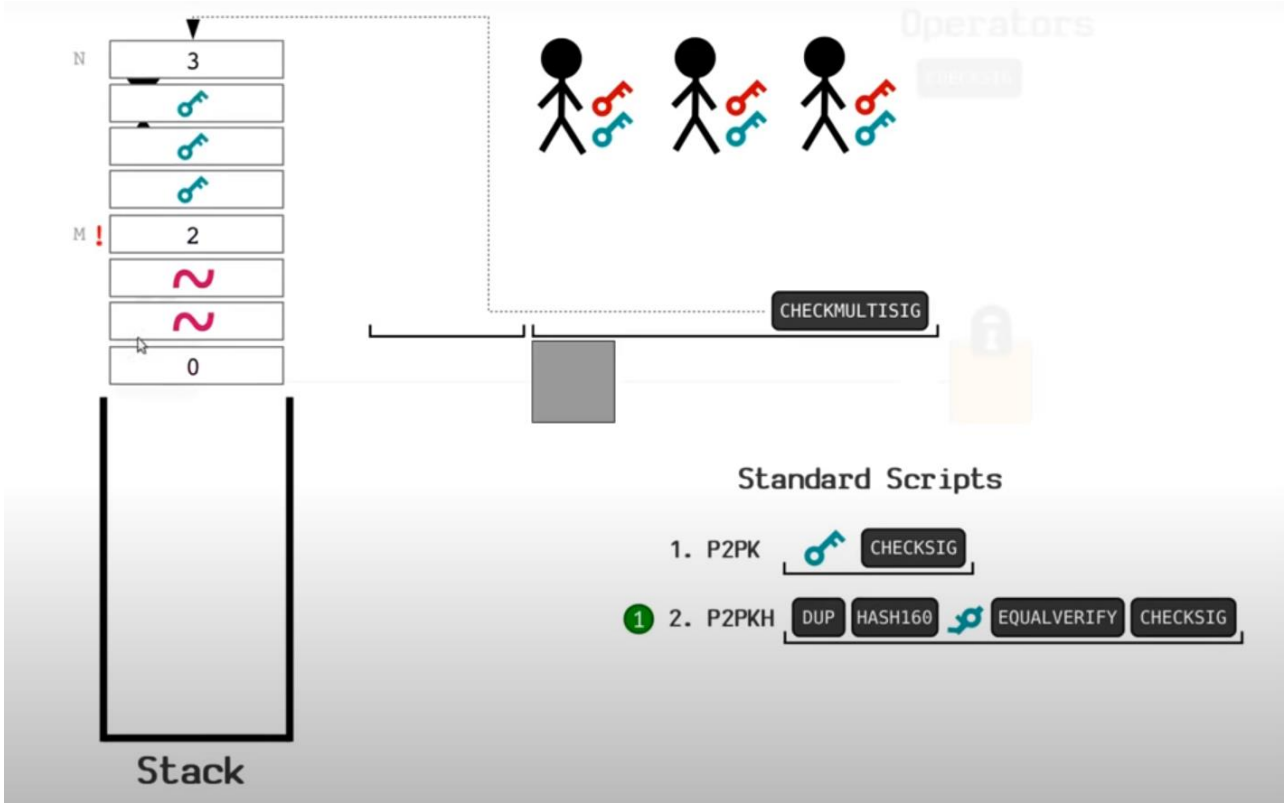

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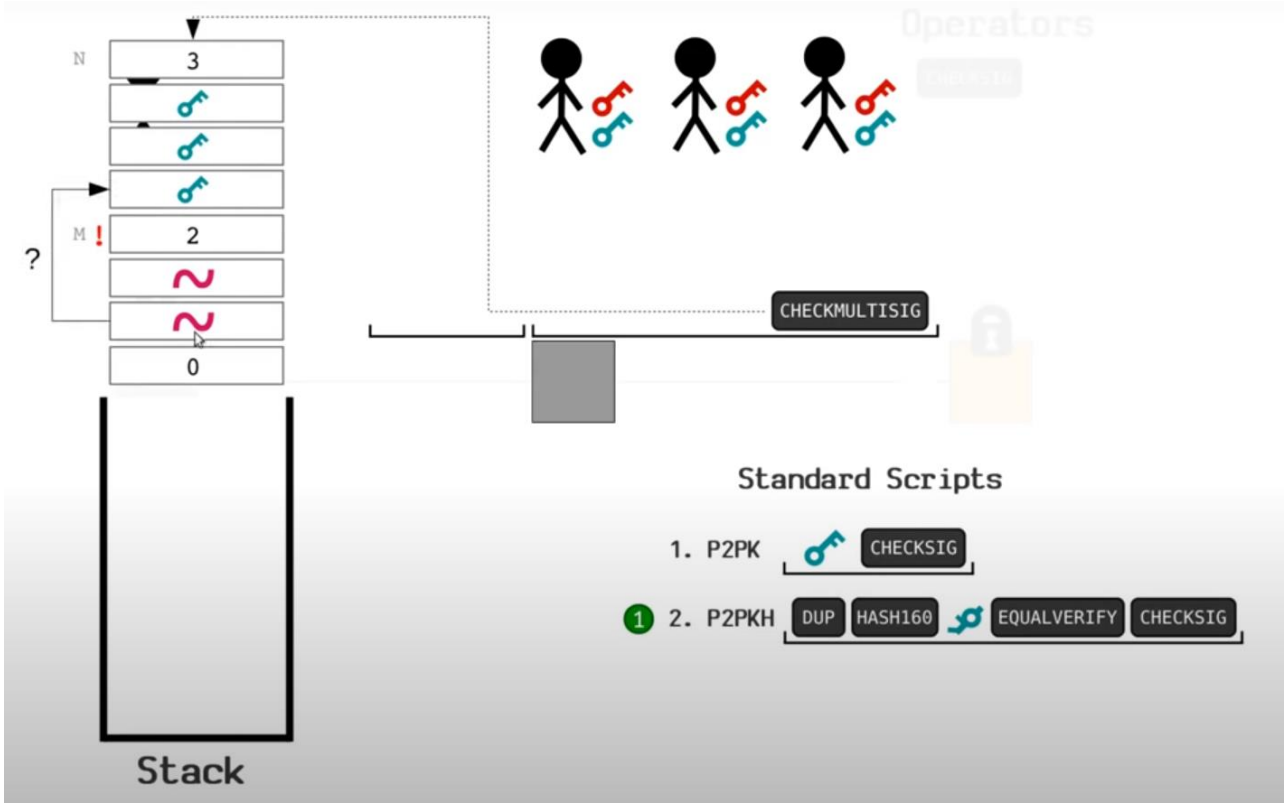

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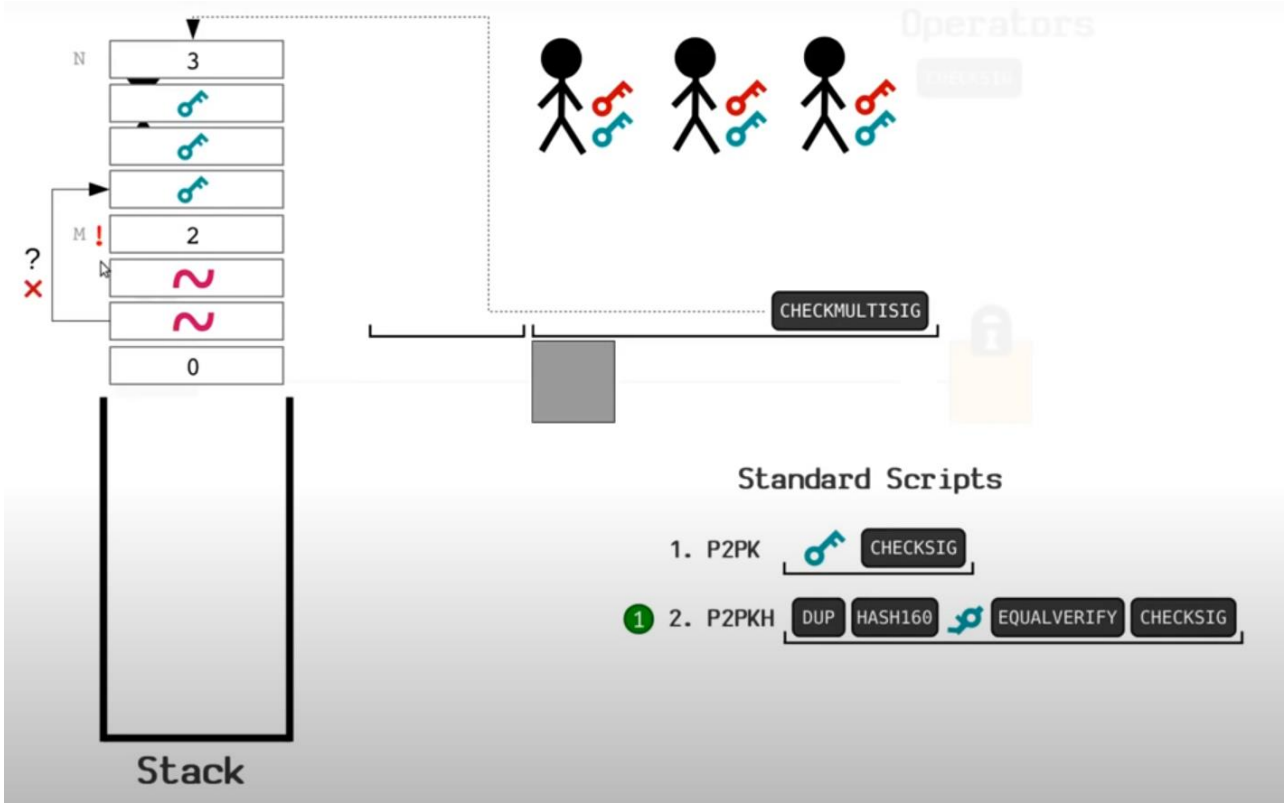

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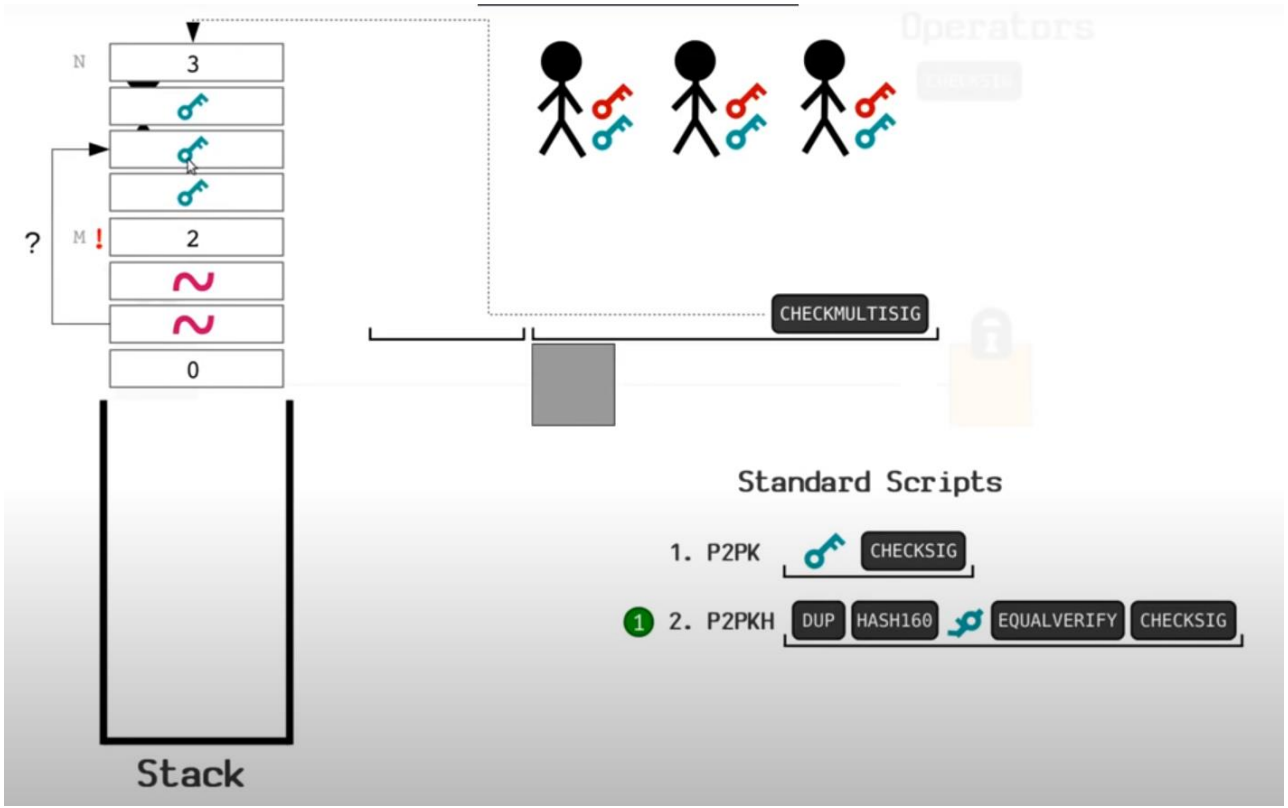

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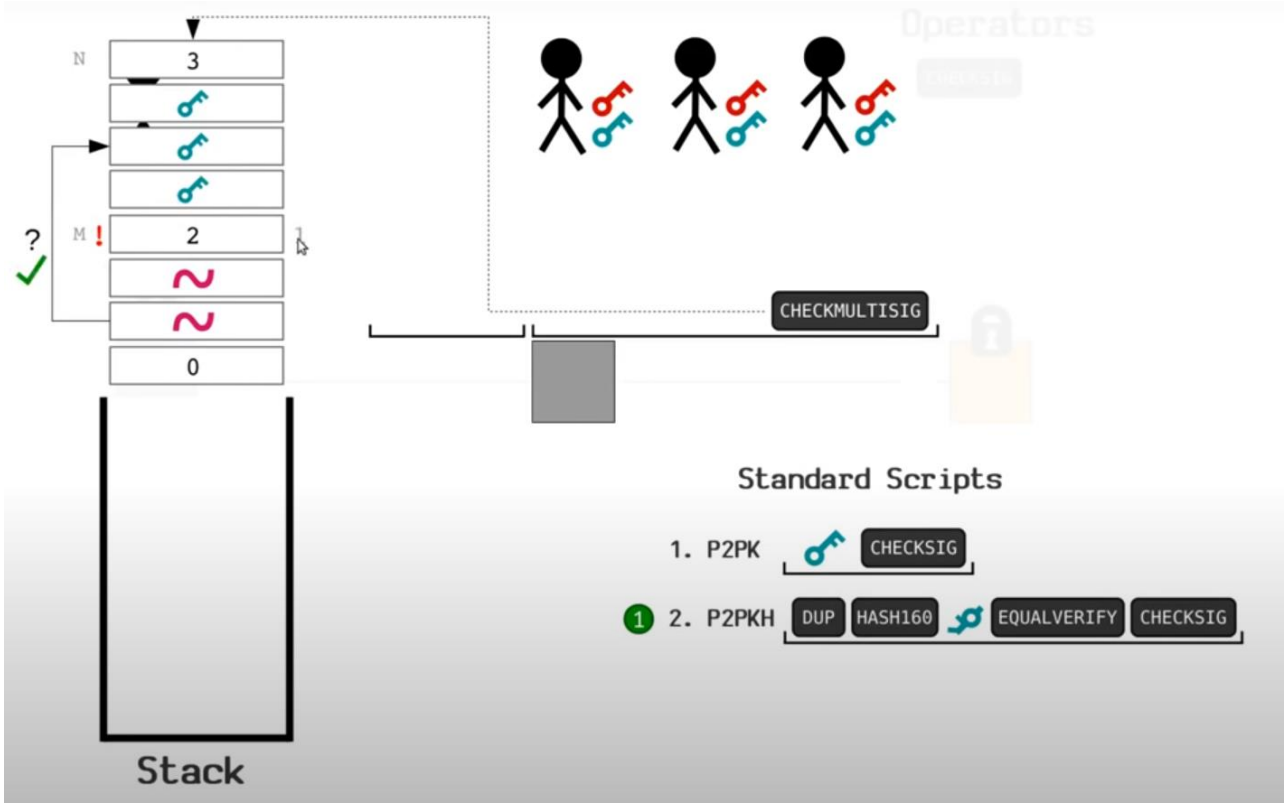

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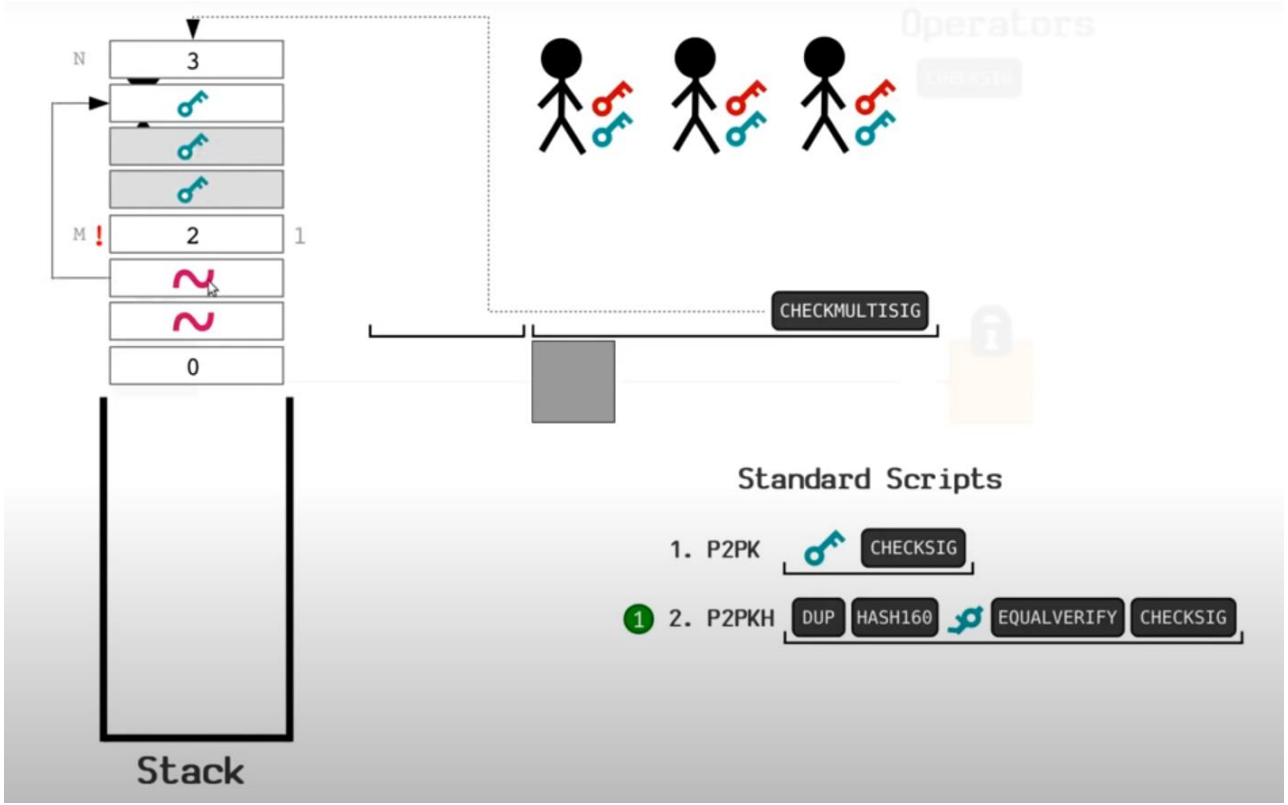

