Bitcoin Script

ENTERING THE PROGRAMMABLE ECONOMY

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ABOUT STEPHANE

2015

Start working on Bitcoin in 2015 at Ledger (hardware wallet)

2016–2017

Work on Ethereum in 2016-2017

- Co-found non-profit organization Asseth
- R&D on Dao1901
- Contribute to the ERC20 Consensys smart contracts
- Dether.io (15,000 ETH raised)

2017–2018

Focus on Bitcoin technical trainings

Founder of Bitcoin Studio

Consultant at Chainsmiths

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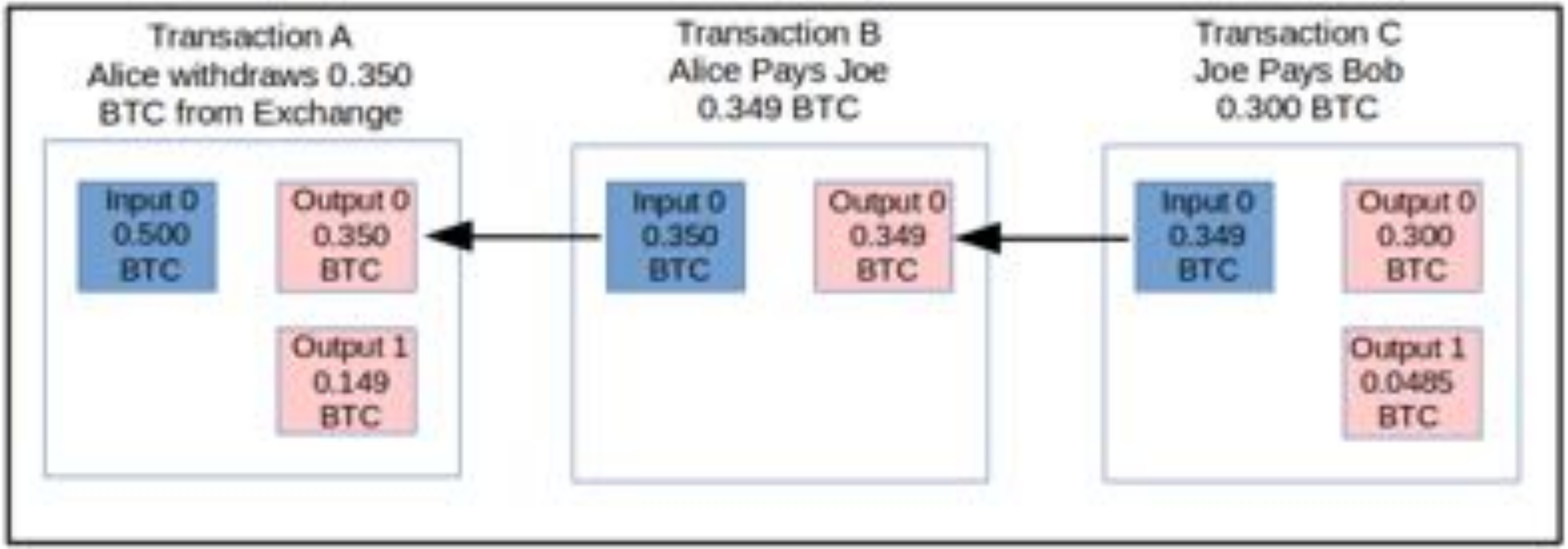
OUTLINE

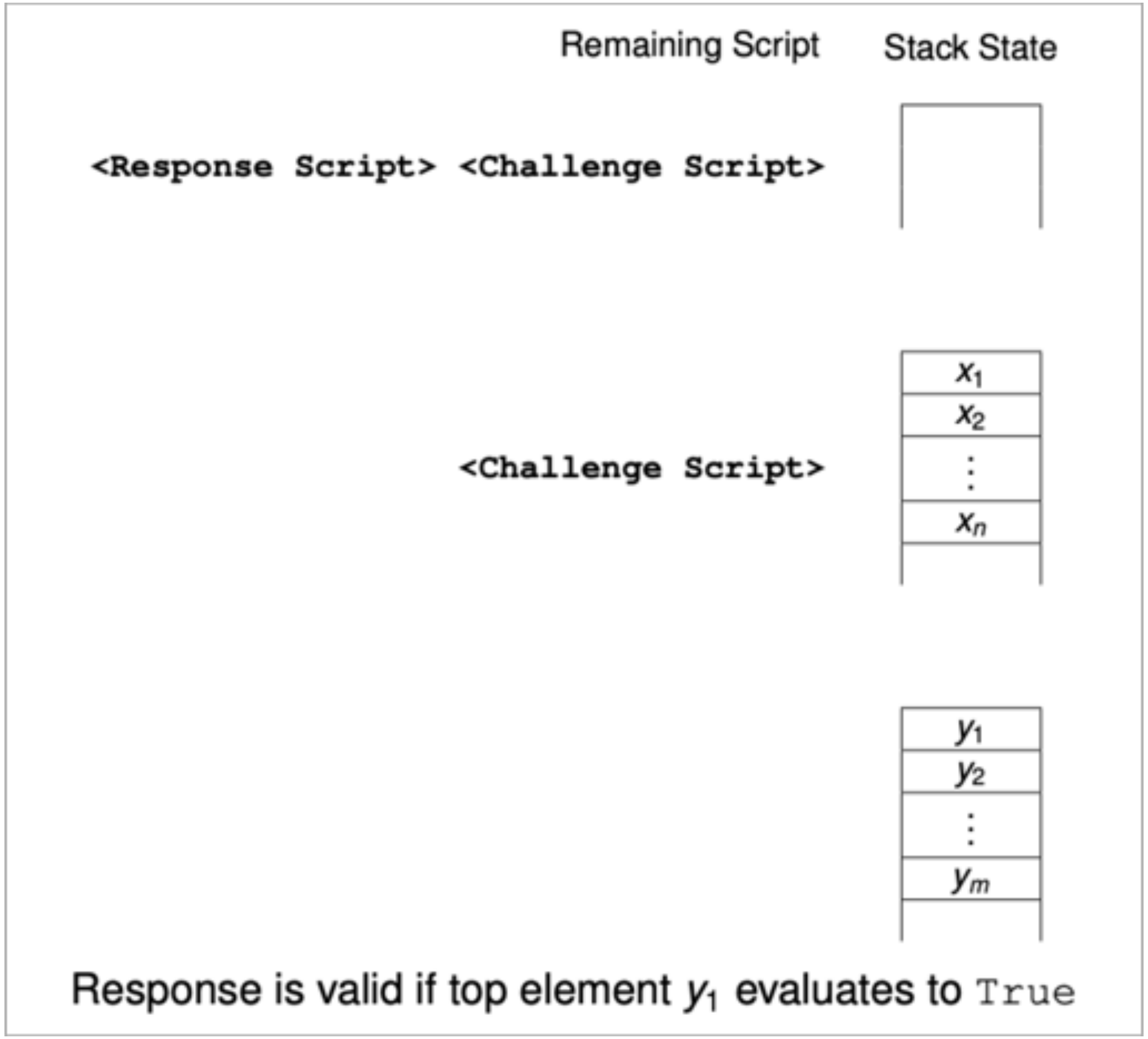
1. Transaction Basics and Standard Output Types
2. Script Validation Logics
3. Opcodes
4. Arbitrary Scripts Examples
5. Future Improvements