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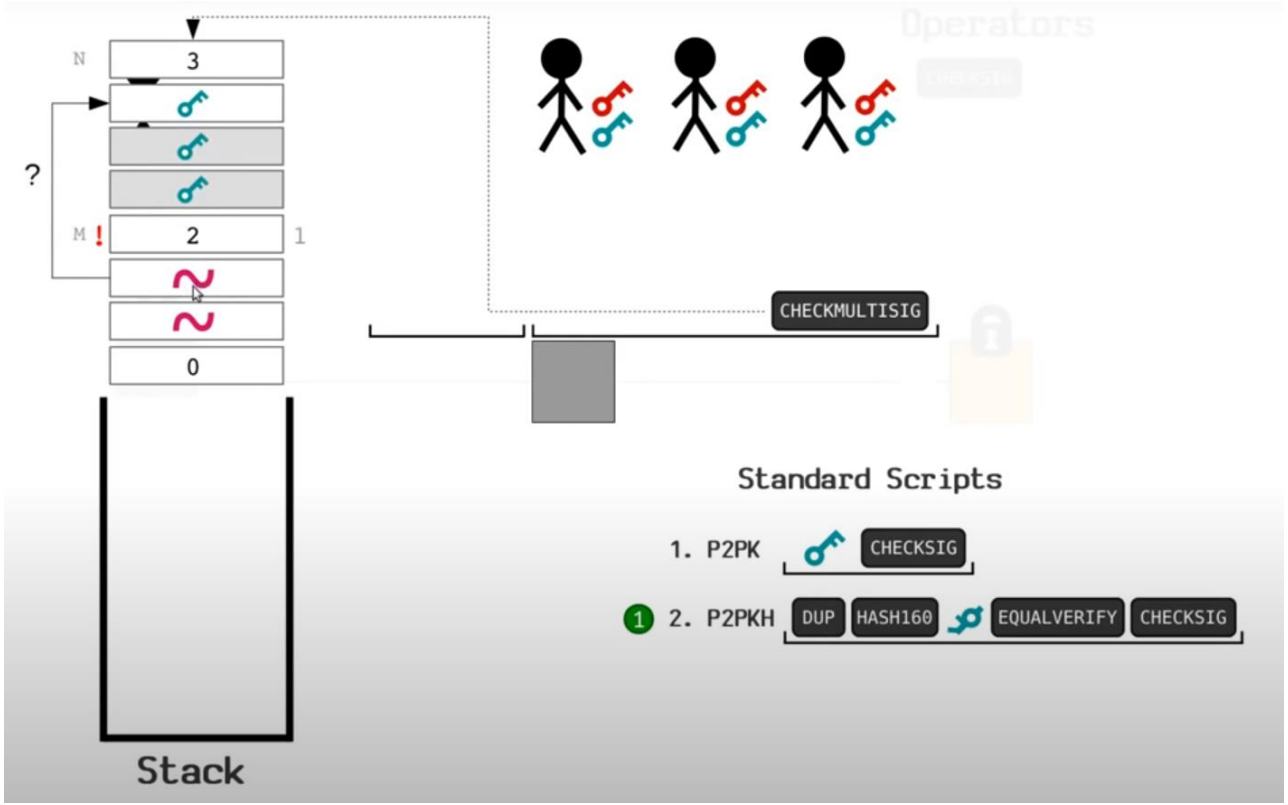

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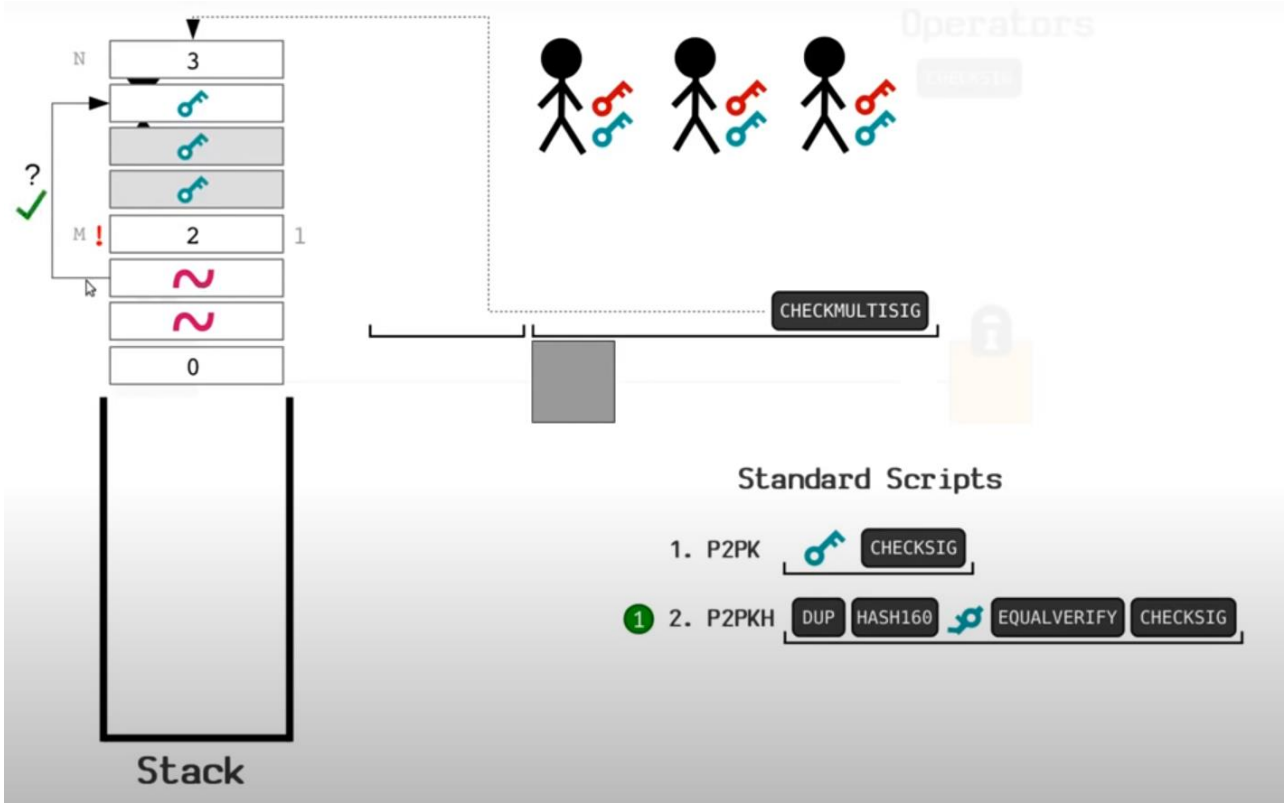

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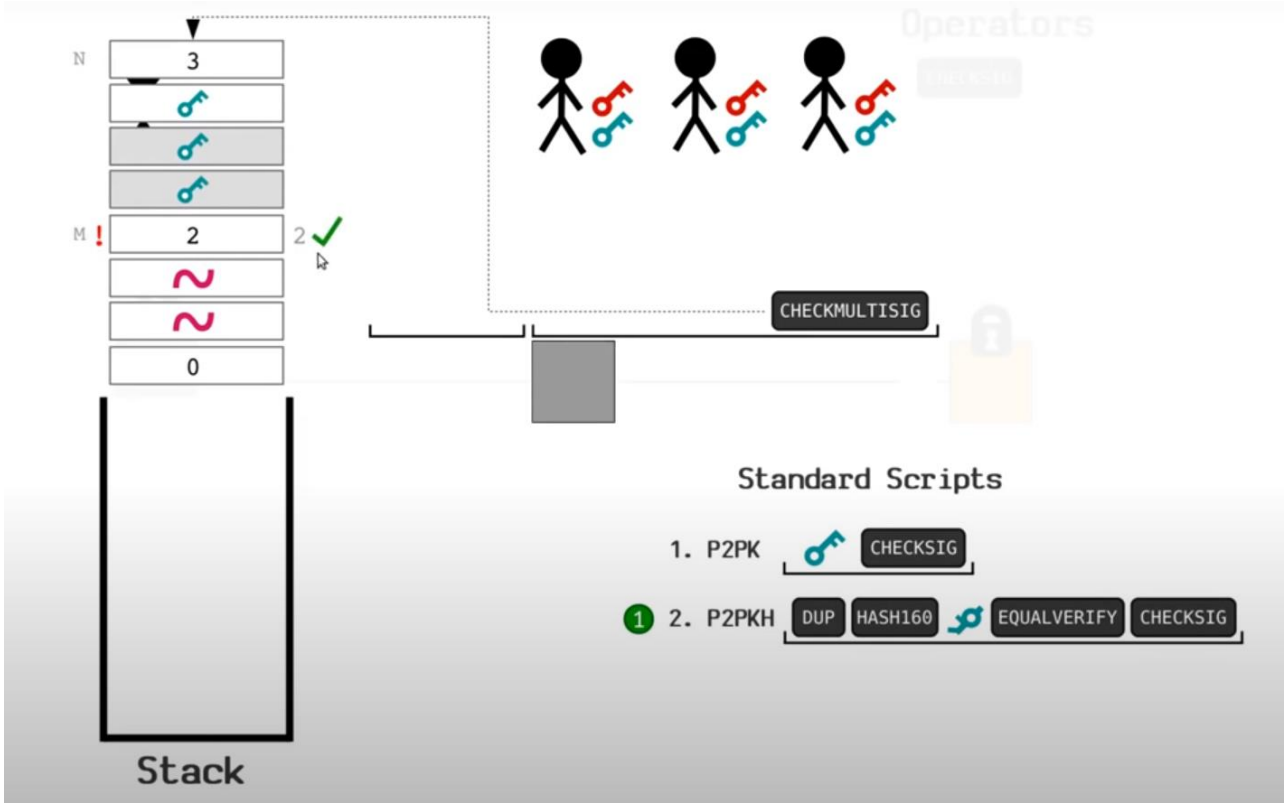

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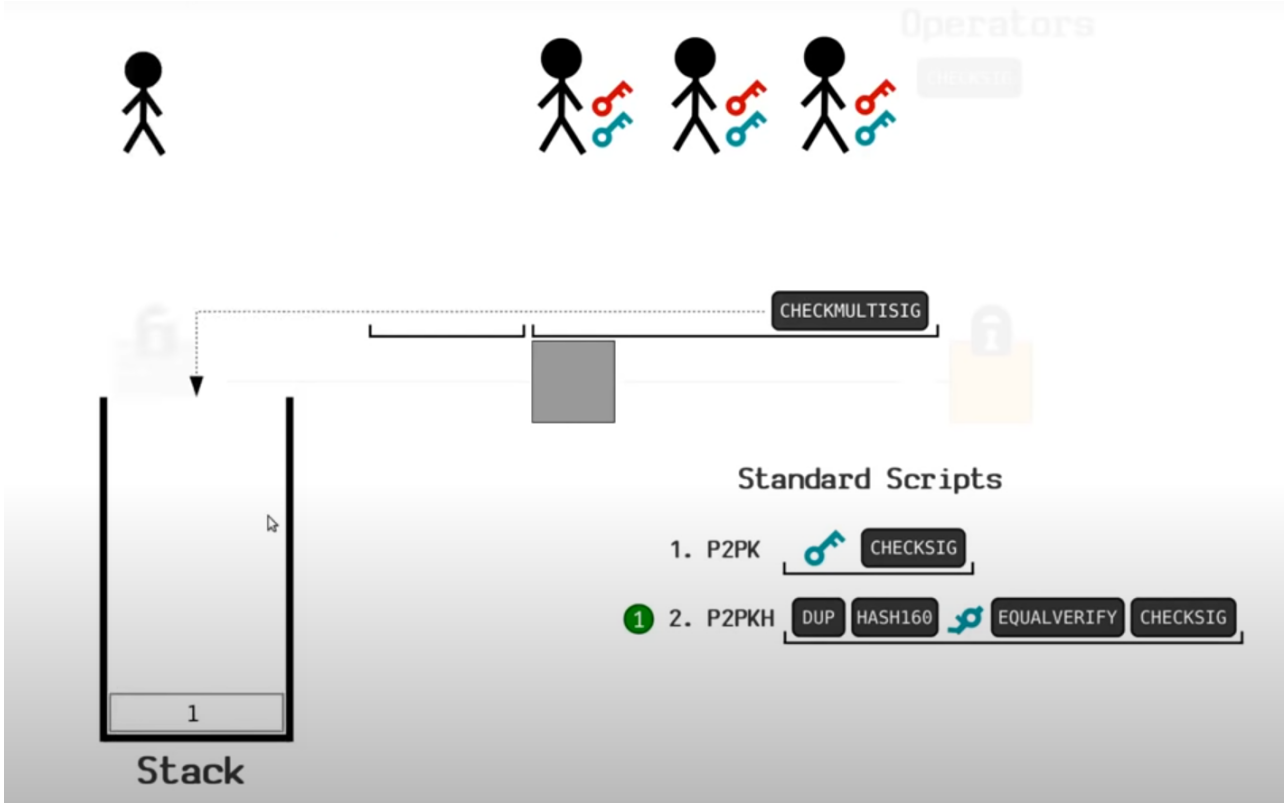

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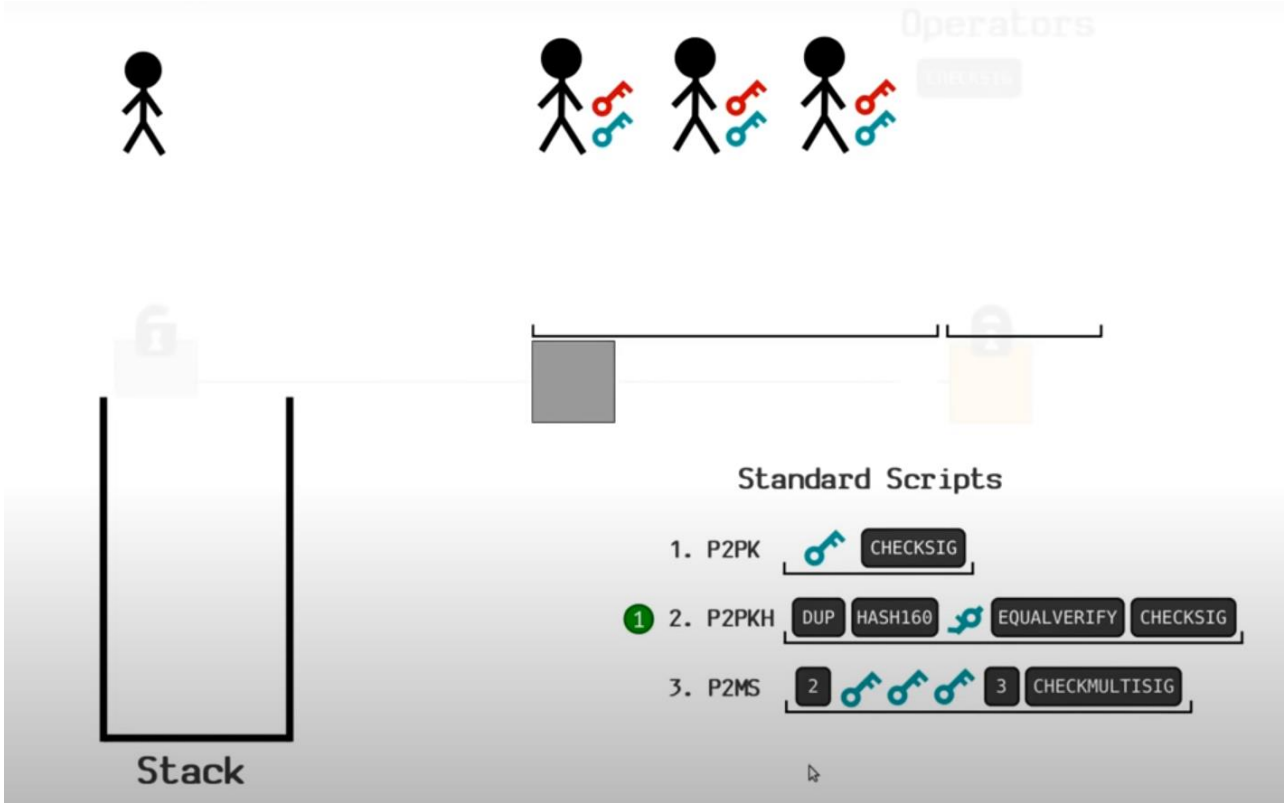

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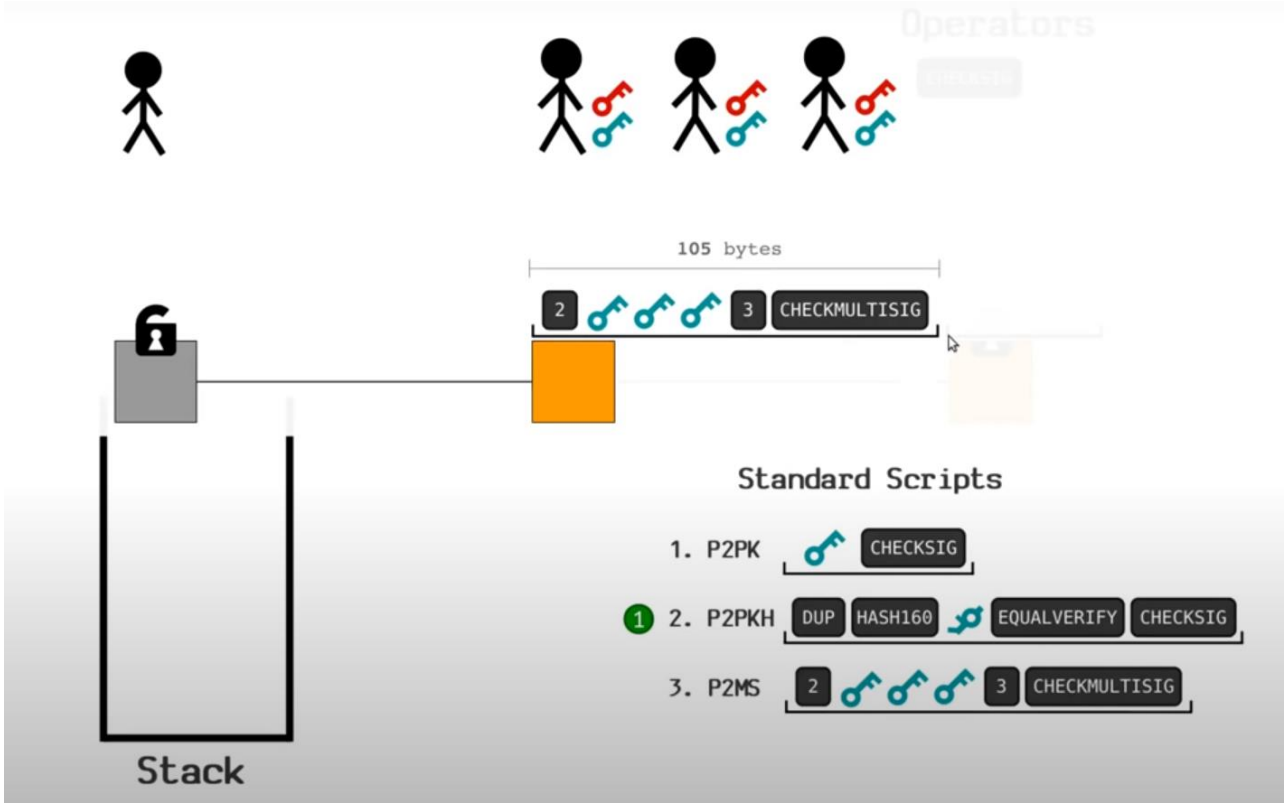
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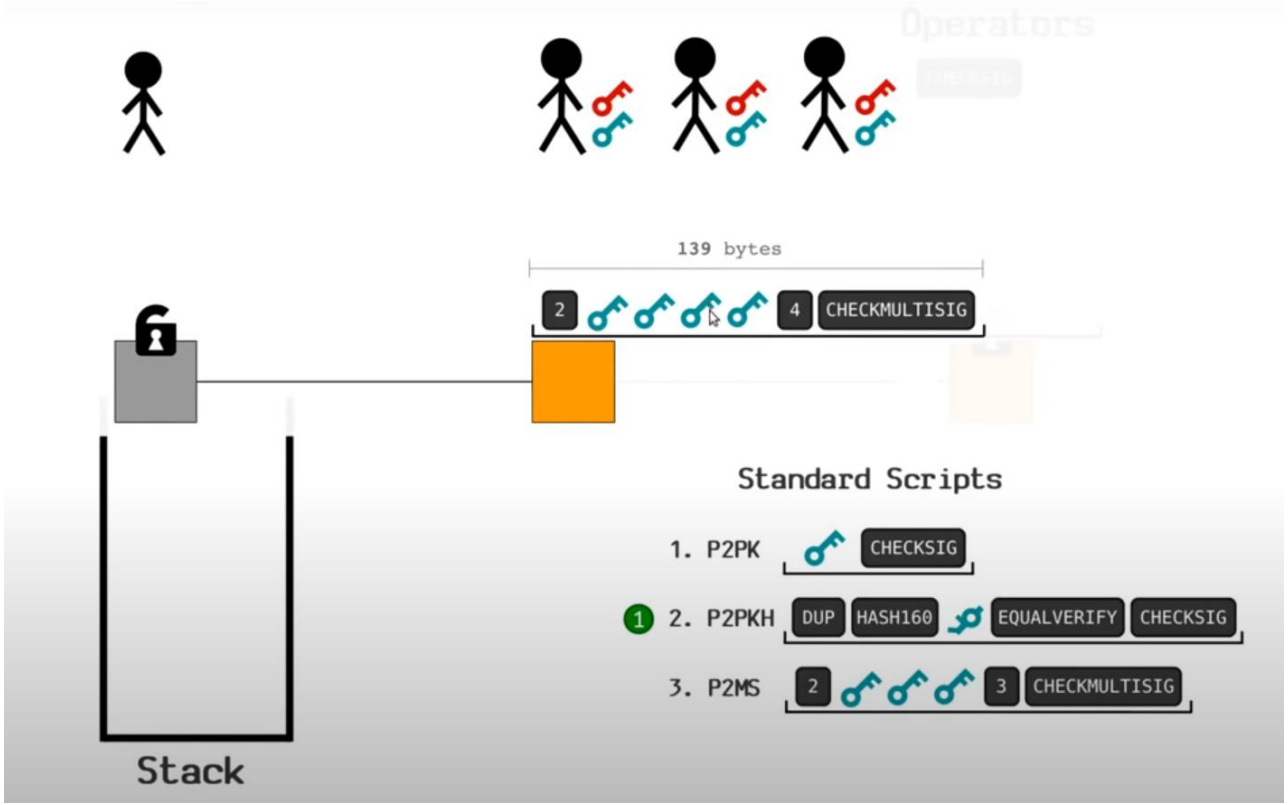
Problem!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CHECKSIG
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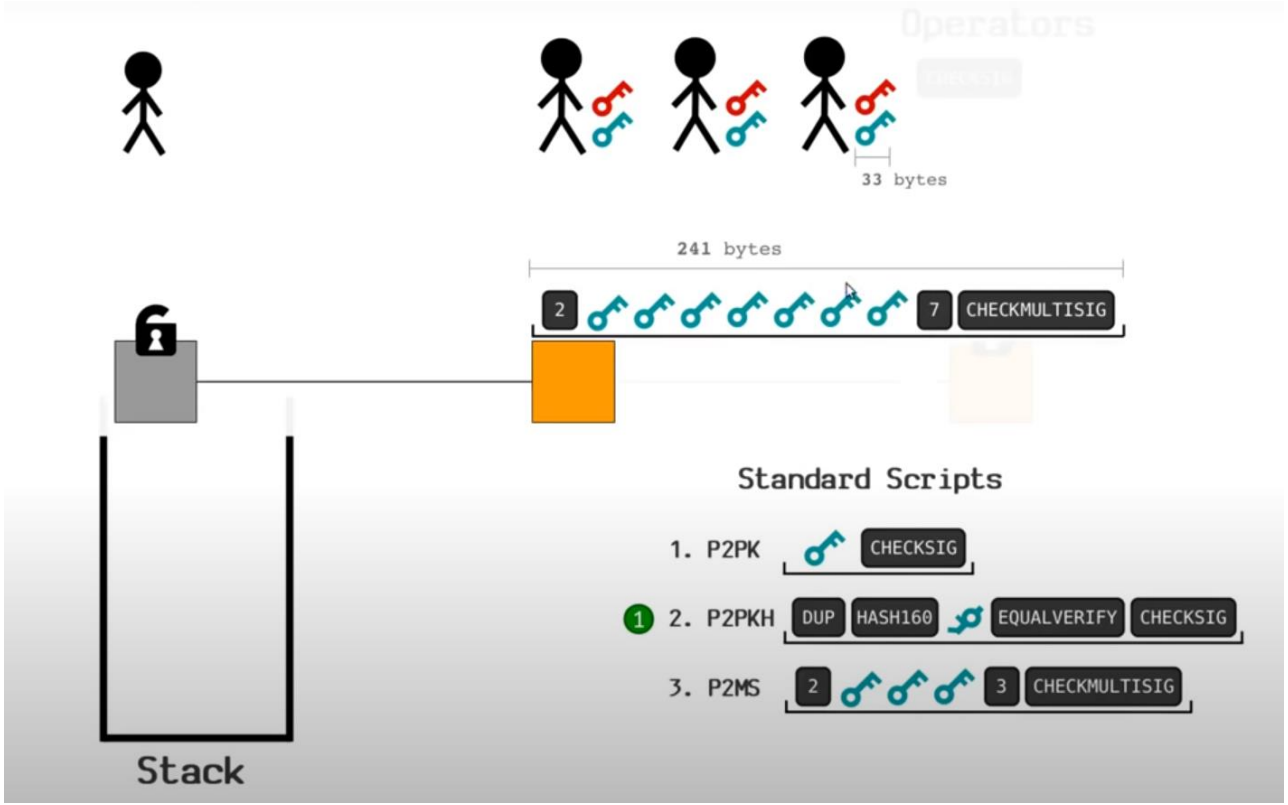
EQUALVERIFY
CHECKSIG
3. P2MS
2
3
CHECKMULTISIG
Stack

Problem!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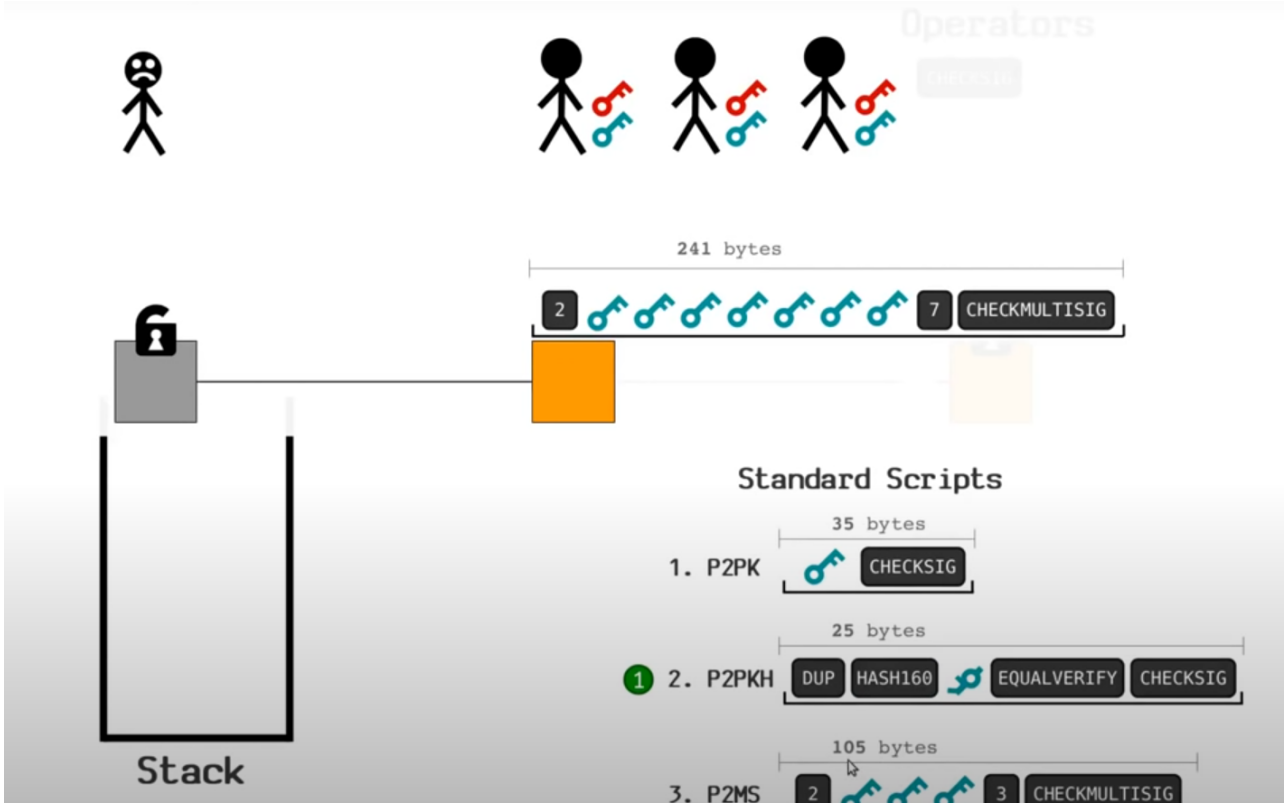
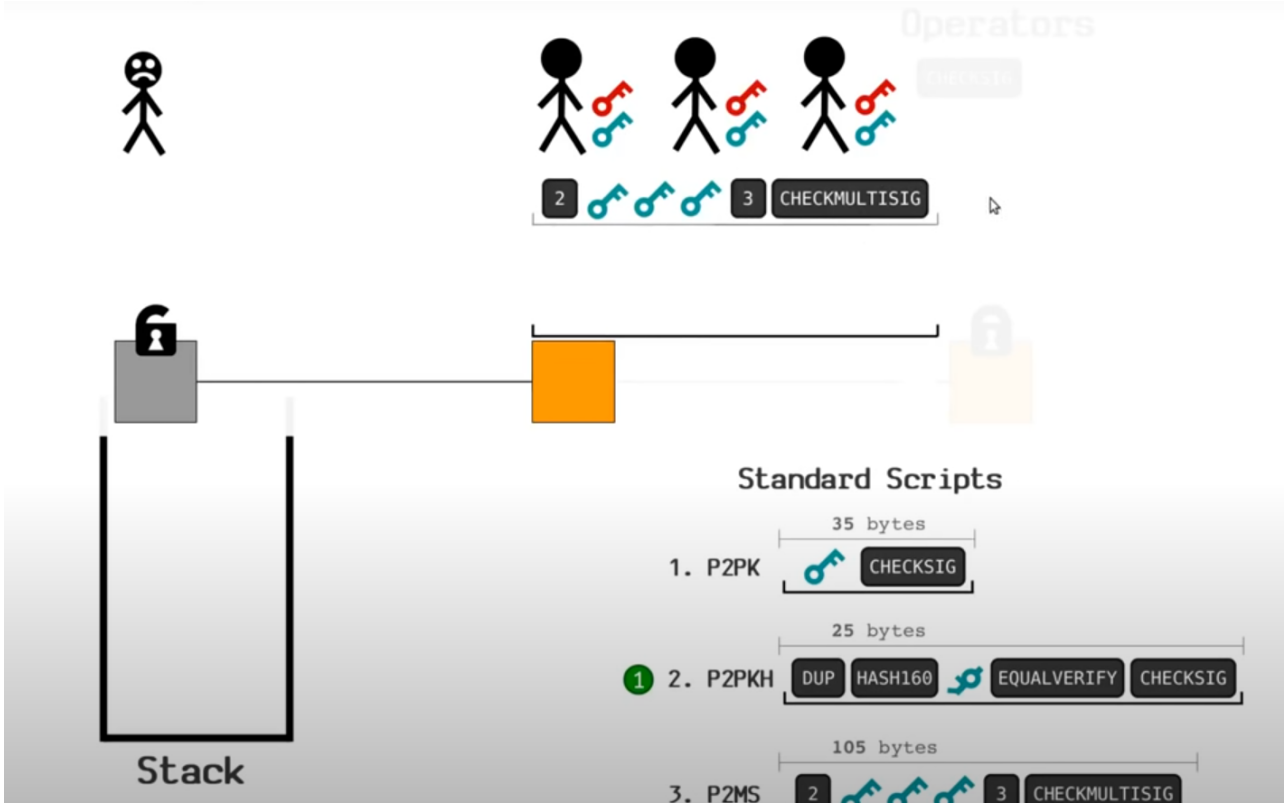
241 bytes
2
7
CHECKMULTISIG
Standard Scripts
1. P2PK
CHECKSIG
1
2. P2PKH
DUP
HASH160
EQUALVERIFY
CHECKSIG
3. P2MS
2
3
CHECKMULTISIG
Stack

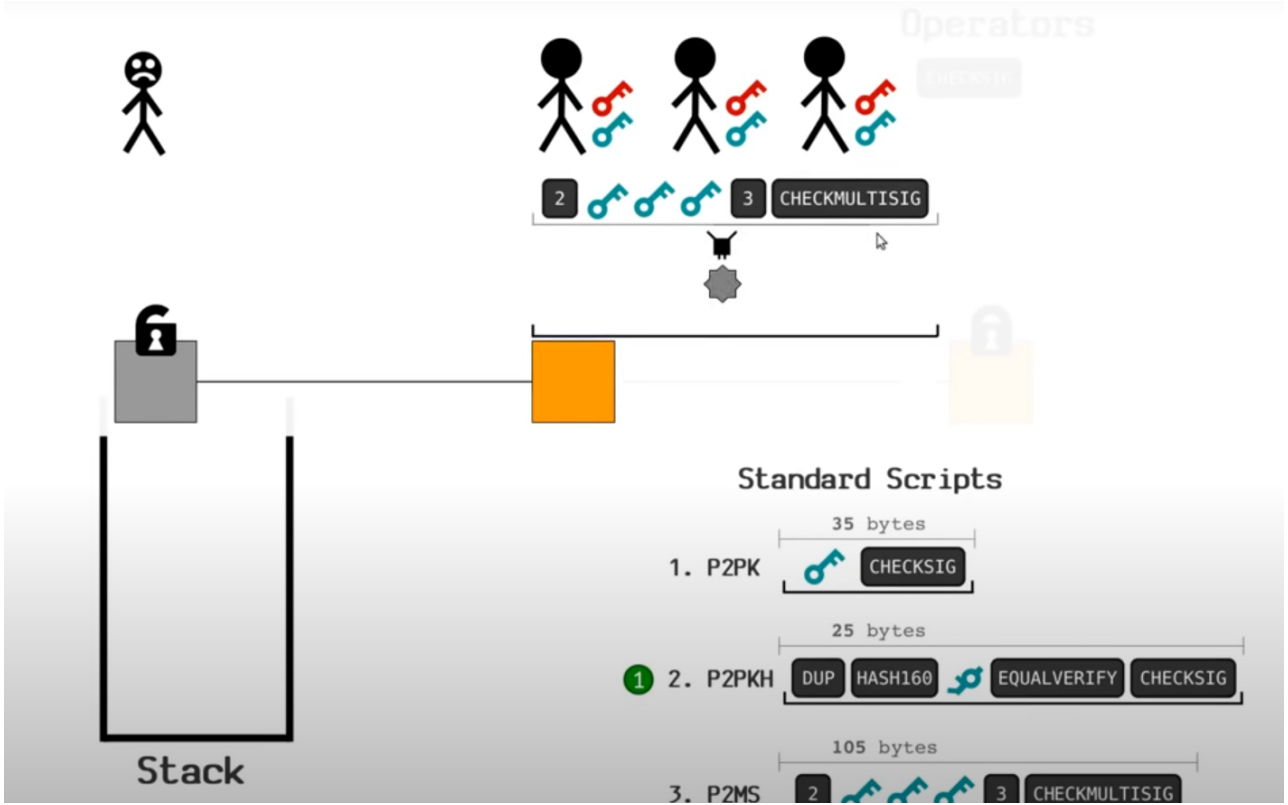
Problem!


241 bytes
2
7
CHECKMULTISIG
Stack
Standard Scripts
35 bytes
1. P2PK
CHECKSIG
25 bytes
1
2. P2PKH
DUP
HASH160
EQUALVERIFY
CHECKSIG
105 bytes
3. P2MS
2
3
CHECKMULTISIG

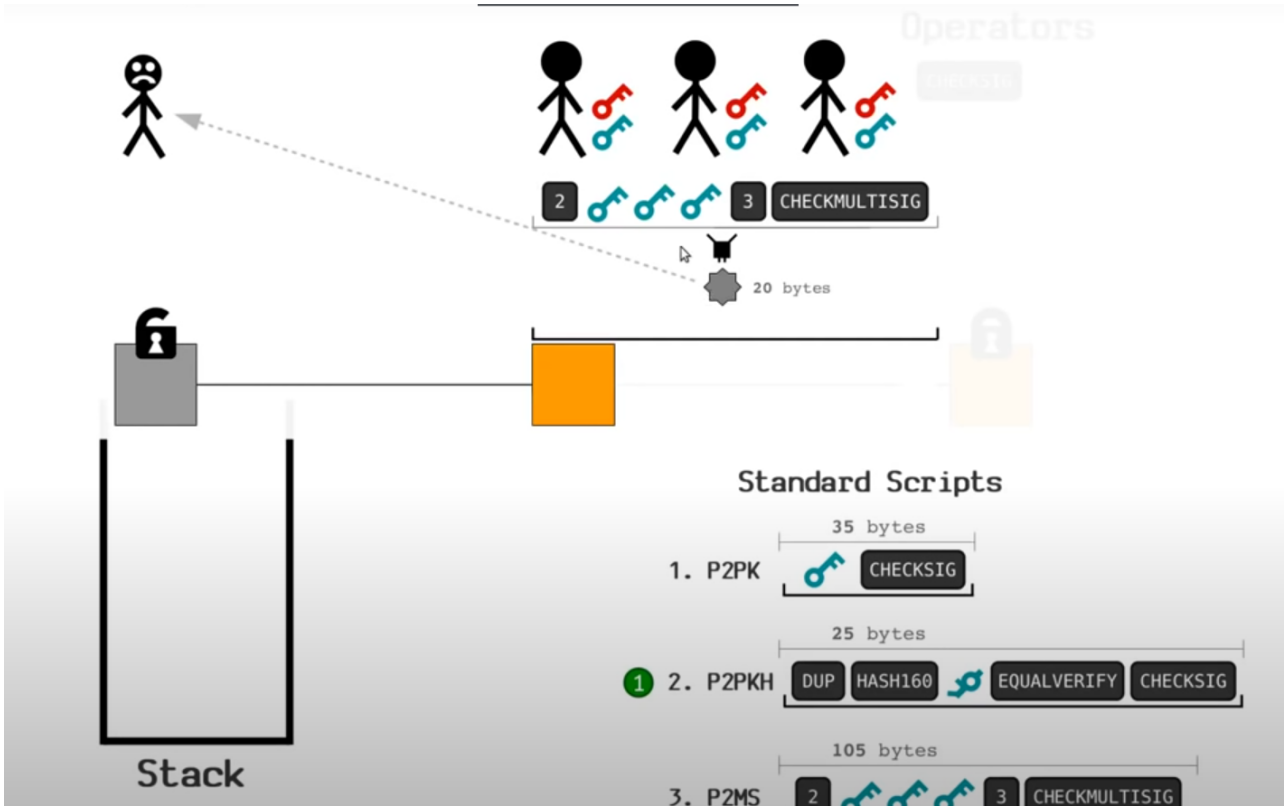
Pay to Script Hash (P2SH)



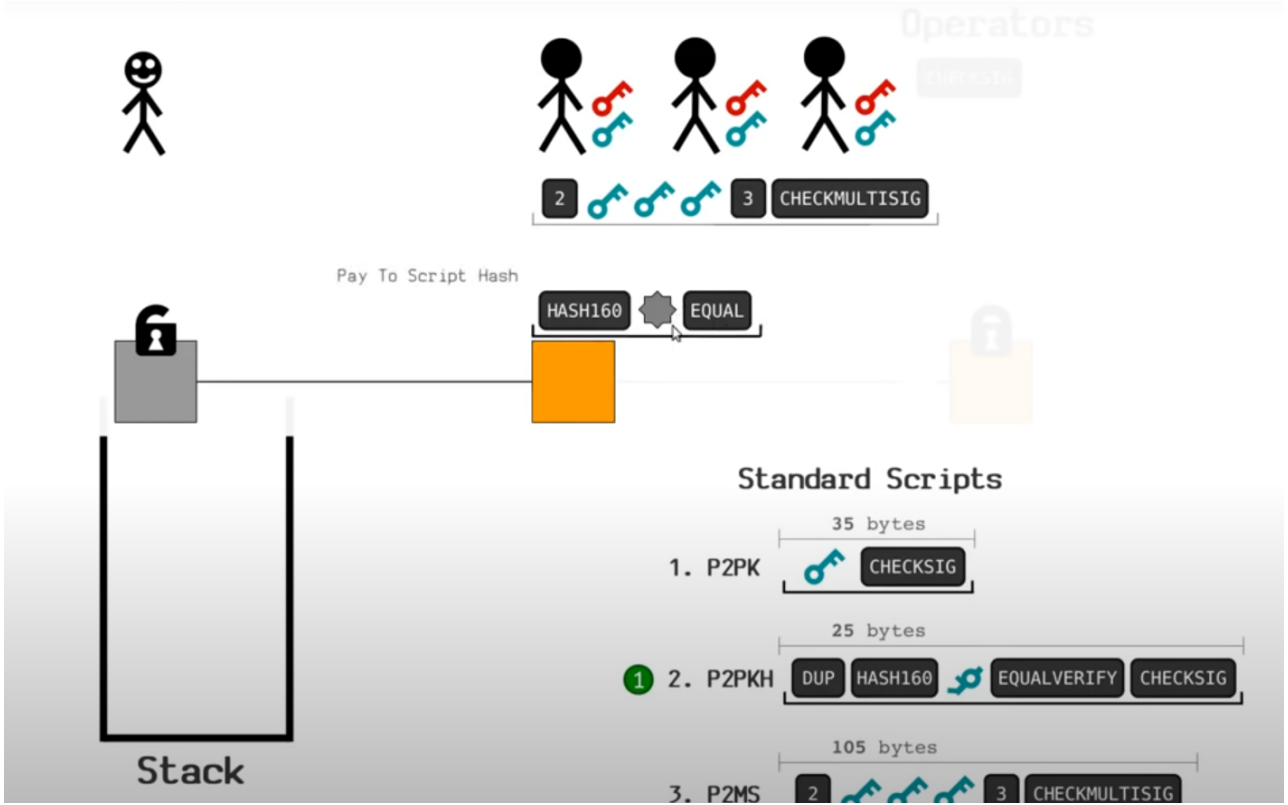
Pay to Script Hash (P2SH)