1 TRANSACTION BASICS AND STANDARD OUTPUT TYPES

INPUT-OUTPUT CHAIN



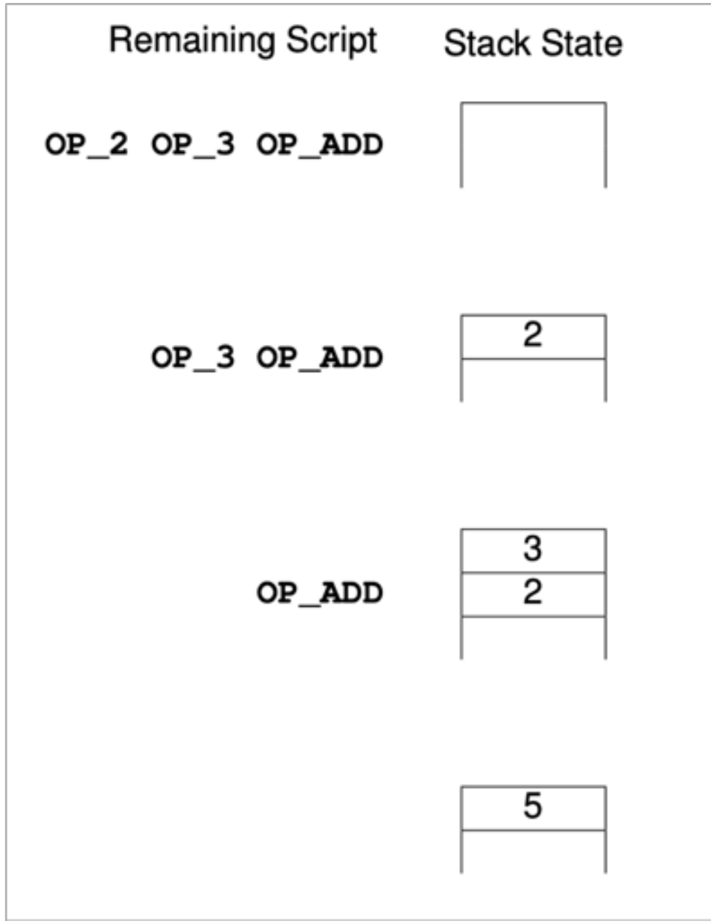
- Any Bitcoin transaction is technically a “smart contract”
- A Bitcoin smart contract is a predicate (returns true or false)
- Achieved through execution of challenge/response scripts
- Every bitcoin validating node executes the scripts
    - All the inputs are validated independently



Remaining Script
Stack State
<Response Script> <Challenge Script>
<Challenge Script>
x_1
x_2
x_n
y_1
y_2
y_m
Response is valid if top element y_1 evaluates to True

REVERSE POLISH NOTATION

- Operators follow their operands
- Commonly used in stack-oriented programming languages



POLICY RULES - STANDARD TX

- IsStandard() and IsStandardTx() tests
  - src/policy/policy.cpp
  - Check that tx is *standard*
  - Check various properties in inputs, outputs and other tx parts

- Only standard tx are mined and relayed by Bitcoin Core nodes

- Safety measures against DoS attacks

- Force good behavior without consensus enforcement
  - More flexible
  - Example: the tx version number

STANDARD OUTPUT TYPES

- TX_PUBKEY
- TX_PUBKEYHASH
- TX_SCRIPTHASH
- TX_MULTISIG (Bare multisig – BIP11)
- TX_NULL_DATA
- TX_WITNESS_V0_KEYHASH
- TX_WITNESS_V0_SCRIPTHASH
- TX_WITNESS_UNKNOWN
- TX_NONSTANDARD

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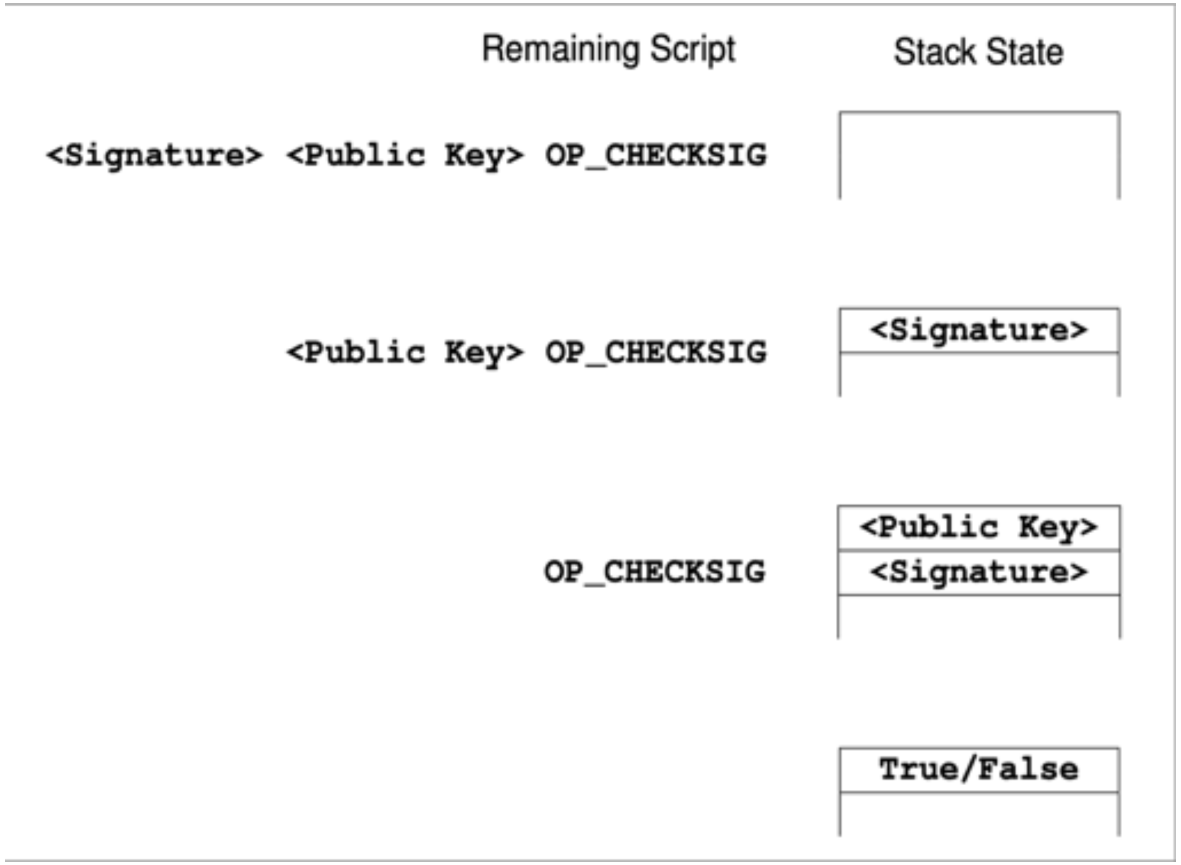
SCRIPT VALIDATION LOGICS