Pay to Script Hash (P2SH)



Pay to Script Hash (P2SH)



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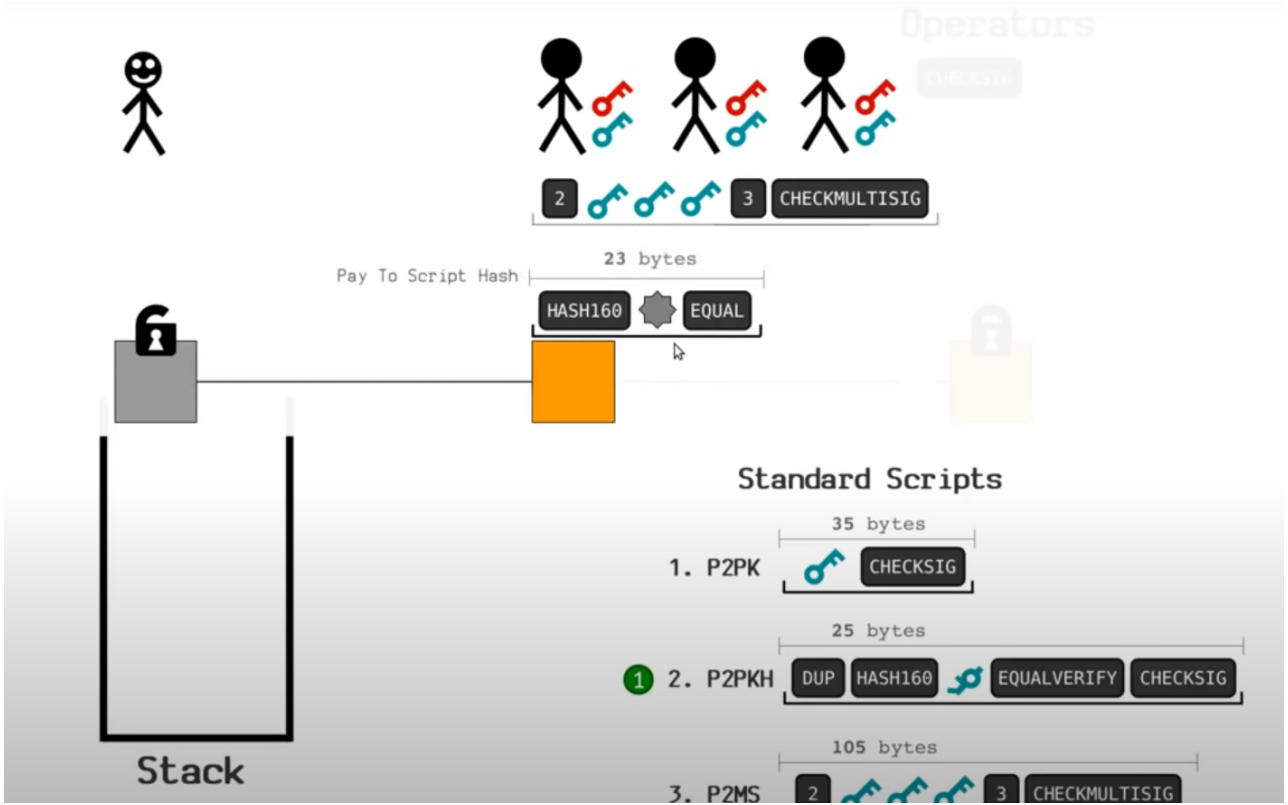
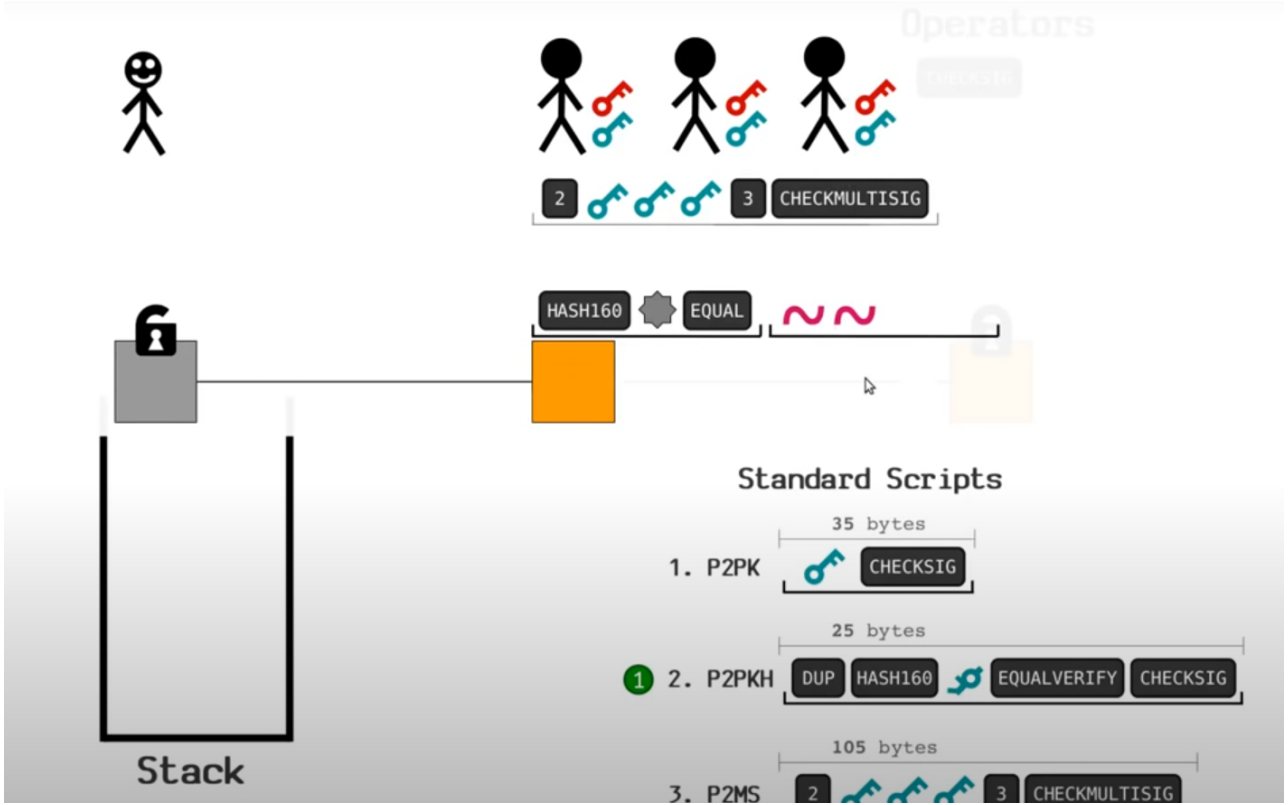


Pay to Script Hash (P2SH)



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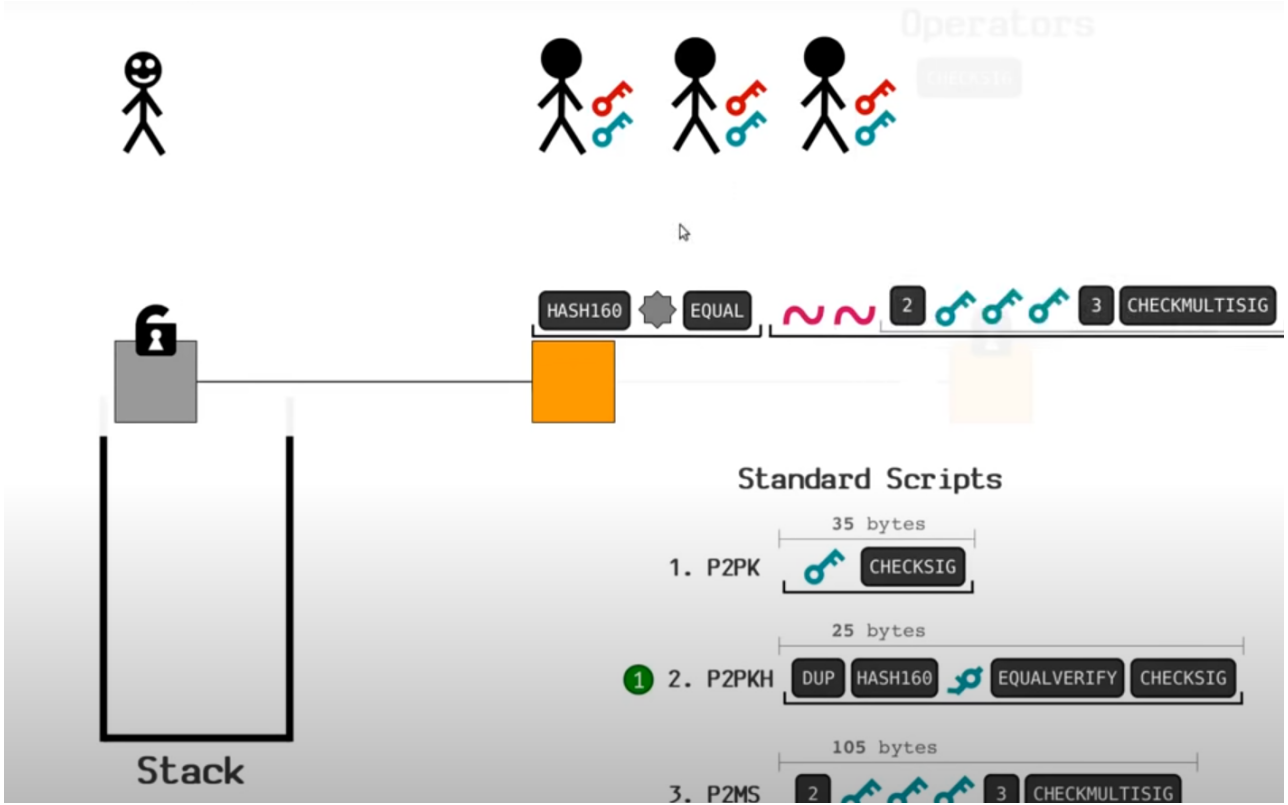

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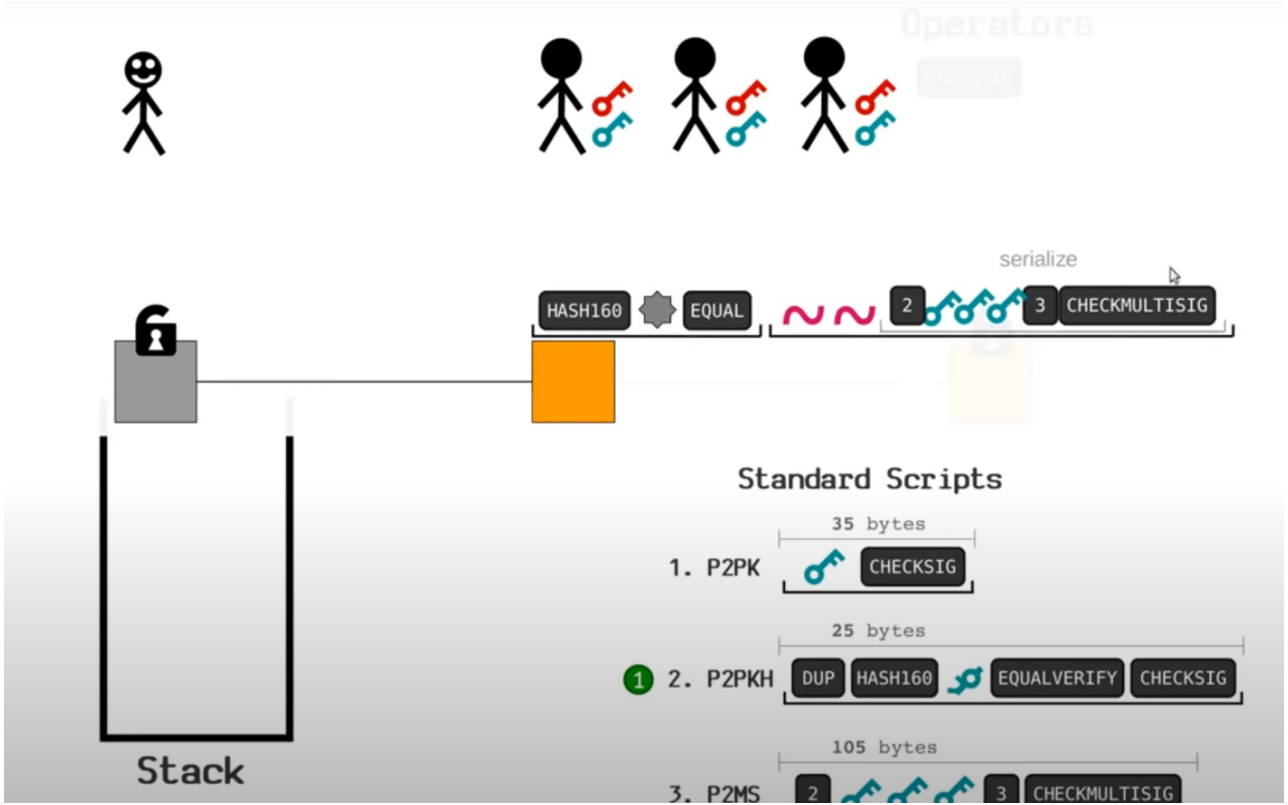

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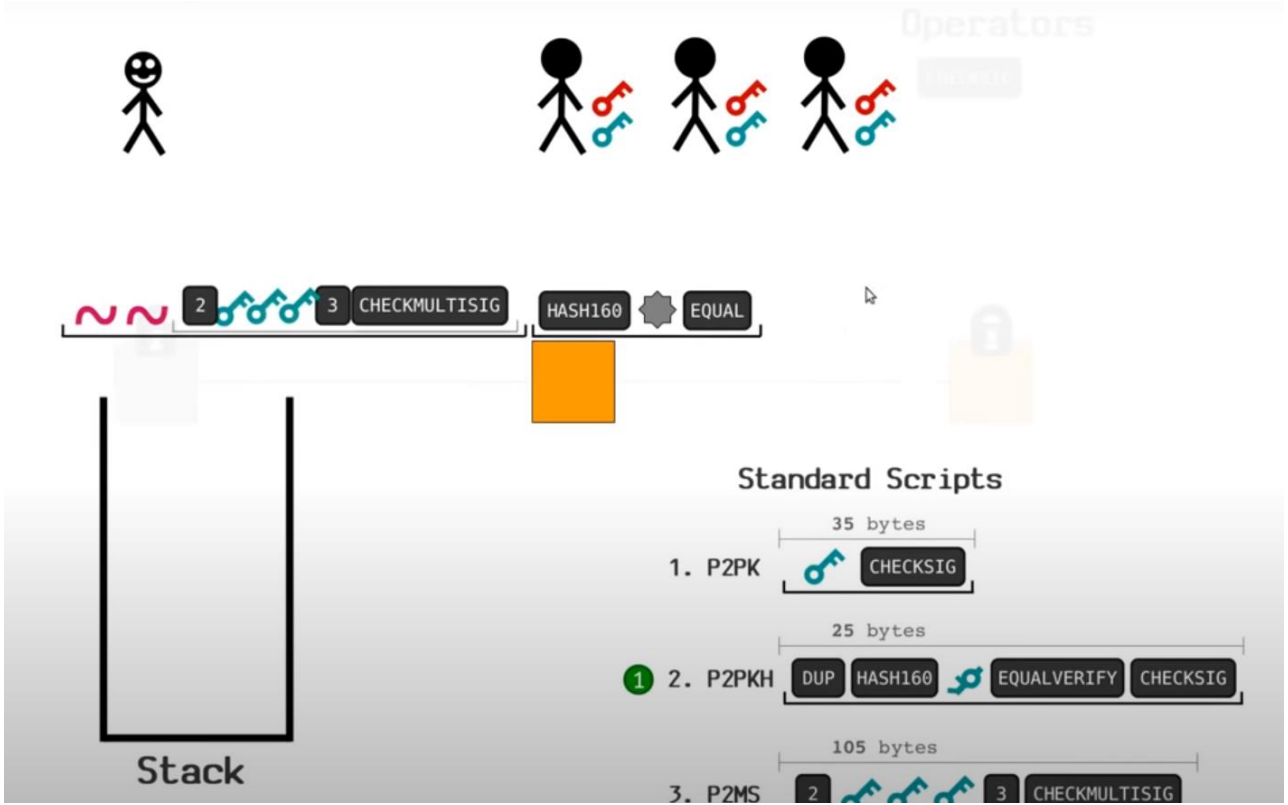

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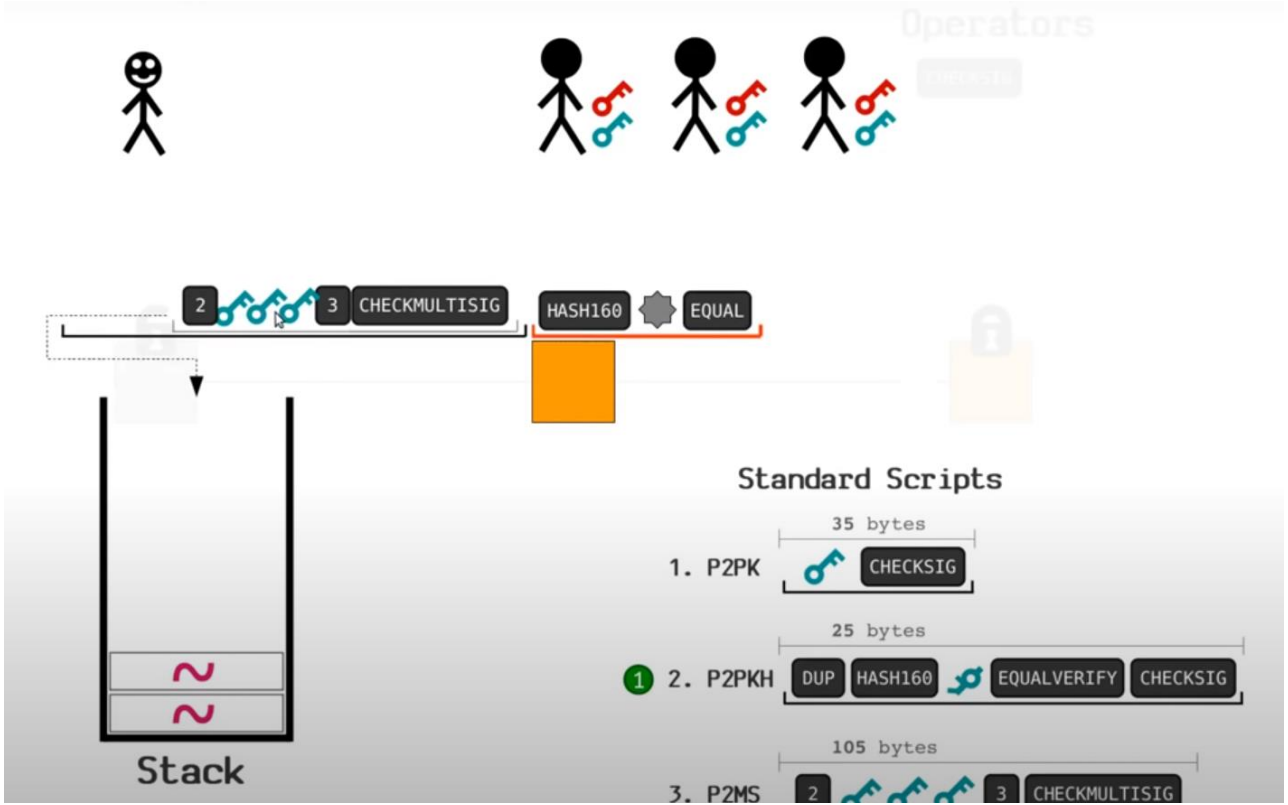

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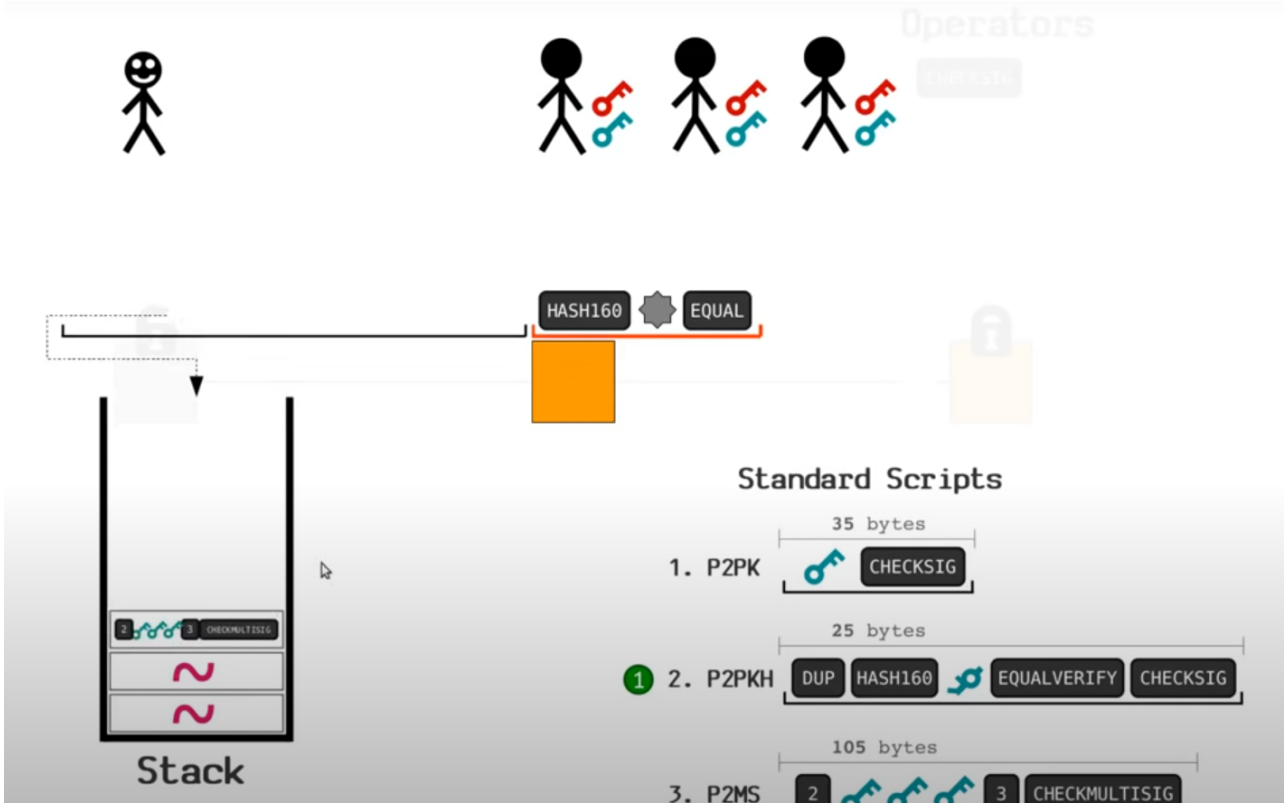

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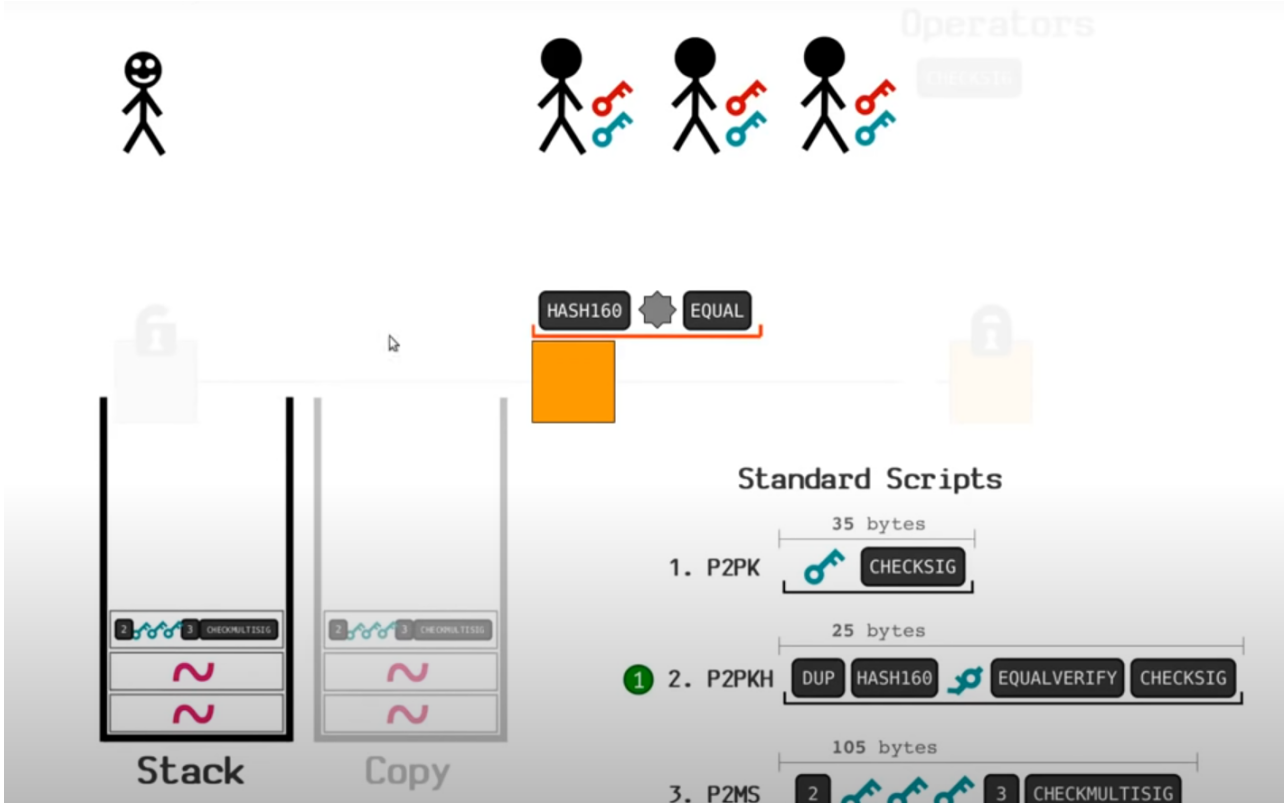

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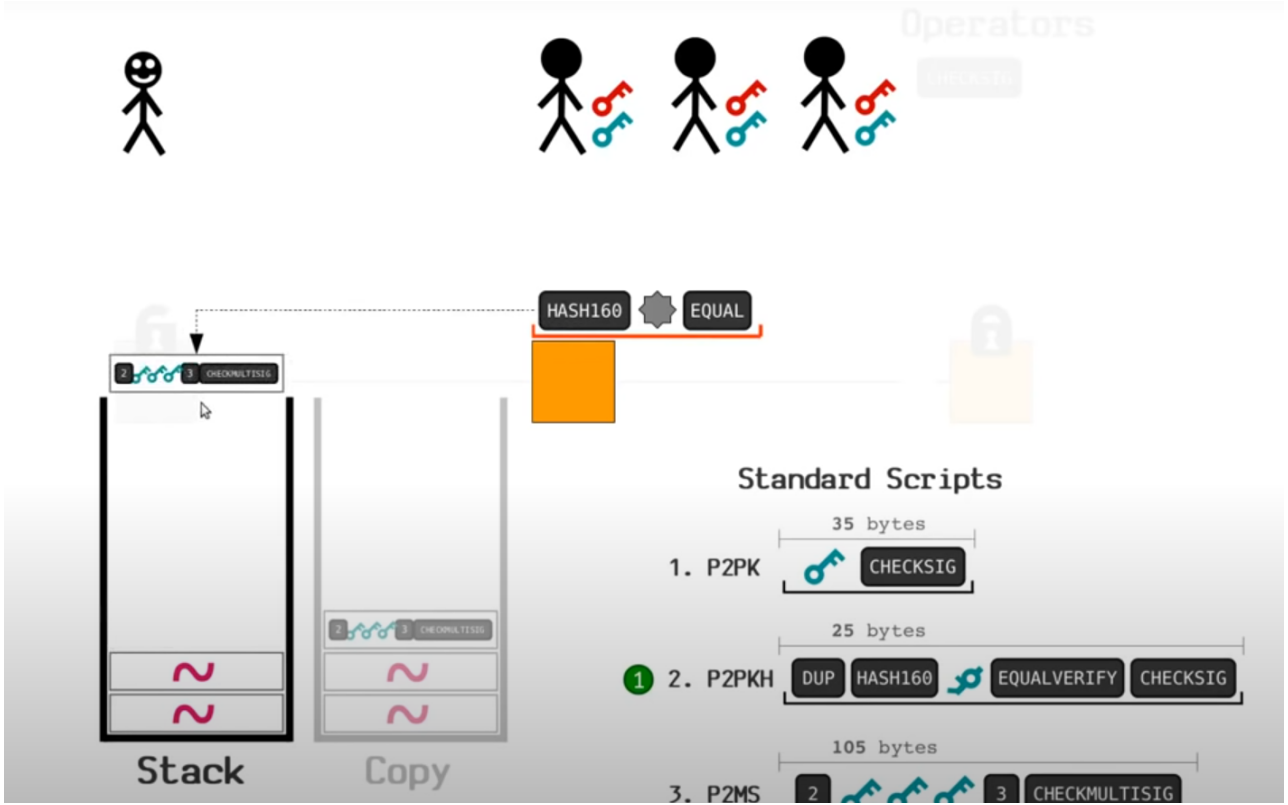

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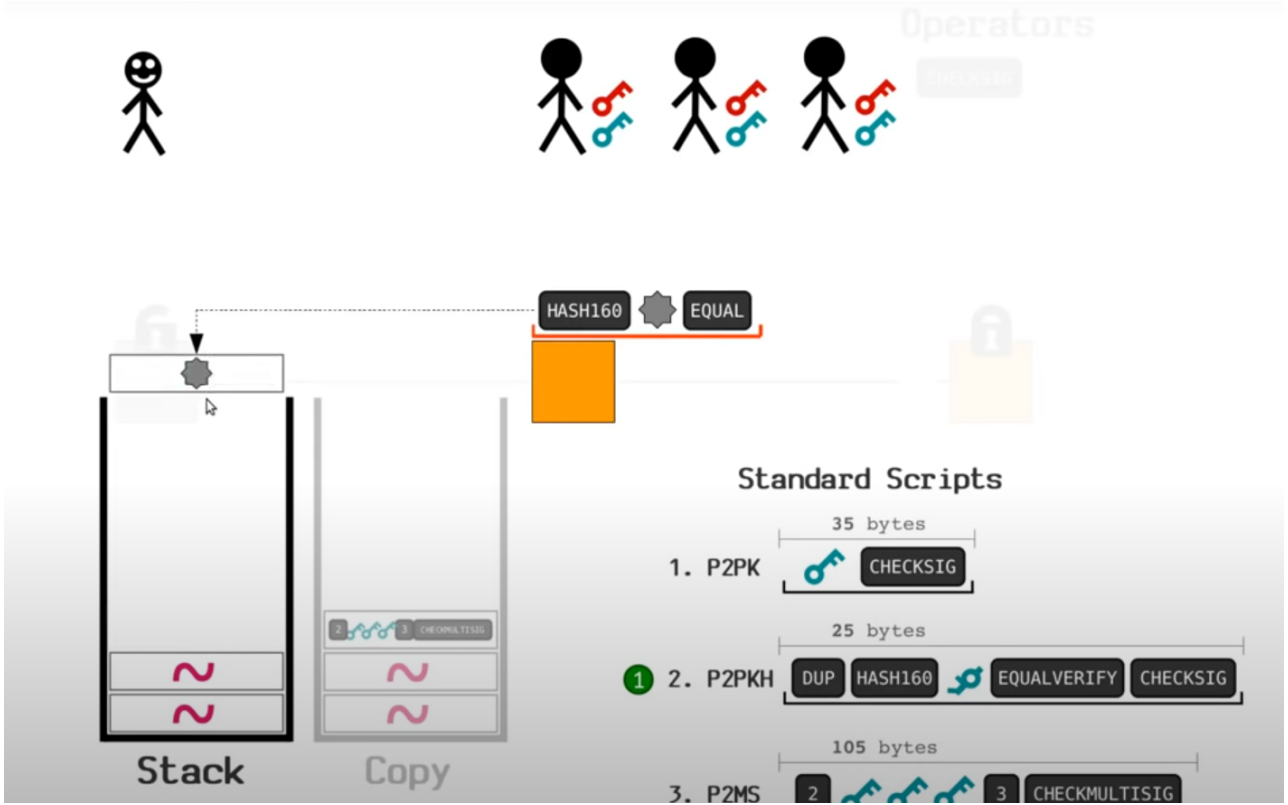

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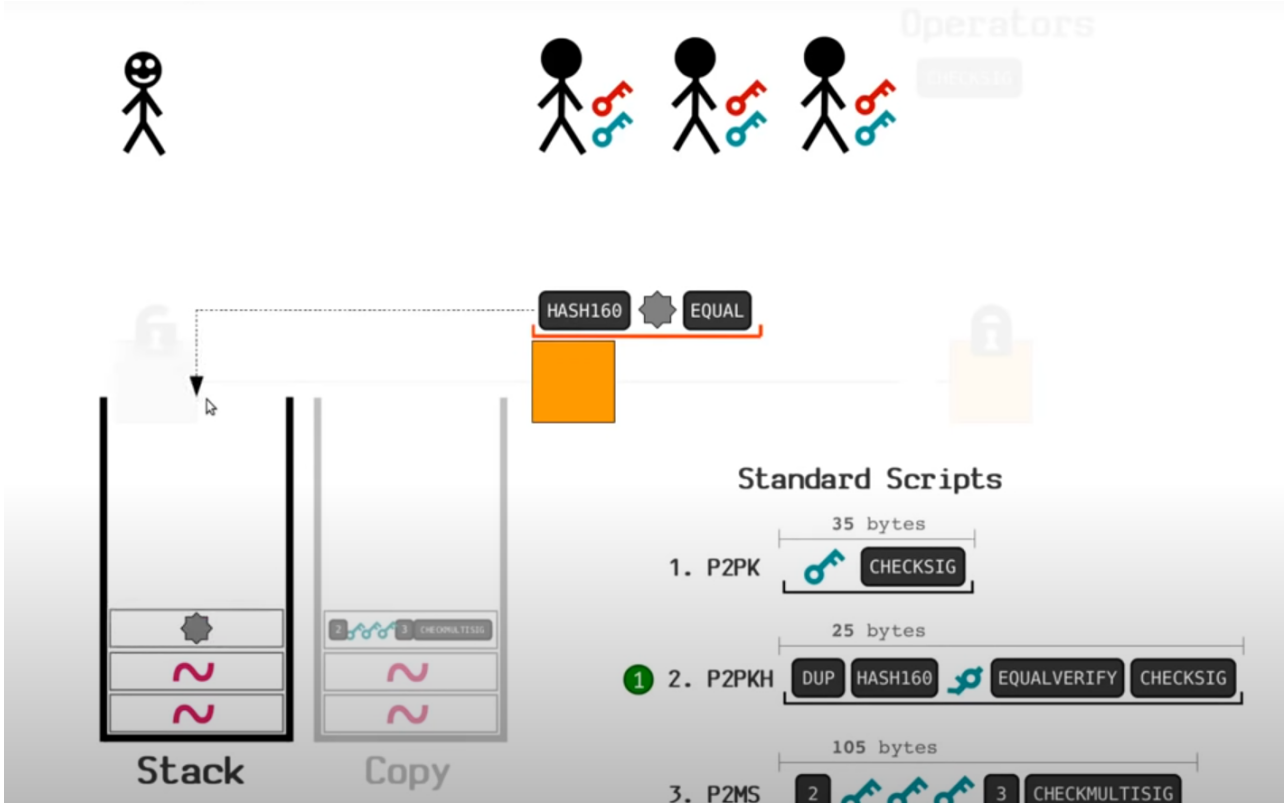
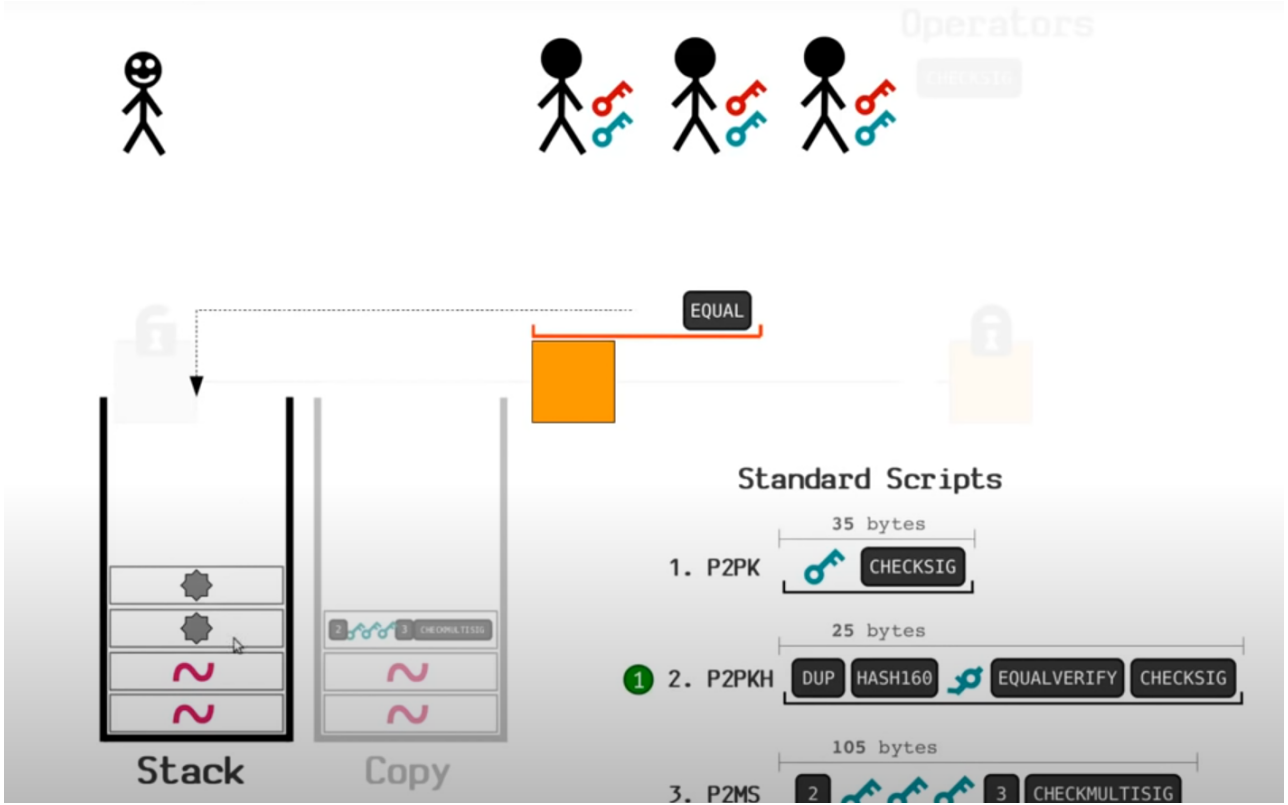


Pay to Script Hash (P2SH)