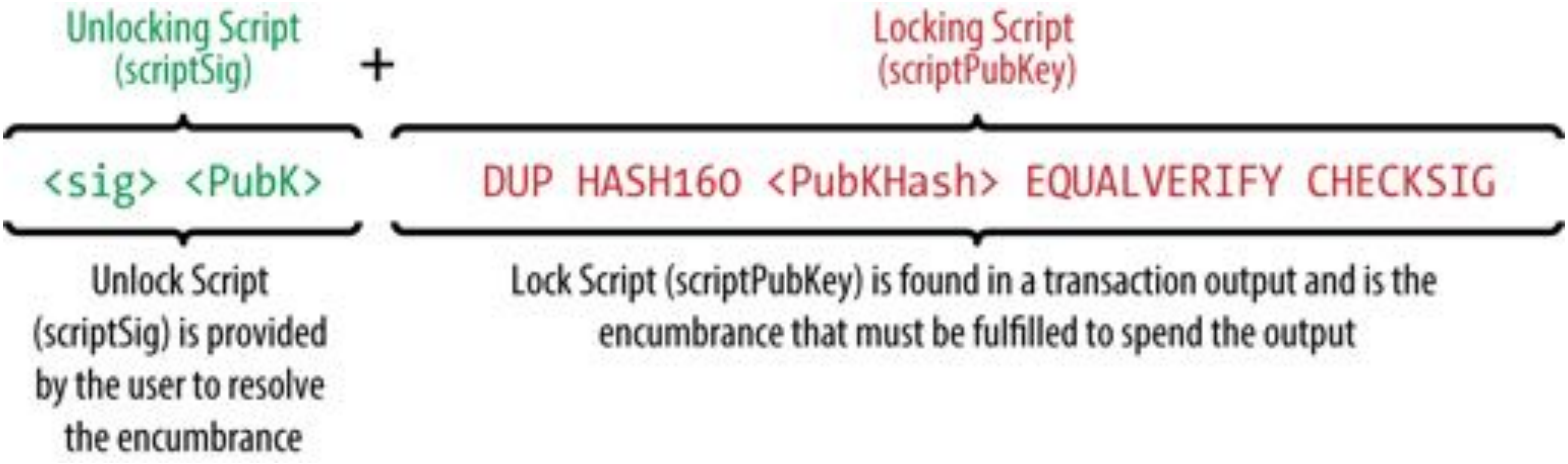
PAY TO PUBLIC KEY

- Challenge script: <Public Key> OP_CHECKSIG
- Response script: <Signature>

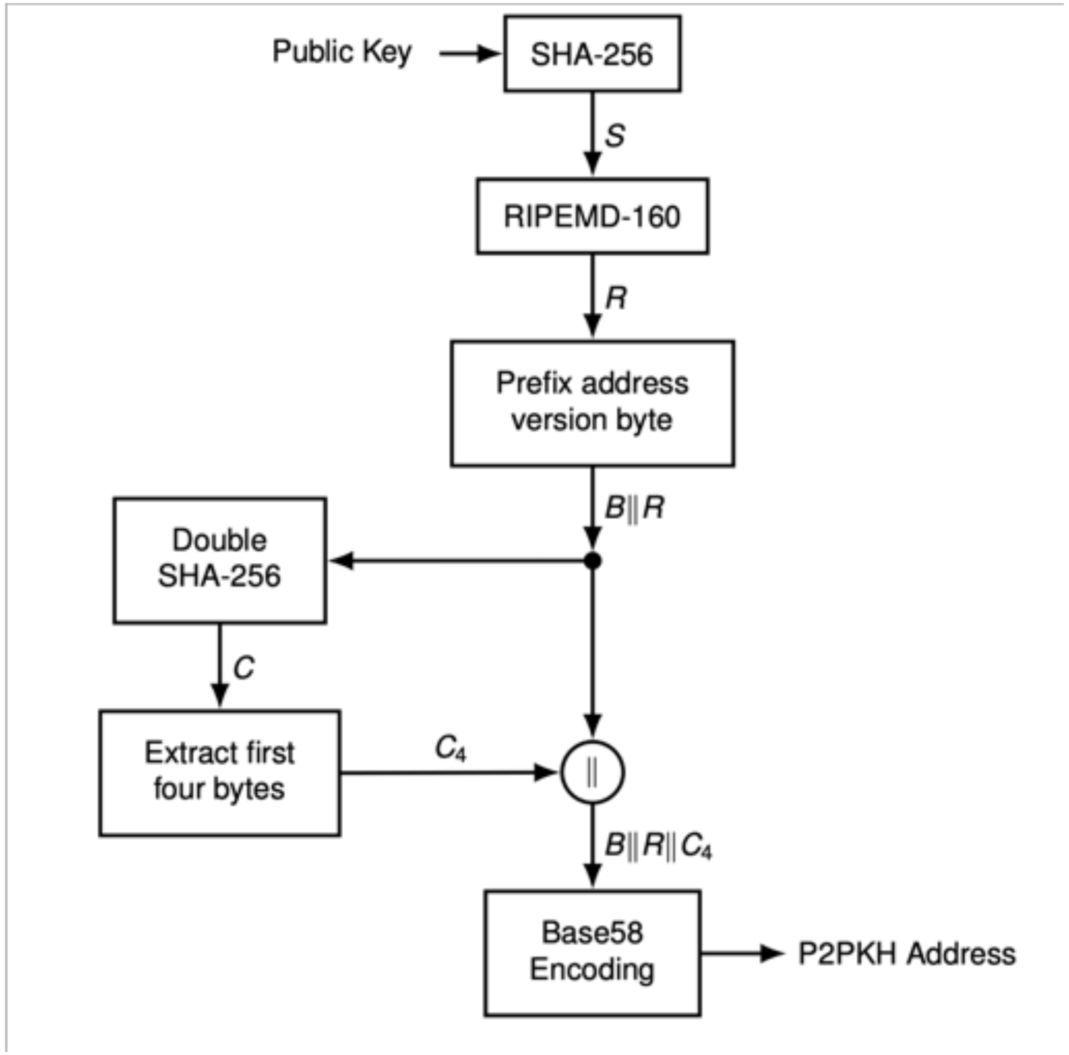


PAY TO PUBLIC KEY HASH

- P2PKH script has two required conditions
  - that the supplied public key match the public-key hash
  - that the supplied signature match that public key

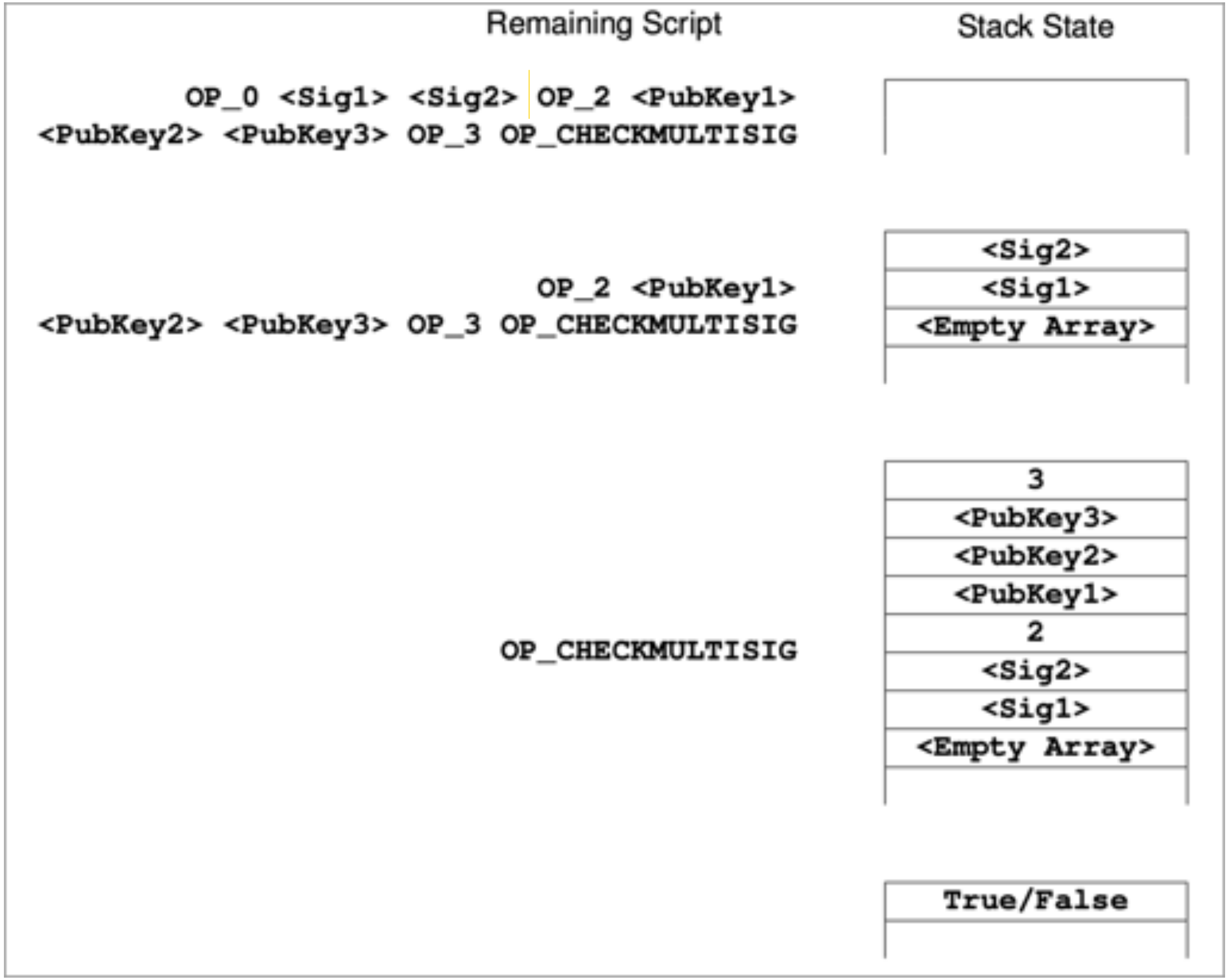


P2PKH ADDRESS



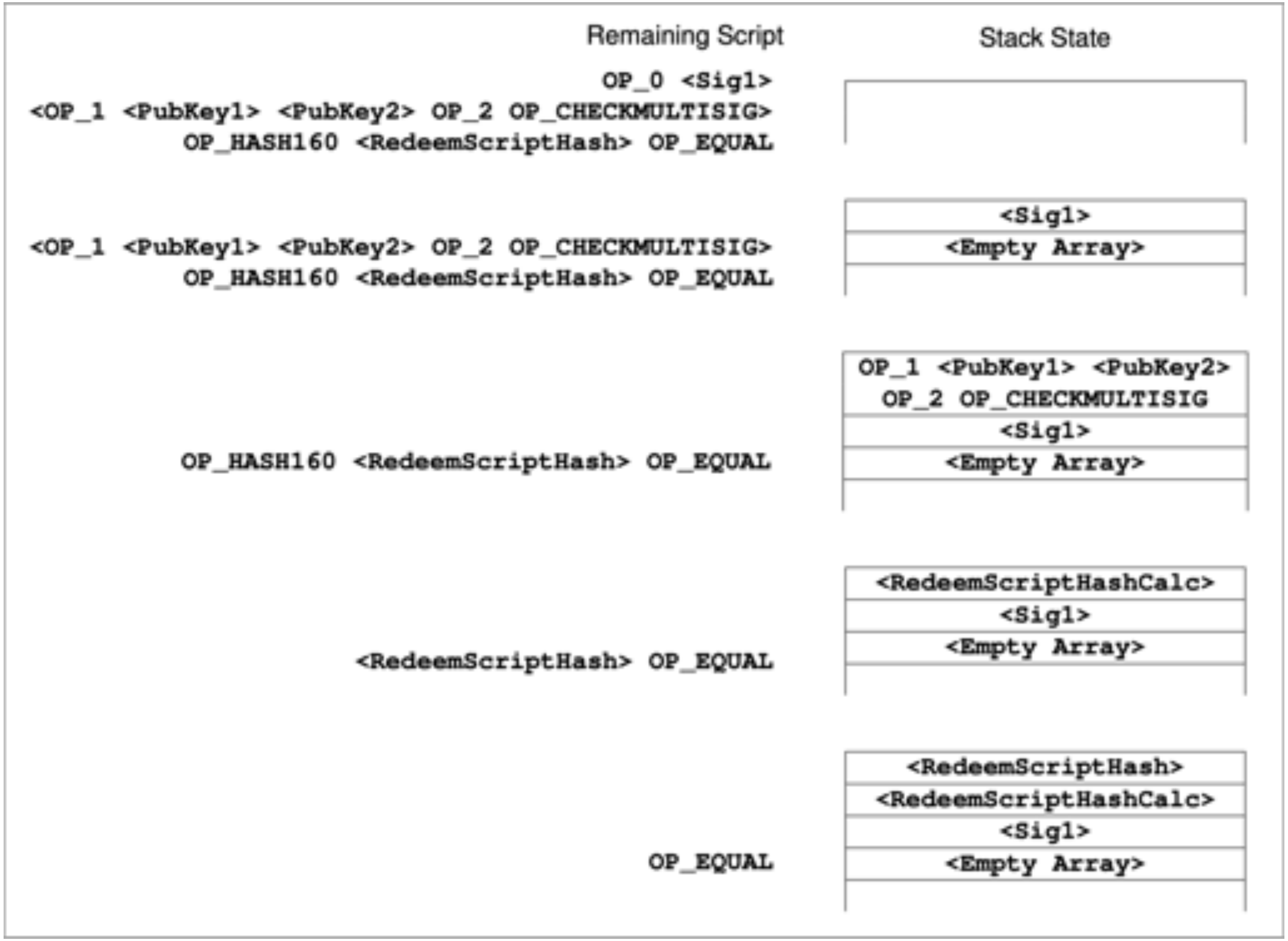
MULTI-SIGNATURE SCRIPTS

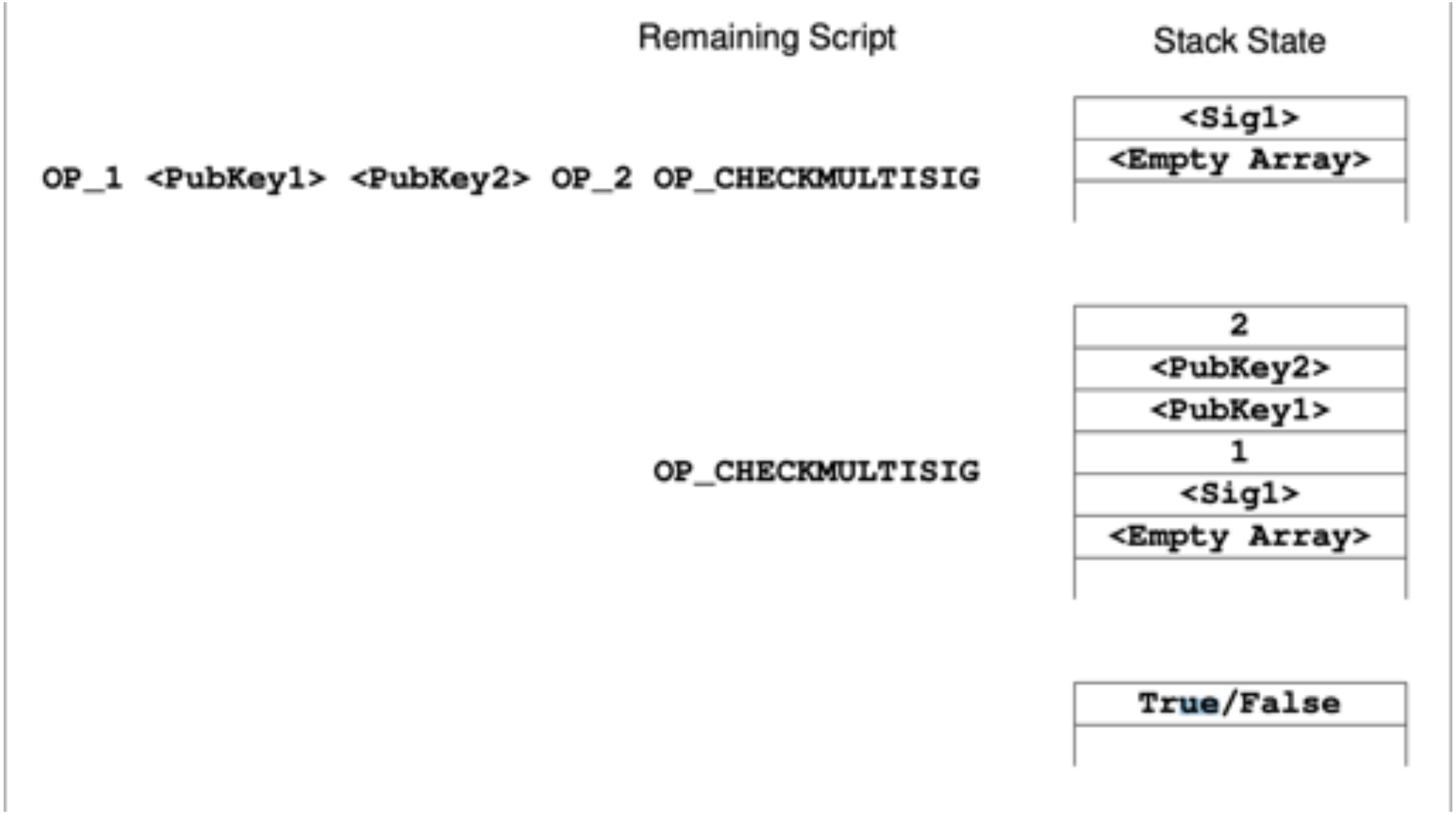
- m-of-n multisig challenge script
  - n public keys up to 3 (standard policy)
  - m <Public Key 1> · · · <Public Key n> n OP_CHECKMULTISIG
- Response script provides signatures created using any m out of the n private keys
  - OP_0 <Signature 1> · · · <Signature m>


Remaining Script
Stack State
OP_0 <Sig1> <Sig2> OP_2 <PubKey1>
<PubKey2> <PubKey3> OP_3 OP_CHECKMULTISIG
<Sig2>
<Sig1>
<Empty Array>