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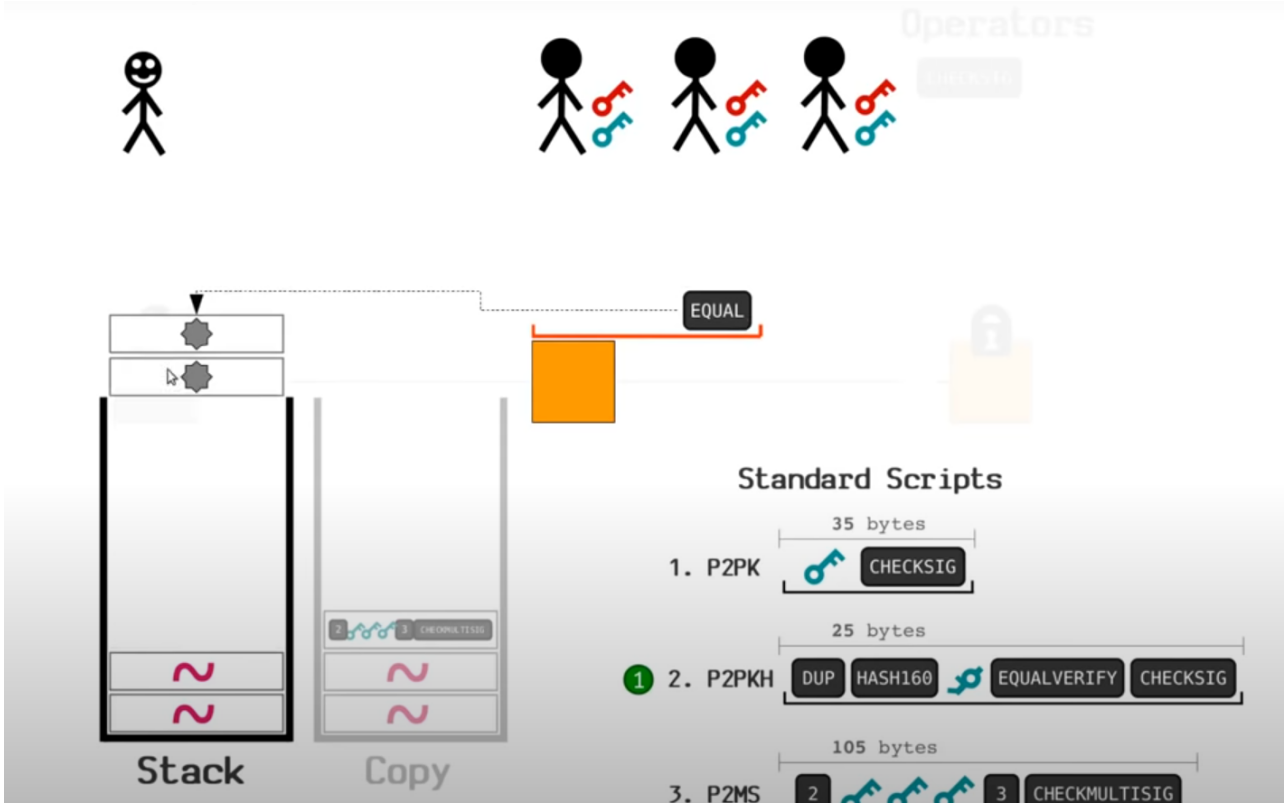

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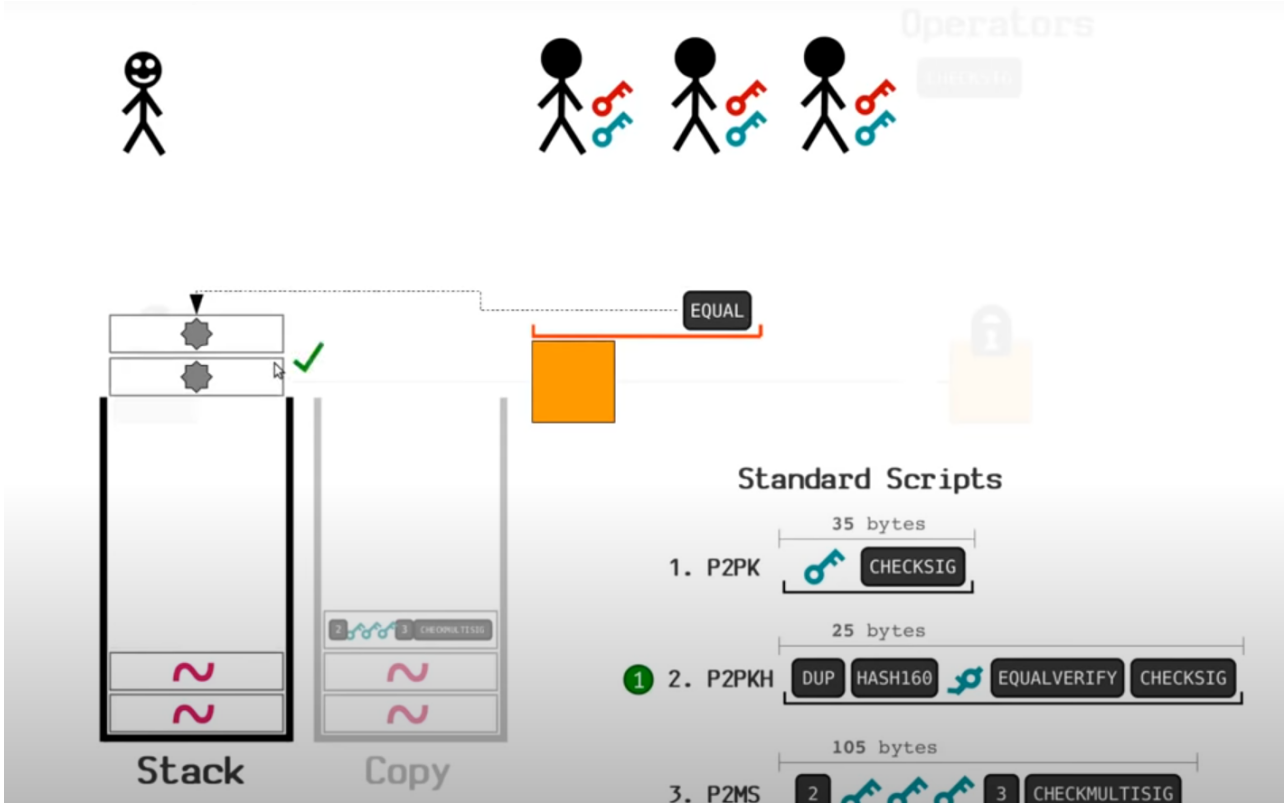

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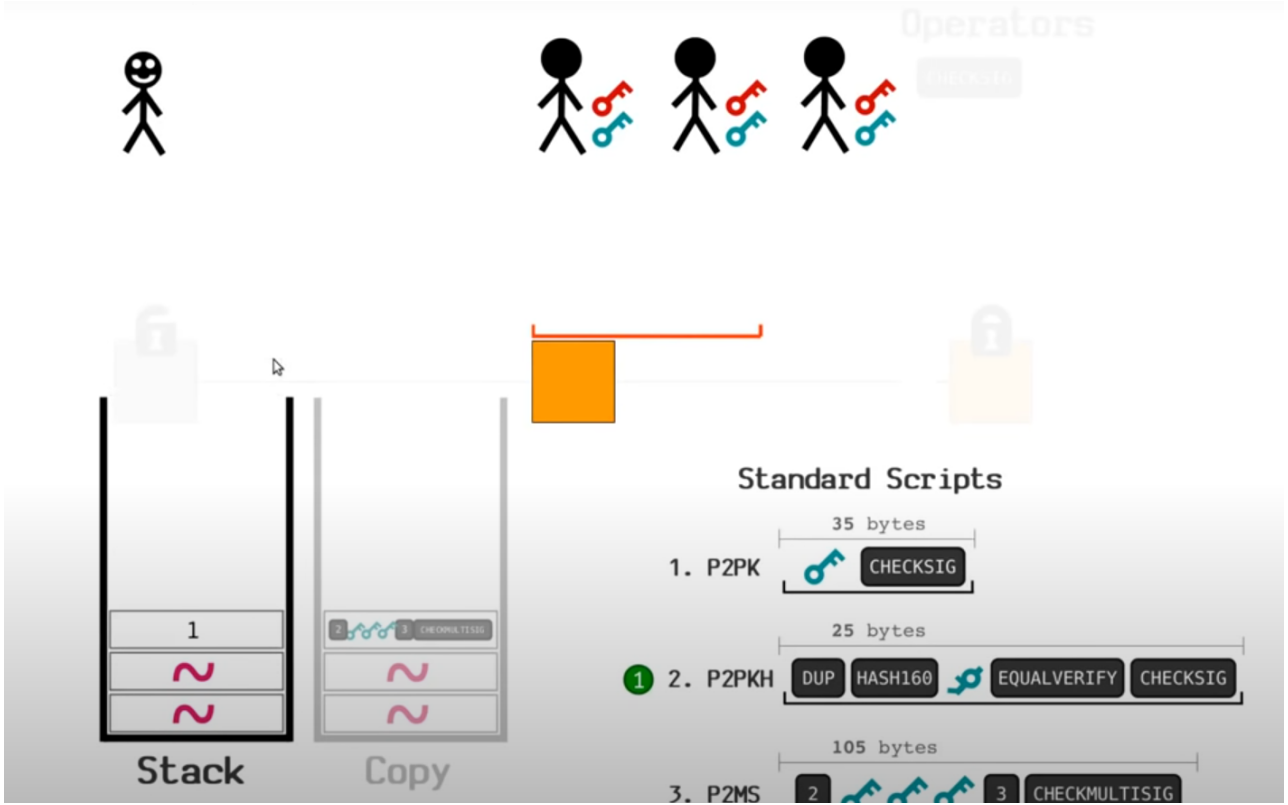

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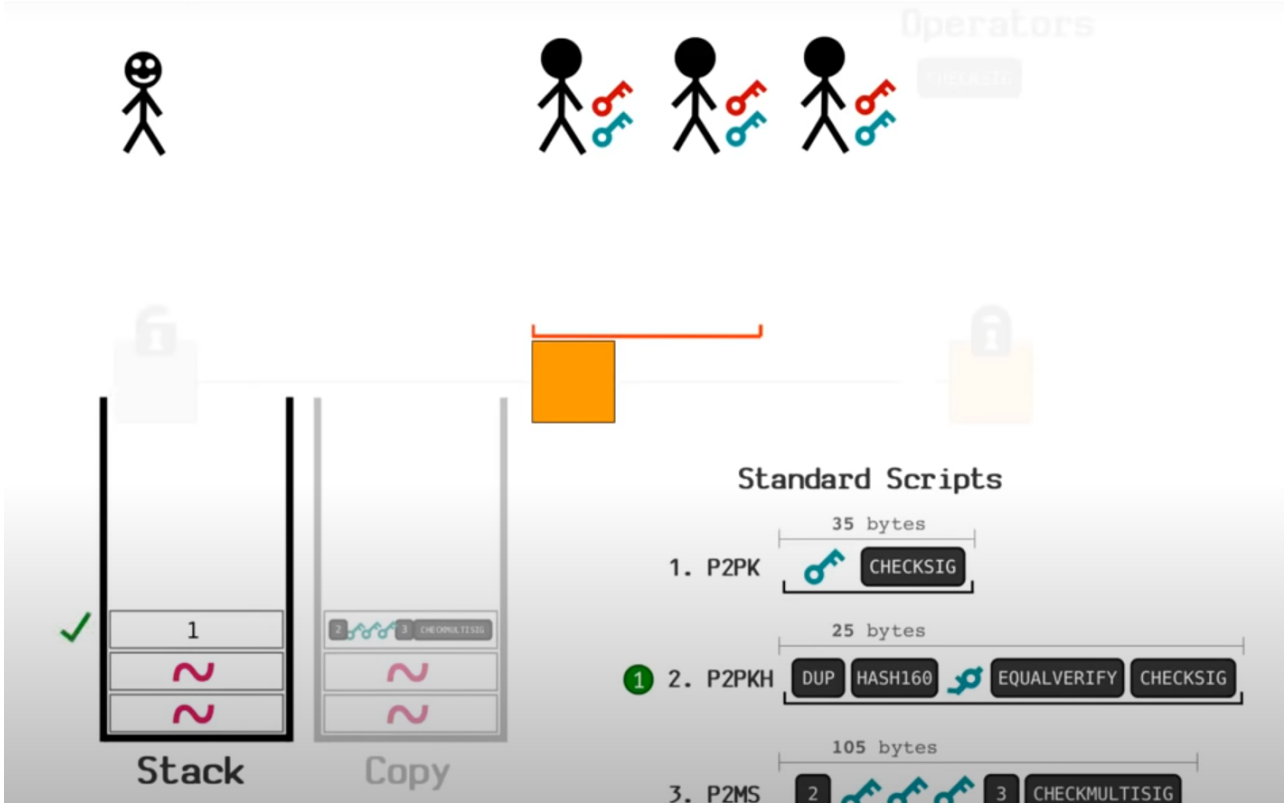

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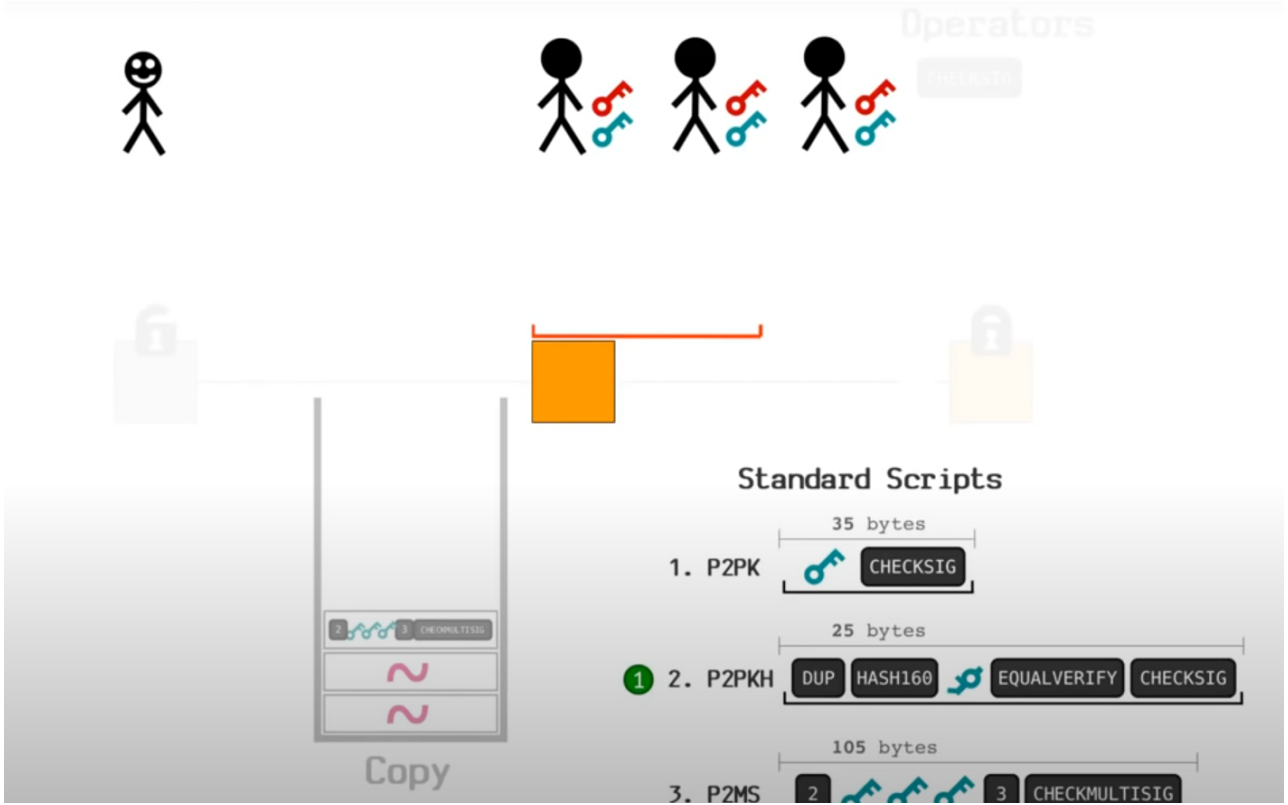

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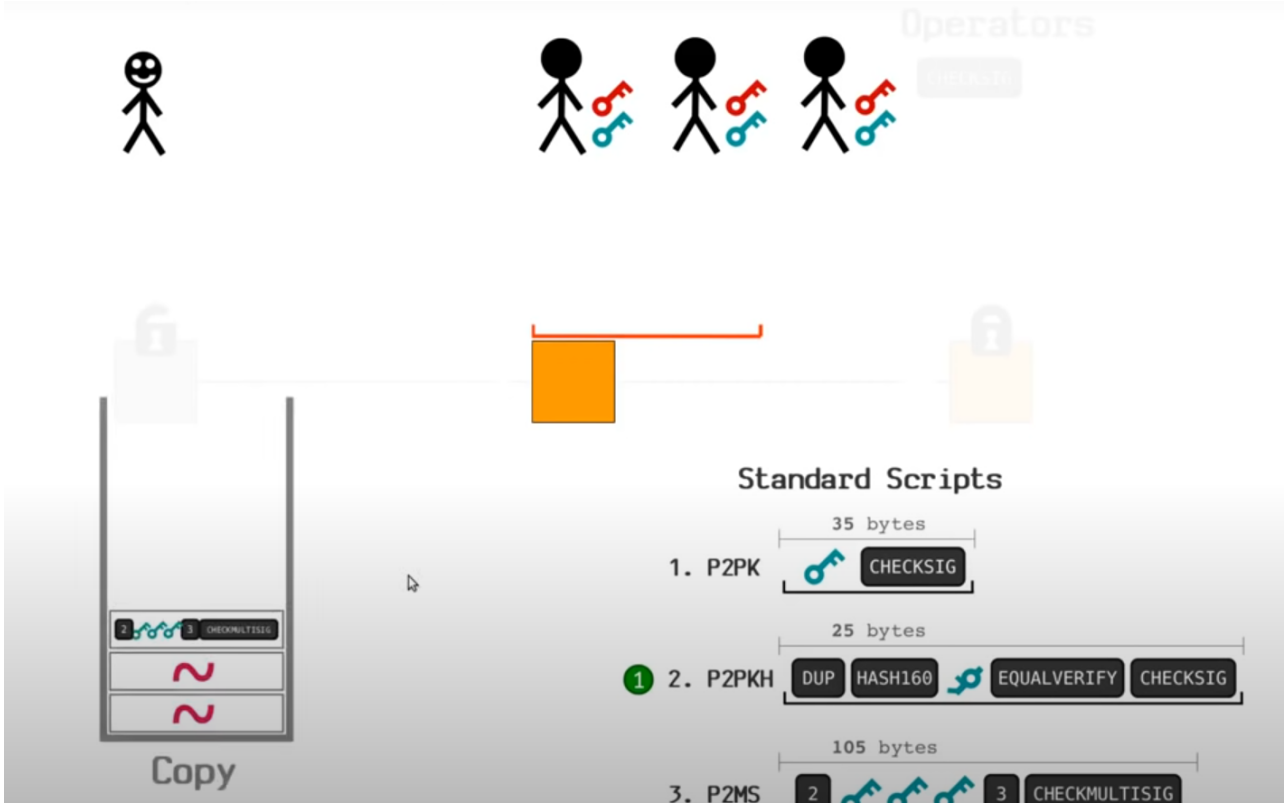

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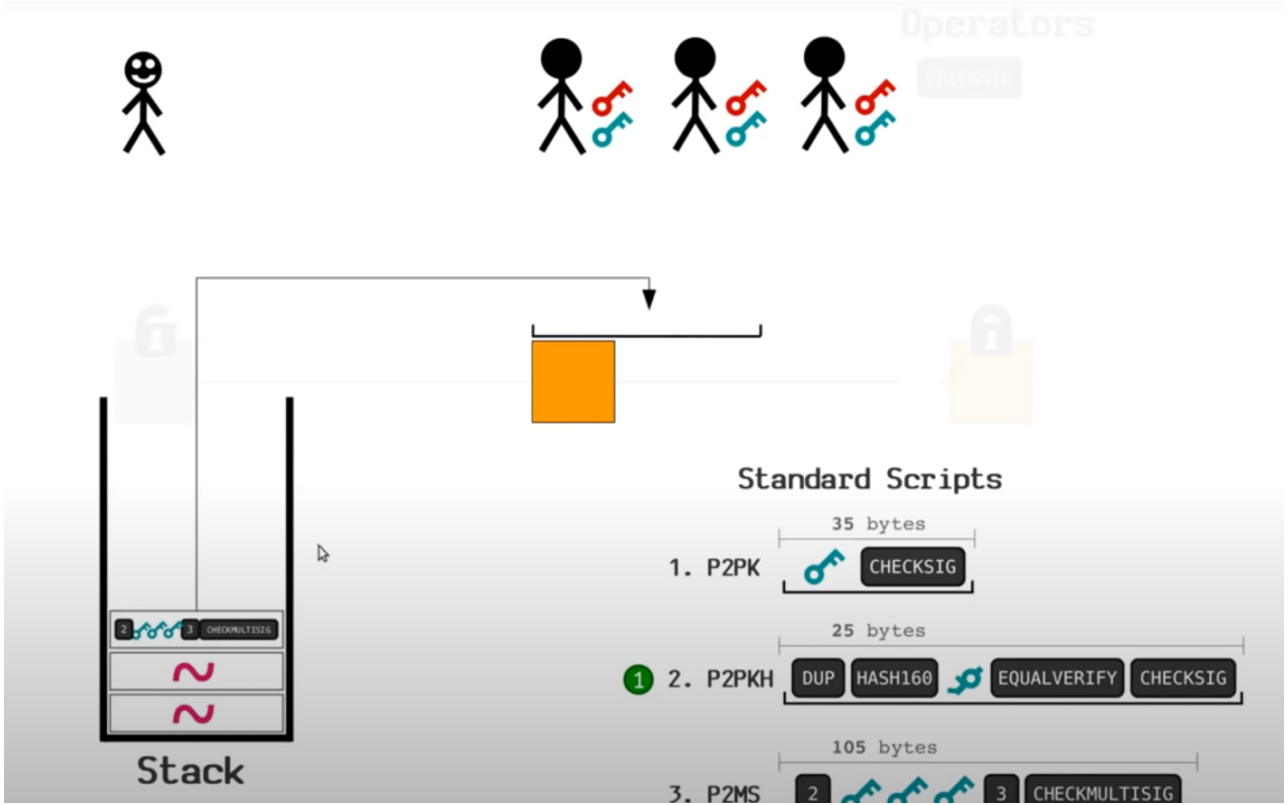

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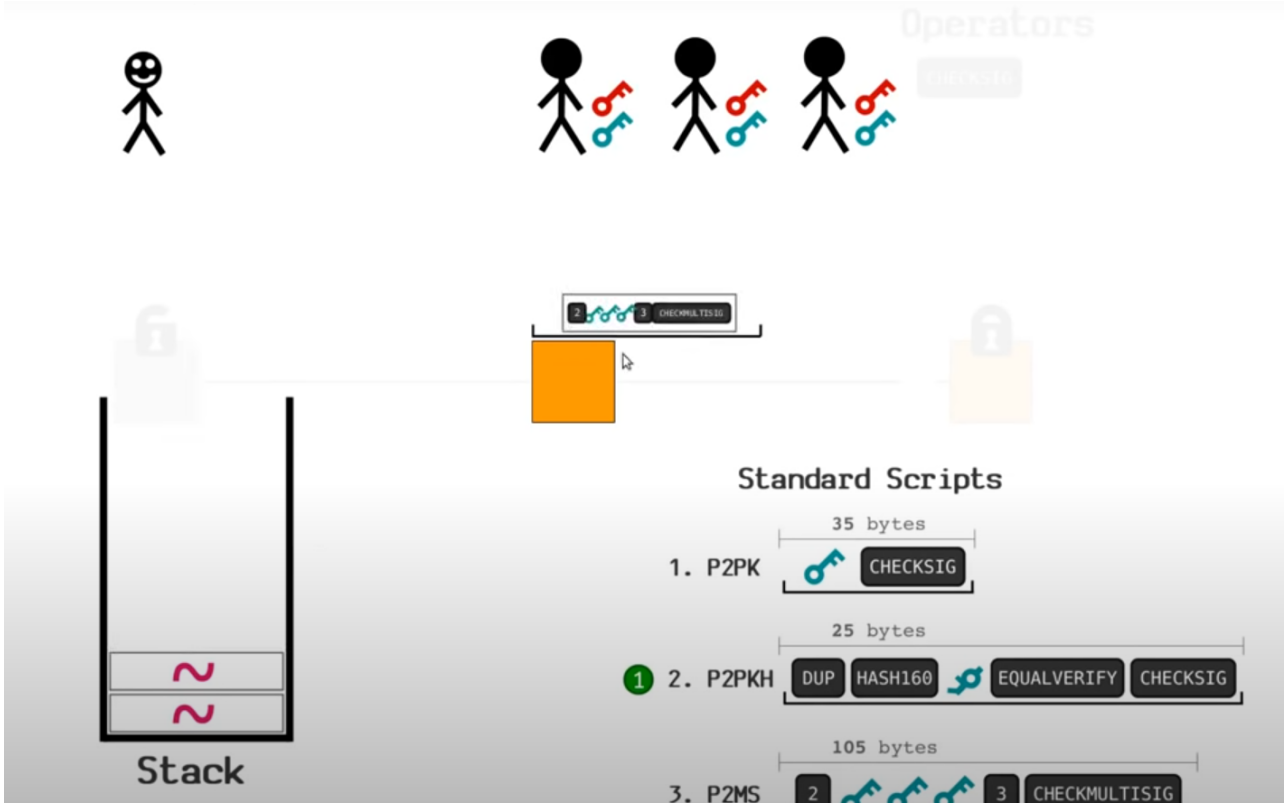

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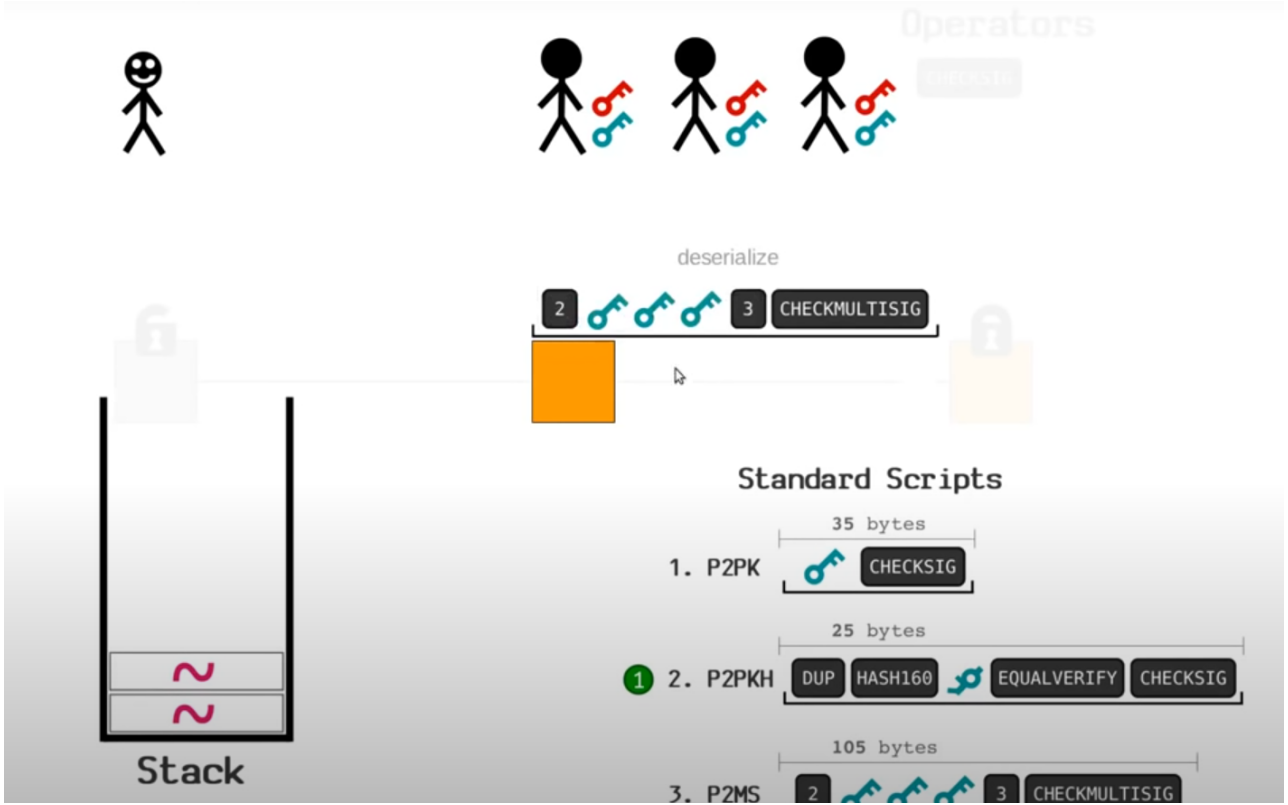

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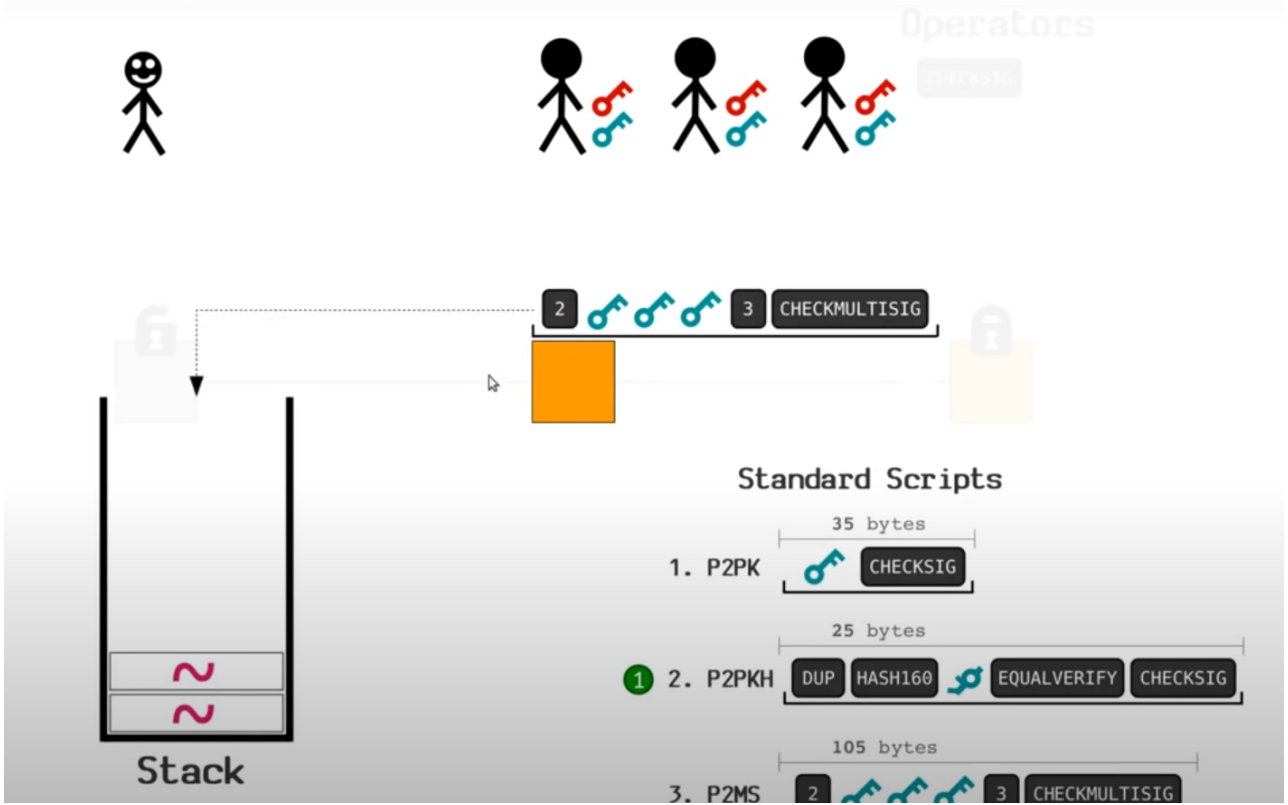

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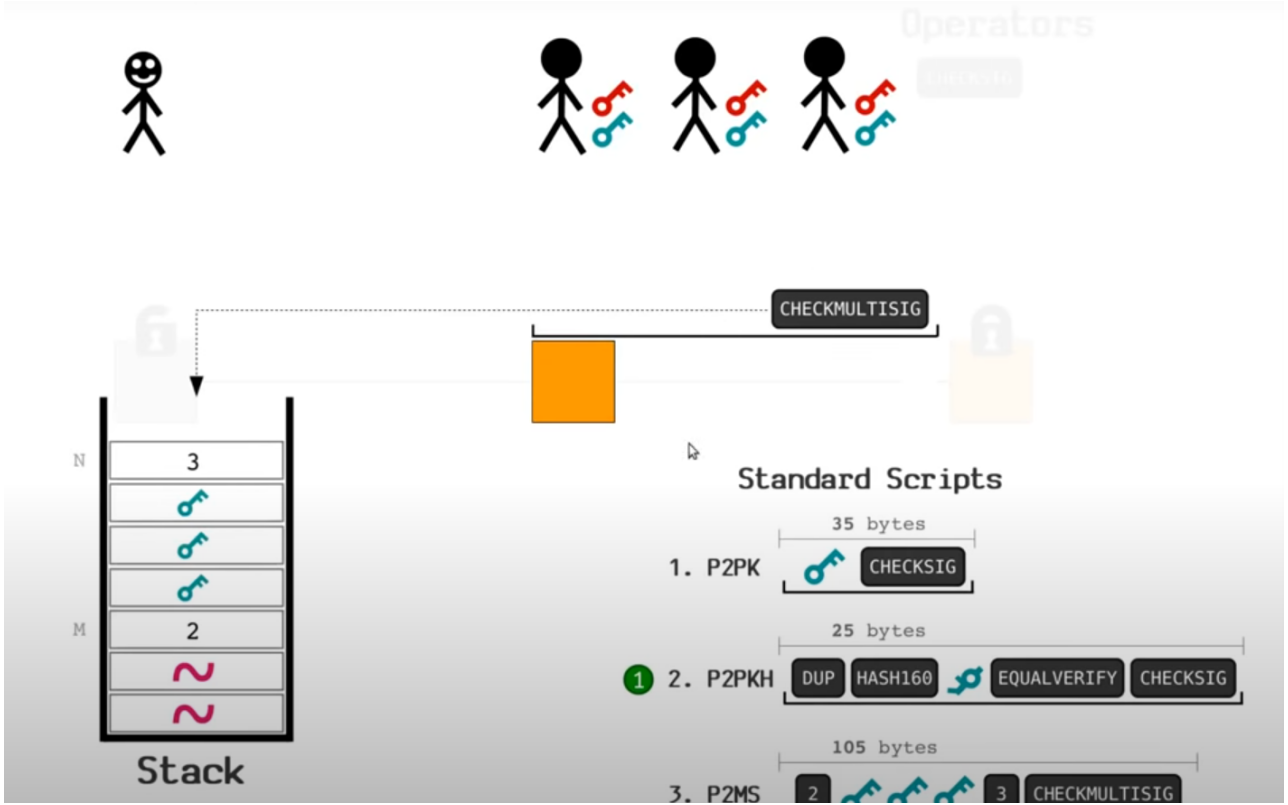
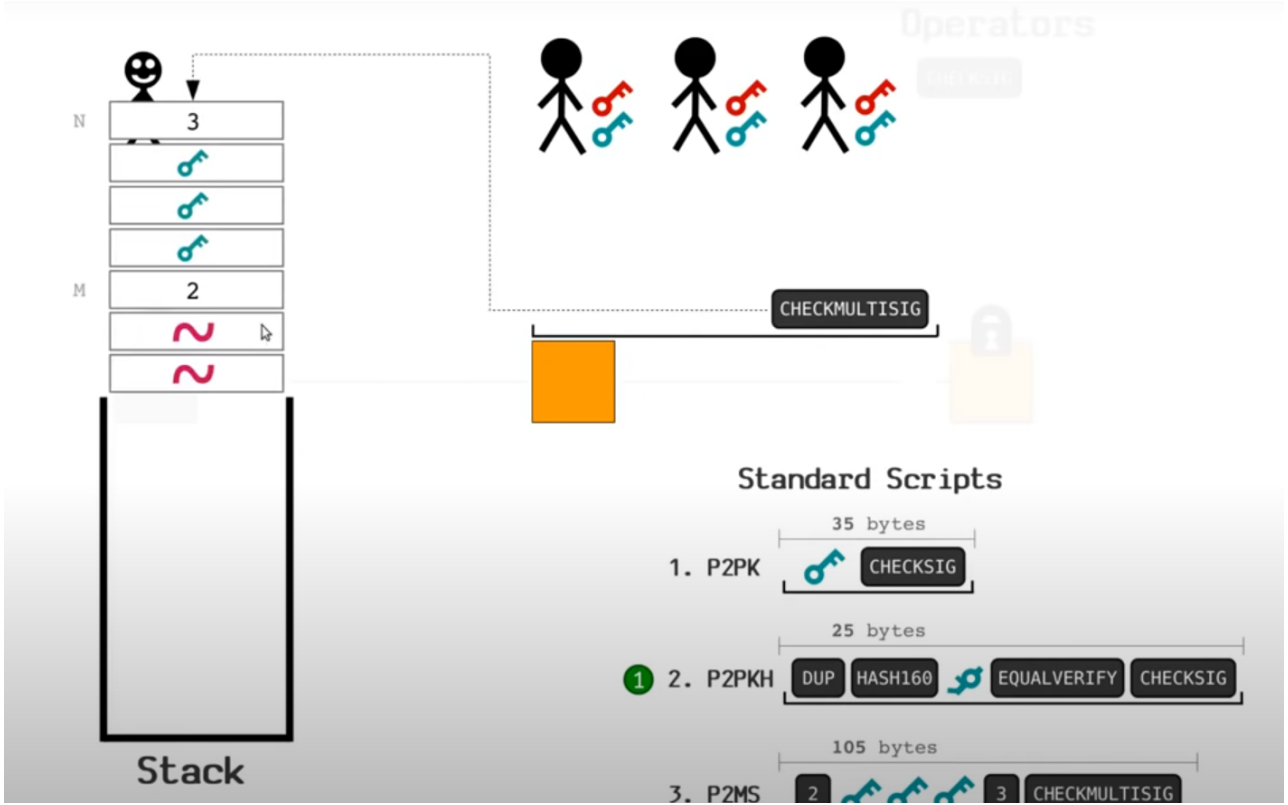


Pay to Script Hash (P2SH)



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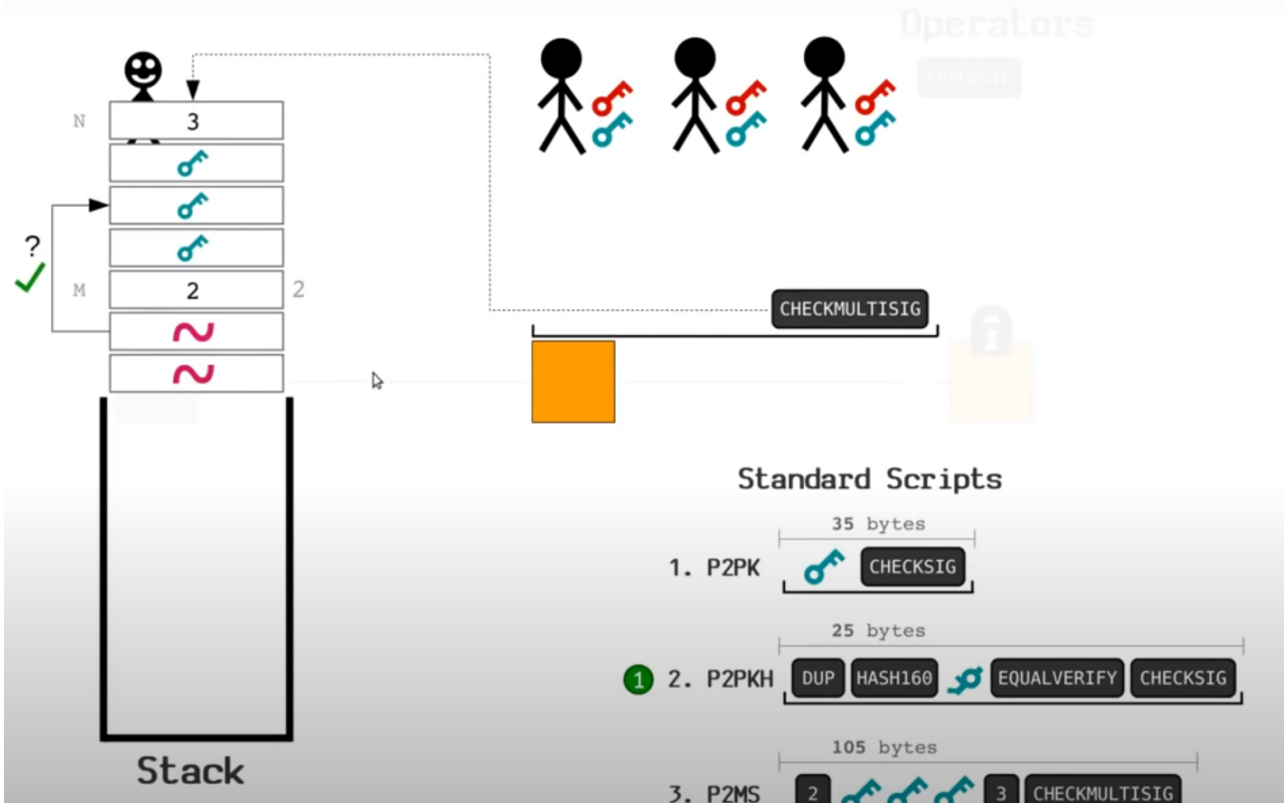