OP_2 <PubKey1>
<PubKey2> <PubKey3> OP_3 OP_CHECKMULTISIG
3
<PubKey3>
<PubKey2>
<PubKey1>
2
<Sig2>
<Sig1>
<Empty Array>
OP_CHECKMULTISIG
True/False

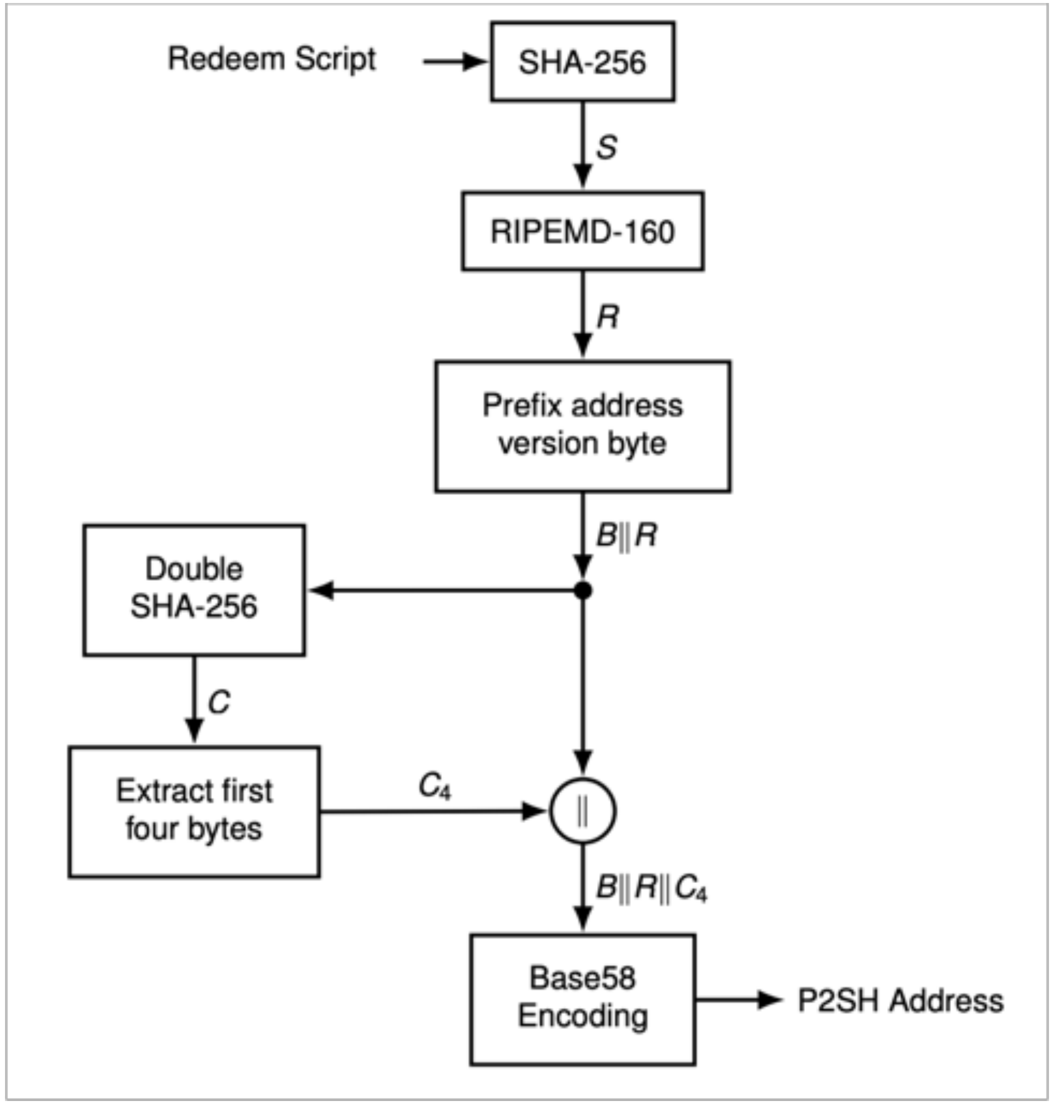
PAY TO SCRIPT HASH

- Allows specification of arbitrary scripts as payment destinations
- Specific two steps validation logic
- Challenge script
  - OP_HASH160 <RedeemScriptHash> OP_EQUAL
- Response script
  - <Response To Redeem Script> <Redeem Script>
- Cannot be used recursively inside the redeemScript itself
  - P2SH inside P2WSH or P2SH is invalid
  - P2WSH inside P2WSH is invalid