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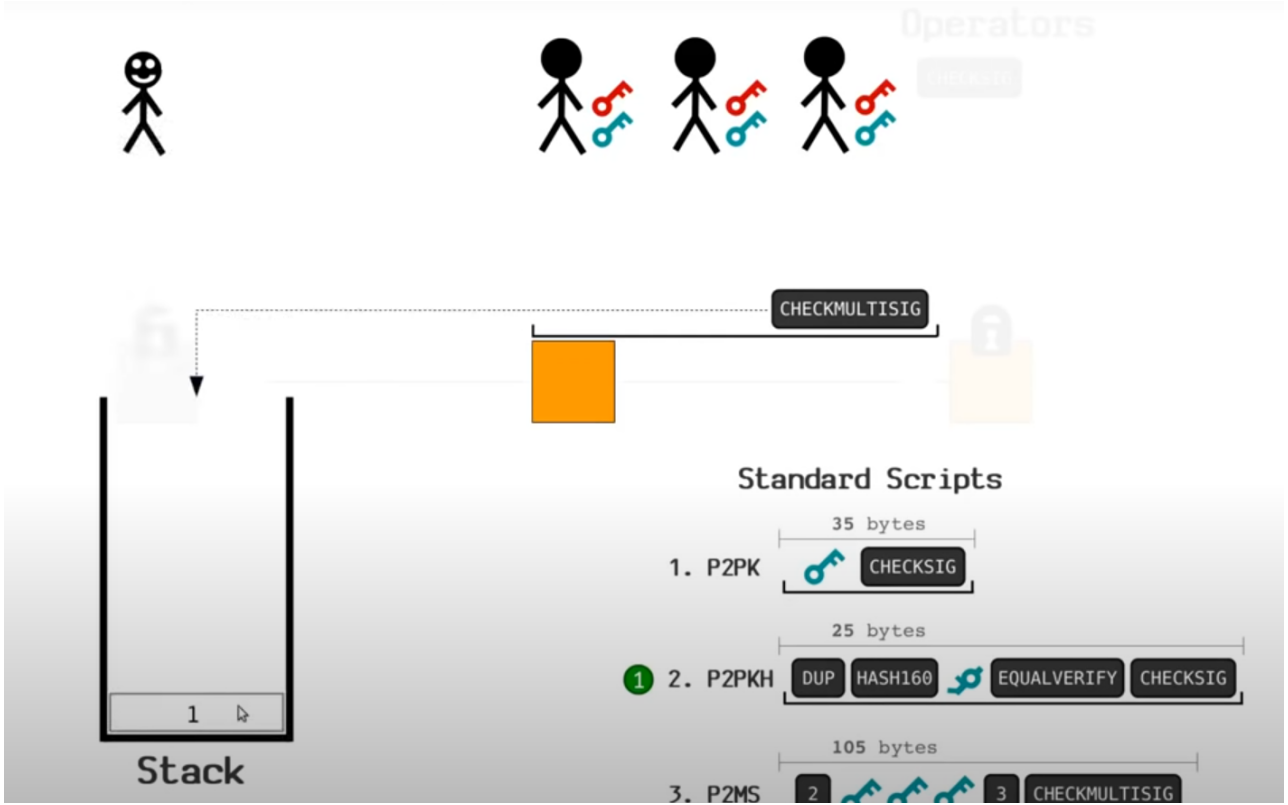
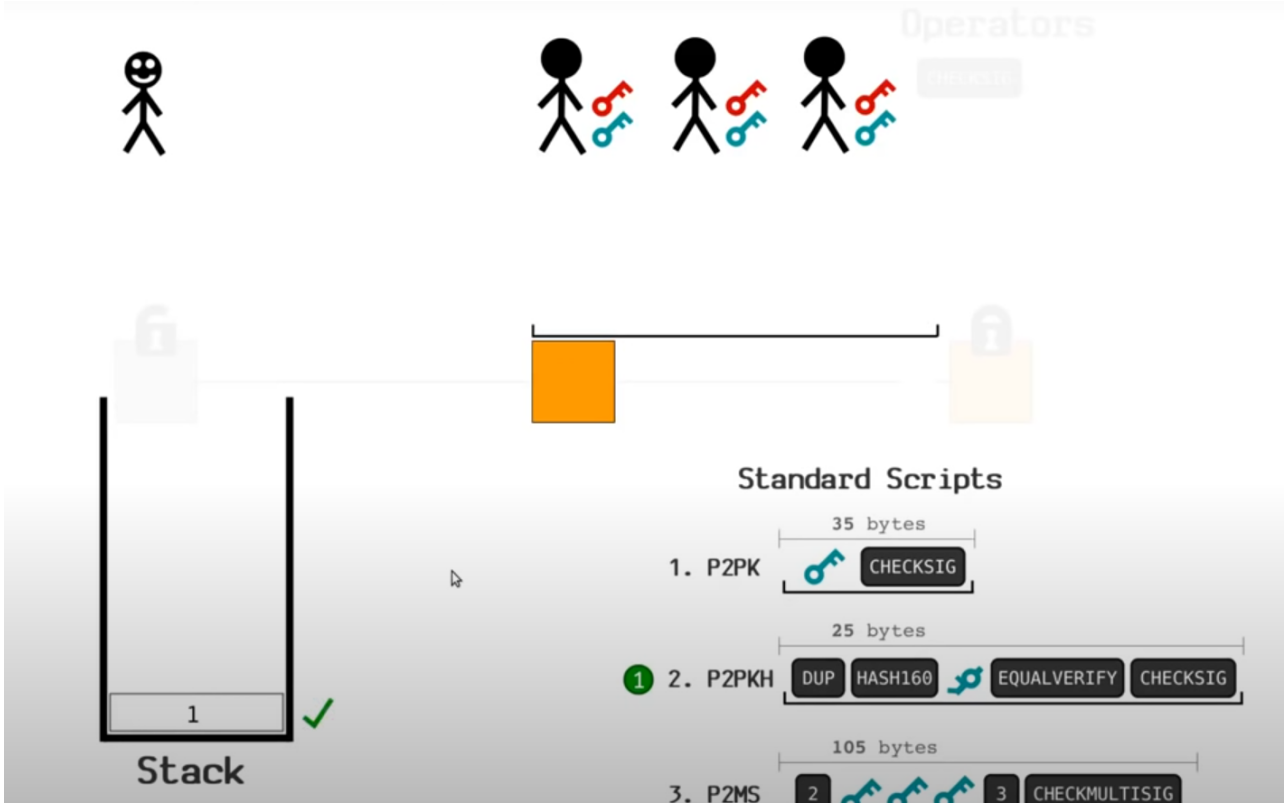
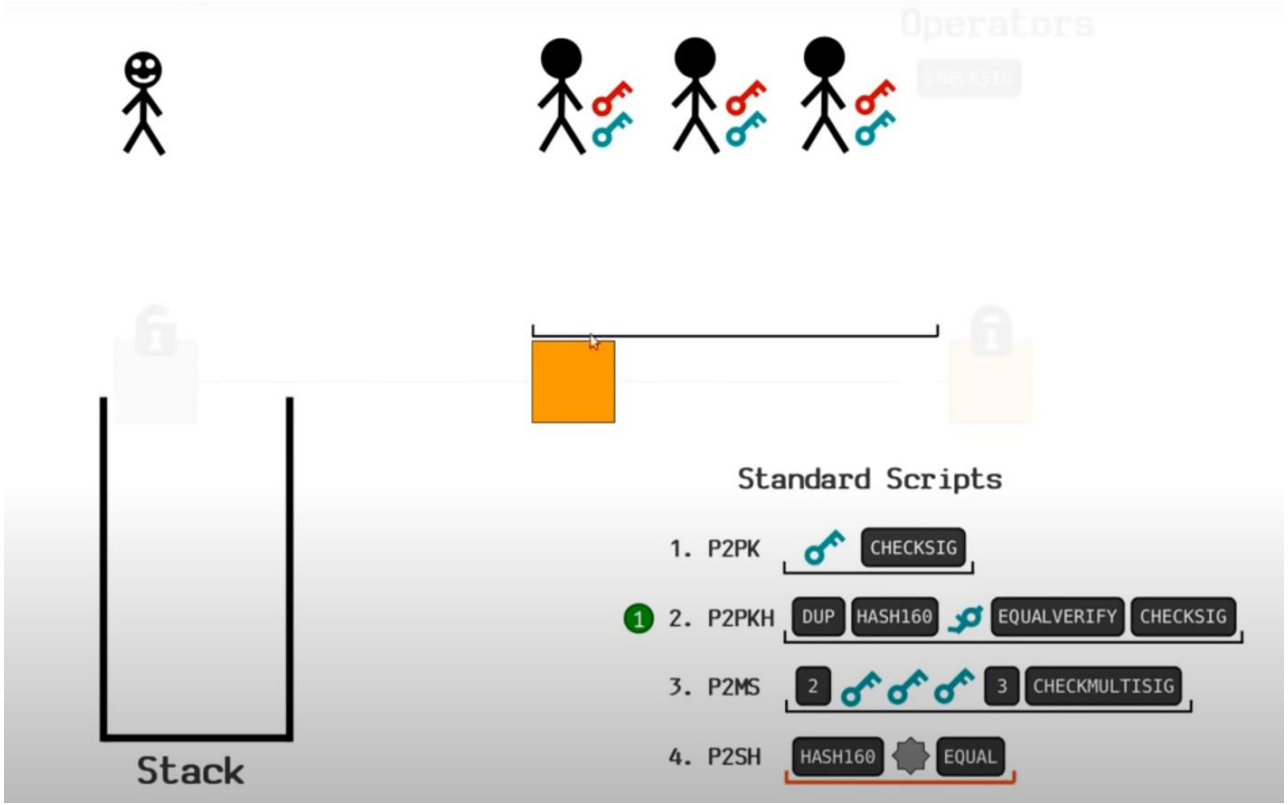


Pay to Script Hash (P2SH)



Pay to Script Hash (P2SH)



Example: a common script

<sig> <pk>	**DUP HASH256** <pkhash> **EQVERIFY CHECKSIG**

stack:	
empty	init
<sig> <pk>	push values
<sig> <pk> <pk>	**DUP**
<sig> <pk> <hash>	**HASH256**
<sig> <pk> <hash> <pkhash>	push value
<sig> <pk>	**EQVERIFY**
1	**CHECKSIG**

verify(pk, Tx, sig)

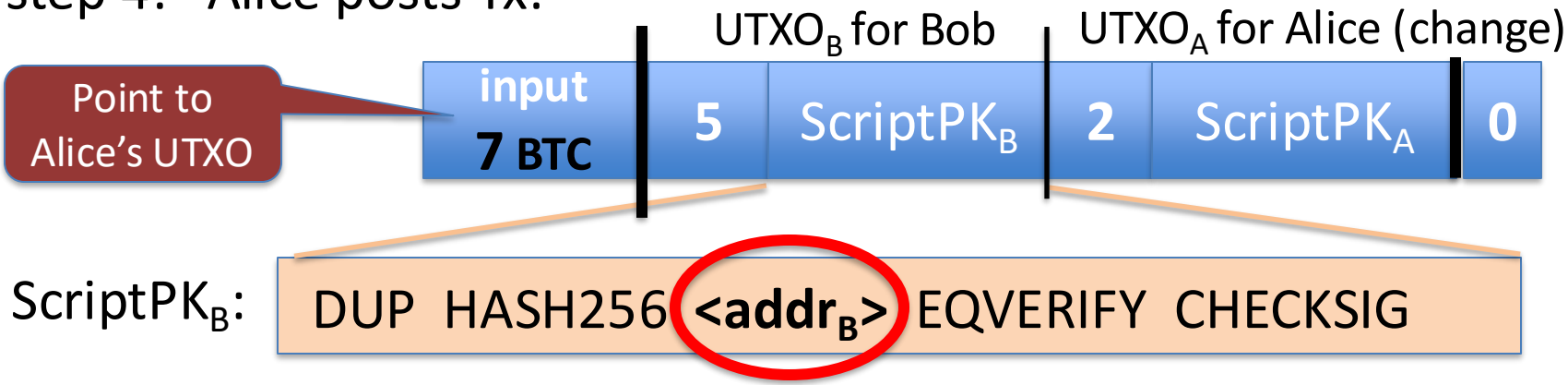
⇒ successful termination

Transaction types: (1) P2PKH

pay to public key hash

Alice want to pay Bob 5 BTC:

- step 1: Bob generates sig key pair $(pk_B, sk_B) \leftarrow Gen()$
- step 2: Bob computes his Bitcoin address as $addr_B \leftarrow H(pk_B)$
- step 3: Bob sends $addr_B$ to Alice
- step 4: Alice posts Tx:



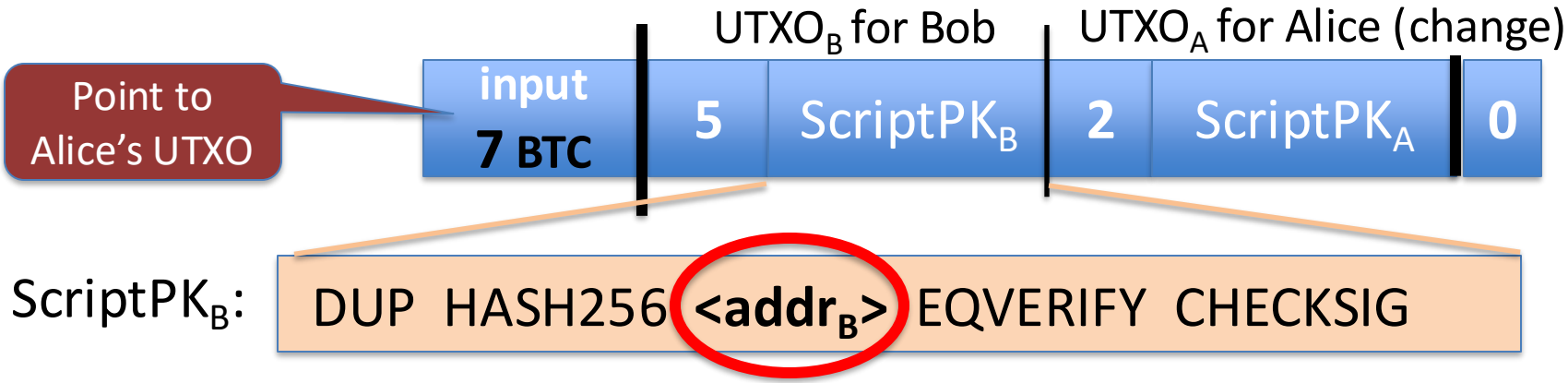
Transaction types: (1) P2PKH

pay to public key hash

"input" contains ScriptSig that authorizes spending Alice's UTXO

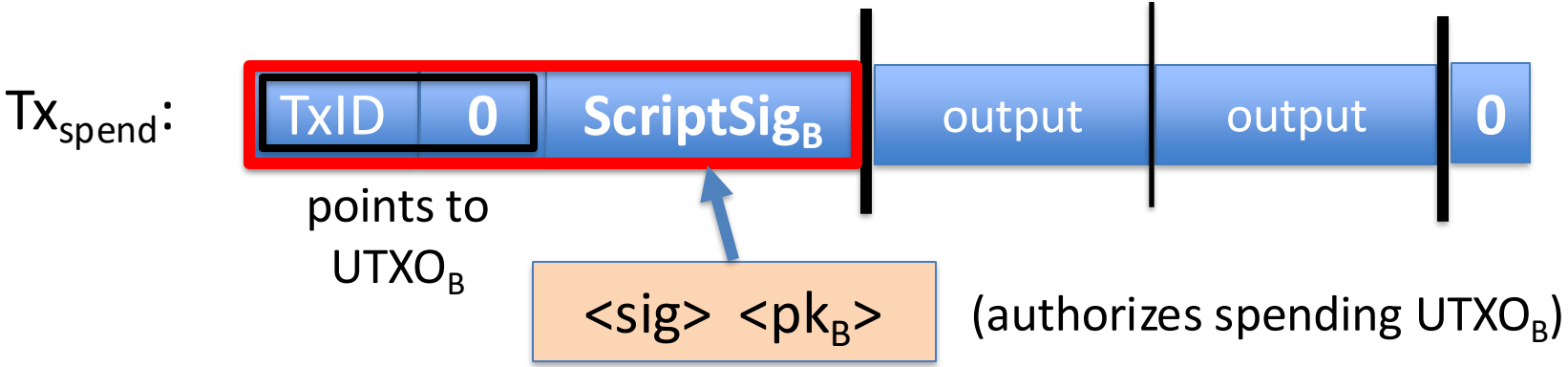
- example: ScriptSig contains Alice's signature on Tx

  $\Longrightarrow$ miners cannot change $ScriptPK_B$ (will invalidate Alice's signature)



Transaction types: (1) P2PKH

Later, when Bob wants to spend his UTXO: create a Tx_{spend}



<sig> = $Sign(sk_B, Tx)$ where $Tx = (Tx_{spend}$ excluding all ScriptSigs) (SIGHASH_ALL)

Miners validate that $ScriptSig_B$ | $ScriptPK_B$ returns true

P2PKH: comments

- Alice specifies recipient's pk in $UTXO_B$
- Recipient's pk is not revealed until UTXO is spent
  (some security against attacks on pk)
- Miner cannot change $<Addr_B>$ and steal funds:
  invalidates Alice's signature that created $UTXO_B$

Segregated Witness

ECDSA malleability:

Given (m, sig) anyone can create (m, sig') with sig ≠ sig'

⇒ miner can change sig in Tx and change TxID = SHA256(Tx)

⇒ Tx issuer cannot tell what TxID is, until Tx is posted

⇒ leads to problems and attacks

Segregated witness: signature is moved to witness field in Tx

TxID = Hash(Tx without witnesses)

Transaction types: (2) P2SH: pay to script hash

(pre SegWit in 2017)

Let's payer specify a redeem script (instead of just pkhash)

Usage: payee publishes hash(redeem script) ⟵ Bitcoint addr.
payer sends funds to that address

ScriptPK in UTXO: HASH160 <H(redeem script)> EQUAL

ScriptSig to spend: $<sig_1>$ $<sig_2>$ … $<sig_n>$ <redeem script>

payer can specify complex conditions for when UTXO can be spent

P2SH

Miner verifies:

(1) <ScriptSig> ScriptPK = true ⟵ payee gave correct script

(2) ScriptSig = true ⟵ script is satisfied

Example P2SH: multisig

Goal: spending a UTXO requires t-out-of-n signatures

Redeem script for 2-out-of-3: (set by payer)

<2> <PK_1> <PK_2> <PK_3> <3> CHECKMULTISIG

hash gives P2SH address

ScriptSig to spend: (by payee) <0> <sig1> <sig3> <redeem script>

Resources

- ECE/COS 470, Pramod Viswanath, Princeton 2024
- CS251, Dan Boneh, Stanford 2023
- Bitcoin Lesson – Transactions by learnmebitcoin