Remaining Script
Stack State
OP_0 <Sig1>
<OP_1 <PubKey1> <PubKey2> OP_2 OP_CHECKMULTISIG>
OP_HASH160 <RedeemScriptHash> OP_EQUAL
<Sig1>
<Empty Array>
<OP_1 <PubKey1> <PubKey2> OP_2 OP_CHECKMULTISIG>
OP_HASH160 <RedeemScriptHash> OP_EQUAL
OP_1 <PubKey1> <PubKey2>
OP_2 OP_CHECKMULTISIG
<Sig1>
<Empty Array>
OP_HASH160 <RedeemScriptHash> OP_EQUAL
<RedeemScriptHashCalc>
<Sig1>
<Empty Array>
<RedeemScriptHash> OP_EQUAL
<RedeemScriptHash>
<RedeemScriptHashCalc>
<Sig1>
<Empty Array>
OP_EQUAL


Remaining Script
Stack State
OP_1 <PubKey1> <PubKey2> OP_2 OP_CHECKMULTISIG
<Sig1>
<Empty Array>
OP_CHECKMULTISIG
2
<PubKey2>
<PubKey1>
1
<Sig1>
<Empty Array>
True/False

P2SH ADDRESS



NULLDATA SCRIPTS

- Challenge script: OP_RETURN <Data>
  - OP_RETURN terminates script execution immediately
- No valid response script exists
  - Null data outputs are unspendable
  - Any bitcoins locked by a null data challenge script are lost forever
- Policy rules
  - Maximum scriptPubkey length for the tx to be relayed is 83 bytes
    - 80 bytes of data, +1 for OP_RETURN, +2 for the pushdata opcodes
  - Only one nulldata output per tx that pays exactly 0 satoshis
- Consensus rules
  - Allow nulldata outputs up to the maximum allowed scriptPubkey size of 10,000 bytes
- Used for asset creation, document notary, digital arts and others

WITNESS VALIDATION LOGIC

- Versioned witness program triggers witness validation logic
  - <version byte> <witness program>
- Located in scriptPubkey in native witness programs
- Located in scriptSig, as a unique stack item, in P2SH witness programs

NATIVE V.0 WITNESS PROGRAMS

- scriptSig is empty
- scriptPubKey is a versioned witness program
  - Version byte 0 + witness program
- Witness
  - <signature> <pubkey> (P2WPKH)
  - data + witnessScript (P2WSH)

- P2WPKH program
  - 20-byte witness program must match pubKey’s HASH160
  - pubKey’s HASH160 and CHECKSIG are done automatically

- P2WSH program
  - 32-byte witness program must match witnessScript’s SHA256
  - witnessScript’s SHA256 and comparison is done automatically
  - The redeem script moved to witness and called witnessScript

NATIVE P2WPKH LOCKING SCRIPT

P2PKH

```
OP_DUP OP_HASH160 0067c8970e65107ffbb436a49edd8cb8eb6b567f OP_EQUALVERIFY OP_CHECKSIG
```

P2WPKH

```
0 0067c8970e65107ffbb436a49edd8cb8eb6b567f
```

Witness version
/ Version byte

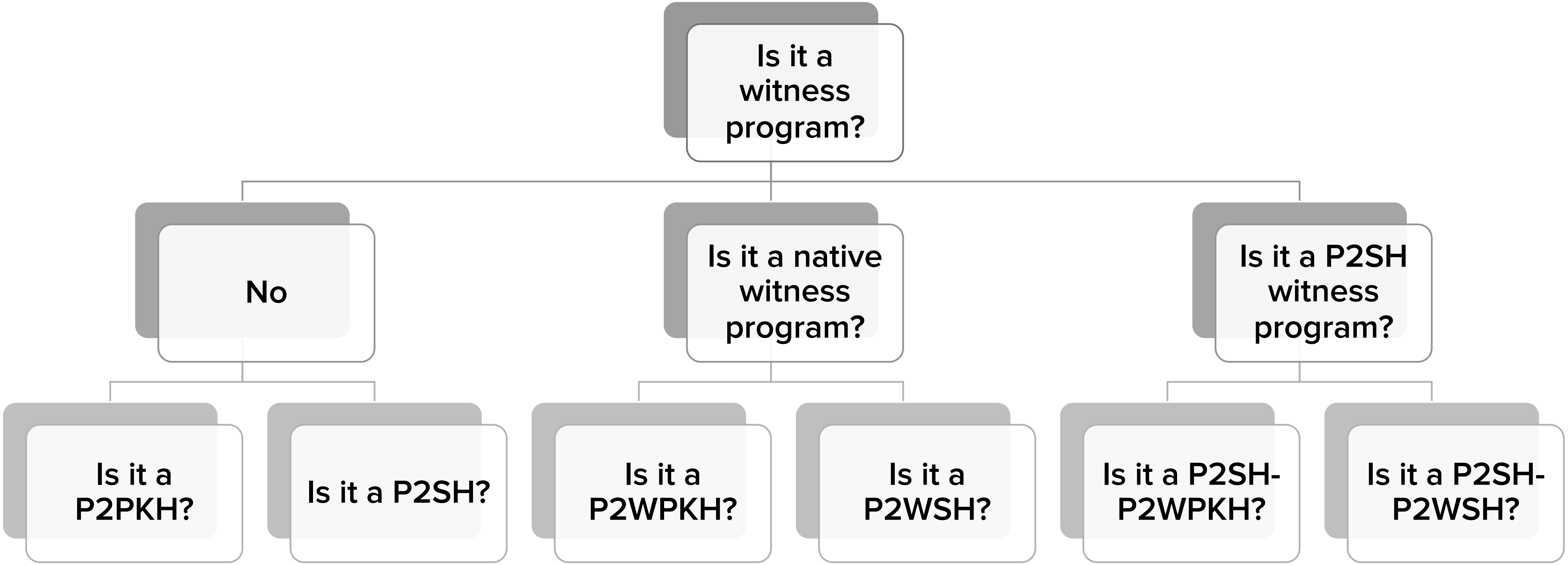
20-bytes witness program

P2SH V.0 WITNESS PROGRAMS

- scriptPubkey is a standard P2SH script
- scriptSig is a versioned witness program
  - VWP pushed onto the stack as a single stack item
  - HASH160
  - Hash comparison
- Witness
  - <signature> <pubkey> (P2SH-P2WPKH)
  - data + witnessScript (P2SH-P2WSH)

- P2SH-P2WPKH
  - 20-byte witness program must match pubKey’s HASH160

- P2SH-P2WSH
  - 32-byte witness program must match witnessScript’s SHA256


Is it a witness program?
No
Is it a native witness program?
Is it a P2SH witness program?
Is it a P2PKH?
Is it a P2SH?
Is it a P2WPKH?
Is it a P2WSH?
Is it a P2SH-P2WPKH?
Is it a P2SH-P2WSH?

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OPCODES

```
// push value
OP_0 = 0x00,
OP_FALSE = OP_0,
OP_PUSHDATA1 = 0x4c,
OP_PUSHDATA2 = 0x4d,
OP_PUSHDATA4 = 0x4e,
OP_1NEGATE = 0x4f,
OP_RESERVED = 0x50,
OP_1 = 0x51,
OP_TRUE=OP_1,
OP_2 = 0x52,
OP_3 = 0x53,
OP_4 = 0x54,
OP_5 = 0x55,
OP_6 = 0x56,
OP_7 = 0x57,
OP_8 = 0x58,
OP_9 = 0x59,
OP_10 = 0x5a,
OP_11 = 0x5b,
OP_12 = 0x5c,
OP_13 = 0x5d,
OP_14 = 0x5e,
OP_15 = 0x5f,
OP_16 = 0x60,

// control
OP_NOP = 0x61,
OP_VER = 0x62,
OP_IF = 0x63,
OP_NOTIF = 0x64,
OP_VERIF = 0x65,
OP_VERNOTIF = 0x66,
OP_ELSE = 0x67,
OP_ENDIF = 0x68,
OP_VERIFY = 0x69,
OP_RETURN = 0x6a,

// stack ops
OP_TOALTSTACK = 0x6b,
OP_FROMALTSTACK = 0x6c,
OP_2DROP = 0x6d,
OP_2DUP = 0x6e,
OP_3DUP = 0x6f,
OP_2OVER = 0x70,
OP_2ROT = 0x71,
OP_2SWAP = 0x72,
OP_IFDUP = 0x73,
OP_DEPTH = 0x74,
OP_DROP = 0x75,
OP_DUP = 0x76,
OP_NIP = 0x77,
OP_OVER = 0x78,
OP_PICK = 0x79,
OP_ROLL = 0x7a,
OP_ROT = 0x7b,
OP_SWAP = 0x7c,
OP_TUCK = 0x7d,

// splice ops
OP_CAT = 0x7e,
OP_SUBSTR = 0x7f,
OP_LEFT = 0x80,
OP_RIGHT = 0x81,
OP_SIZE = 0x82,

// bit logic
OP_INVERT = 0x83,
OP_AND = 0x84,
OP_OR = 0x85,
OP_XOR = 0x86,
OP_EQUAL = 0x87,
OP_EQUALVERIFY = 0x88,
OP_RESERVED1 = 0x89,
OP_RESERVED2 = 0x8a,

// numeric
OP_1ADD = 0x8b,
OP_1SUB = 0x8c,
OP_2MUL = 0x8d,
OP_2DIV = 0x8e,
OP_NEGATE = 0x8f,
OP_ABS = 0x90,
OP_NOT = 0x91,
OP_0NOTEQUAL = 0x92,

OP_ADD = 0x93,
OP_SUB = 0x94,
OP_MUL = 0x95,
OP_DIV = 0x96,
OP_MOD = 0x97,
OP_LSHIFT = 0x98,
OP_RSHIFT = 0x99,

OP_BOOLAND = 0x9a,
OP_BOOLOR = 0x9b,
OP_NUMEQUAL = 0x9c,
OP_NUMEQUALVERIFY = 0x9d,
OP_NUMNOTEQUAL = 0x9e,
OP_LESSTHAN = 0x9f,
OP_GREATERTHAN = 0xa0,
OP_LESSTHANOREQUAL = 0xa1,
OP_GREATERTHANOREQUAL = 0xa2,
OP_MIN = 0xa3,
OP_MAX = 0xa4,

OP_WITHIN = 0xa5,

// crypto
OP_RIPEMD160 = 0xa6,
OP_SHA1 = 0xa7,
OP_SHA256 = 0xa8,
OP_HASH160 = 0xa9,
OP_HASH256 = 0xaa,
OP_CODESEPARATOR = 0xab,
OP_CHECKSIG = 0xac,
OP_CHECKSIGVERIFY = 0xad,
OP_CHECKMULTISIG = 0xae,
OP_CHECKMULTISIGVERIFY = 0xaf,

// expansion
OP_NOP1 = 0xb0,
OP_CHECKLOCKTIMEVERIFY = 0xb1,
OP_NOP2 = OP_CHECKLOCKTIMEVERIFY,
OP_CHECKSEQUENCEVERIFY = 0xb2,
OP_NOP3 = OP_CHECKSEQUENCEVERIFY,
OP_NOP4 = 0xb3,
OP_NOP5 = 0xb4,
OP_NOP6 = 0xb5,
OP_NOP7 = 0xb6,
OP_NOP8 = 0xb7,
OP_NOP9 = 0xb8,
OP_NOP10 = 0xb9,

OP_INVALIDOPCODE = 0xff,
```

DISABLED OPCODES

- Bitwise logic operators
  - OP_INVERT, OP_AND, OP_OR, OP_XOR
- Arithmetic
  - OP_2MUL, OP_2DIV, OP_MUL, OP_DIV, OP_MOD, OP_LSHIFT, OP_RSHIFT
- String operators
  - OP_CAT, OP_SUBSTR, OP_LEFT, OP_RIGHT
- Reenabling them in legacy script execution context requires a hard fork
  - It makes previously invalid blocks valid
- Reenabling them in a new segwit script version can be done with a SF

DATA PUSH

- Direct push for short data up to 75 bytes (01 - 4b)
  - The opcode itself is the length in bytes
  - Often written as OP_PUSHBYTES in explorers
- OP_PUSHDATA1 for 8-bit values (0 to 255)
  - 4c + next byte contains byte length of data to be pushed
- OP_PUSHDATA2 for 16-bit values (0 to 65 535)
  - 4d + next two bytes contains byte length of data to be pushed
- OP_PUSHDATA4 for 32-bit values (0 to 4 294 967 296)
  - 4e + next four bytes contains byte length of data to be pushed
  - Allows pushing up to 4GB onto the stack
  - But no real use because of 520 bytes data push limit policy
- Minimal push policy
  - Only use OP_PUSHDATA1 when direct push is not possible
  - Only use OP_PUSHDATA2 when an OP_PUSHDATA1 is not possible, etc.

OP_VERIFY

- VERIFY is a conditional operator
- Pops the top item on the stack and sees if it's true; if not *it ends execution of the script*
- VERIFY is usually incorporated into other opcodes
  - OP_EQUALVERIFY, OP_CHECKLOCKTIMEVERIFY, OP_CHECKSEQUENCEVERIFY, OP_NUMEQUALVERIFY, OP_CHECKSIGVERIFY, OP_CHECKMULTISIGVERIFY
  - Each of these opcodes does its core action and then does a verify afterward
- This is how we check conditions that are absolutely required for a script to succeed

IF / THEN

- OP_IF, OP_ELSE, OP_ENDIF
- OP_NOTIF, OP_ELSE, OP_ENDIF
- OP_IFDUP
  - Duplicates the top stack item only if it's not 0
- IF conditional checks the truth of what's *before it* (top item on the stack)
- IF conditional tends to be in the locking script and what it's checking tends to be in the unlocking script

OP_CHECKLOCKTIMEVERIFY

- Absolute timelocking of UTXO

- Blockheight $<$ 500 million $>=$ timestamp

- 1495652013 OP_CHECKLOCKTIMEVERIFY
  - Check against May 24, 2017

- The opcode actually use the nLocktime field for consensus enforcement
  - So when respending a UTXO with CLTV, we must set the nLocktime to enable the tx

OP_CHECKSEQUENCEVERIFY

- Relative timelocking of UTXO
- 100 OP_CHECKSEQUENCEVERIFY
  - UTXO held for a hundred blocks past its mining
- 4224679 OP_CHECKSEQUENCEVERIFY
  - 6 months encoded according to BIP68
  - Multiple of 512 seconds + 23rd bit to true (here in decimal)
- The opcode actually use the nSequence field for consensus enforcement
  - So when respending a UTXO with CSV, we must set the nSequence to enable the tx
- Used in Lightning Network to chain transactions
  - A child tx cannot be used until the parent tx has been propagated, mined, and aged by the time specified in the relative timelock

ALTSTACK

- OP_TOALTSTACK, OP_FROMALTSTACK
- Common feature in stack-based languages (cf. Forth)
- Not used in practice
- We can avoid using OP_(TO|FROM)ALTSTACK by putting things onto the stack in a different order
  - There are 18 stack manipulation operators, but only OP_DUP is used with any regularity

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SCRIPTS EXAMPLES

POOR MAN'S 1 OF 2 MULTISIG

```
IF
    OP_DUP
    OP_HASH160
    OP_PUSHBYTES_20 <pubKeyHashA>
ELSE
    OP_DUP
    OP_HASH160
    OP_PUSHBYTES_20 <pubKeyHashB>
ENDIF

 OP_EQUALVERIFY
 OP_CHECKSIG
```

- Alice unlocking script
  - <signatureA> <pubKeyA> True

- Bob unlocking script
  - <signatureB> <pubKeyB> False

POOR MAN'S 1 OF 2 MULTISIG #2

```
OP_DUP OP_HASH160 <pubKeyHashA> OP_EQUAL
IF
    OP_CHECKSIG
ELSE
    OP_DUP OP_HASH160 <pubKeyHashB> OP_EQUALVERIFY OP_CHECKSIG
ENDIF
```

- Alice unlocking script
    - <signatureA> <pubKeyA>

- Bob unlocking script
    - <signatureB> <pubKeyB>

ALGEBRA PUZZLES

- x + y = 99
  - OP_ADD 99 OP_EQUAL
  - 98 1
- 3x + 7 = 13
  - OP_DUP OP_DUP 7 OP_ADD OP_ADD OP_ADD 13 OP_EQUAL
  - 2
- x + y = 3, y + z = 5, x + z = 4
  - OP_3DUP OP_ADD 5 OP_EQUALVERIFY OP_ADD 4 OP_EQUALVERIFY OP_ADD 3 OP_EQUAL
  - 1 2 3

COMPUTATIONAL PUZZLES

- Crowdsourcing a computation
  - Script requires the answer to computation, fund the P2SH as a reward

- Peter Todd’s hash collision bounties
  - <value1> <value2>
  - OP_2DUP OP_EQUAL OP_NOT OP_VERIFY OP_SHA1 OP_SWAP OP_SHA1 OP_EQUAL
  - When SHA-1 was broken, 2.48 BTC were claimed

HASHLOCK

- Restricts the spending of an output until a specified piece of data is publicly revealed

- We can create multiple outputs all restricted by the same hashlock

- OP_HASH256 6fe28c0ab6f1b372c1a6a246ae63f74f931e8365e15a089c68d6190000000000 OP_EQUAL
  - Solution is the genesis block header

- No signature, so not secure

- Hashlock enables payment relay
    - Allows to bind two otherwise unrelated transactions together
- Alice wants to pay Carol using Bob as an intermediary
    - Carol produces a hash from a secret *s*
    - Gives the hash to Alice
    - Alice pays Bob with his sig + hash
    - Bob pays Carol with her sig + hash
    - Spending Bob's payment requires Carol to publish *s*
    - Also allowing Bob to spend Alice's payment
- Payment relay of this sort is both contrived and insecure
    - But groundwork for much more robust protocols

HASHED TIMELOCK CONTRACT

- General mechanism for off-chain contract negotiation
    - Secret can be presented within an invalidation time window
    - Sharing the secret guarantee to the counterparty that the transaction will never be broadcast

```
HASH160 DUP <R-HASH> EQUAL
IF
   "24h" CHECKSEQUENCEVERIFY
   2DROP
   <Alice's pubkey>
ELSE
   <Commit-Revocation-Hash> EQUAL
   NOTIF
      "2015/10/20 10:33" CHECKLOCKTIMEVERIFY DROP
   ENDIF
   <Bob's pubkey>
ENDIF
CHECKSIG
```

5

FUTURE IMPROVEMENTS

ELEMENTS

- Can operate as a standalone blockchain or as a pegged sidechain
- Advanced features extending the Bitcoin protocol

- Includes several new script opcodes
  - Reintroduces most disabled opcodes
  - OP_DETERMINISTICRANDOM produces a random num within a range from a seed
  - OP_CHECKSIGFROMSTACK verifies a signature against a message on the stack

- Launched sidechains
  - Elements Alpha: Bitcoin's testnet sidechain launched in 2015
  - Liquid: Bitcoin's mainnet sidechain launched in 2018

CHECKSIGFROMSTACK

- Push signed msg from script to the stack, and check that it verifies

- Some use cases
  - Create a new type of lightning channel similar to Eltoo but better
  - Oracles
  - Delegation of authorisation to spend an output
  - Covenants (with OP_CAT)
  - Secure multiparty computations

- Hopefully shipped on late 2019 Soft Fork

COVENANTS

- Restricts how funds are allowed to be spent
- Reverse covenants (input restrictions)
  - An input can only be created with this other one
  - An input can only be created if this other one doesn't exist
- Can be recursive, applying to a chain of tx
- Allows covenant vaults (E.G. Sirer)
  - Can revert a fraudulent transaction
  - Can burn hacked coins
  - Can't pay a merchant with a vault payment

SECURE MULTIPARTY COMPUTATION

- Lottery protocols that ensure that any party that aborts after learning the outcome pays a monetary penalty to all other parties

SIMPLICITY

- Bitcoin Script replacement
  - Thanks to Segwit script versioning
  - More expressive and ultra safe
  - Paper from Dr. Russell O’Connor of Blockstream in 2017
- Typed, combinator-based, functional, without recursion, sequent-calculus-based, formal denotational semantics in Coq, MAST-native
- Allows static analysis
  - Compiles to a low-level model (the Bit Machine)
  - Useful to measure the amount of computation of a script
- First step is to implement it in Elements
- Higher-level languages that compile down to Simplicity is possible, not the hard part

SCRIPT SYSTEM GOALS

- Privacy
- Space efficiency
- Computational efficiency

- We want to convince the network that what we are trying to do is authorized
  - Today, every full node validate every transactions
  - Why not just proving correct execution?

- Execution vs verifiability
- Ultimate goal is a Zero-Knowledge proof system

MERKLE BRANCHES IN SCRIPT (MAST)

- BIP114 - Merklized Abstract Syntax Trees (Merkle tree + AST)
  - AST allows to split a program into its individual parts
- BIP116 / BIP 117 - MAST constructs without AST

- Usually scripts are just an OR of a few keys, timelocks and hashlocks

- Why reveal all possibilities?
  - Put all disjunctions in a Merkle tree
  - Only reveal the actually taken branch

- More privacy, more storage and computational efficiency

SCHNORR-BASED CONTRACTS

- Schnorr signatures are linear, not ECDSA
  - We can add and substract signatures
- Scriptless scripts
  - A way to do alchemy with signatures
  - Smart contracts executed off-chain, only by the parties involved
  - A valid transaction has a signature that proves correct contract execution
- Discreet log contracts
  - A way to do alchemy with public keys
  - An oracle determines division of funds
- Atomic coinswap (Adam Gibson), etc.

CONCLUSION

- Few building blocks are enough to create interesting financial smart contracts and second layer networks
- Script versioning is awesome
- We are aiming towards a verification system, less an execution platform
  - On-chain storage/execution inherently doesn’t scale
  - EC Schnorr will enable this paradigm shift
- Bitcoin future is bright, BUIDL