Bitcoin Transactions

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January 11, 2024

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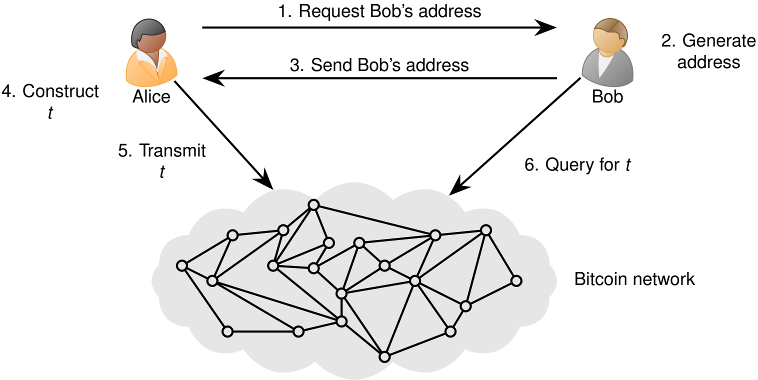
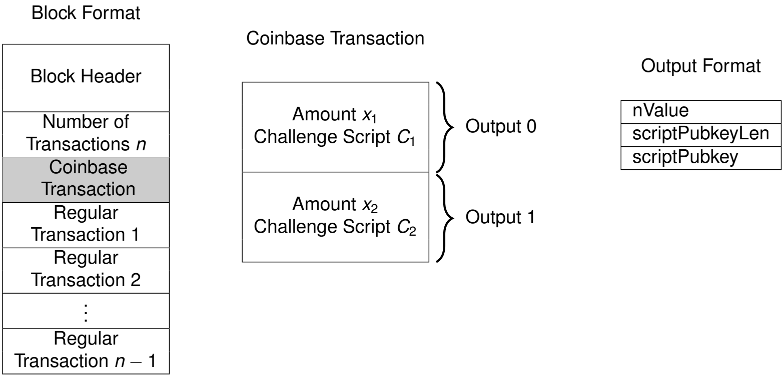
Bitcoin Payment Workflow



- Merchant Bob shares address out of band (not using Bitcoin P2P)
- Customer Alice broadcasts transaction *t* which pays the address
- Miners collect broadcasted transactions into a candidate block
- One of the candidate blocks containing *t* is mined
- Merchant waits for confirmations on *t* before providing goods

Coinbase Transaction Format



Block Format

Block Header

Number of Transactions n

Coinbase Transaction

Regular Transaction 1

Regular Transaction 2

$\vdots$

Regular Transaction $n-1$

Coinbase Transaction

Amount x_1
Challenge Script C_1

Output 0

Amount x_2
Challenge Script C_2

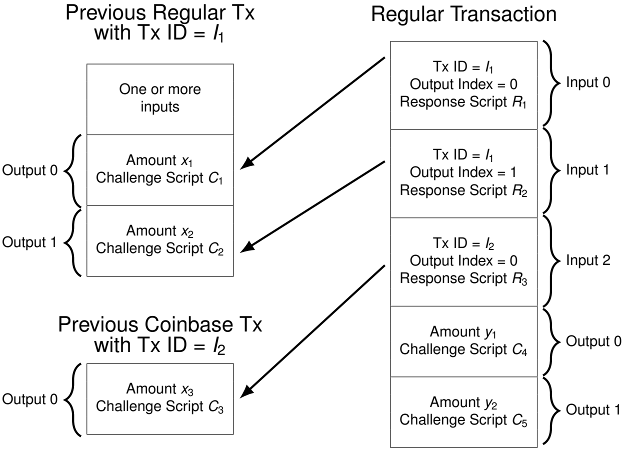
Output 1

Output Format

nValue
scriptPubkeyLen
scriptPubkey

- nValue contains number of satoshis locked in output
  - 1 Bitcoin = 10^8 satoshis
- scriptPubkey contains the challenge script
- scriptPubkeyLen contains byte length of challenge script

Regular Transaction Format



Previous Regular Tx with Tx ID = l_1

One or more inputs

Output 0: Amount x_1 Challenge Script C_1

Output 1: Amount x_2 Challenge Script C_2

Previous Coinbase Tx with Tx ID = l_2

Output 0: Amount x_3 Challenge Script C_3

Regular Transaction

Input 0: Tx ID = l_1 Output Index = 0 Response Script R_1

Input 1: Tx ID = l_1 Output Index = 1 Response Script R_2

Input 2: Tx ID = l_2 Output Index = 0 Response Script R_3

Output 0: Amount y_1 Challenge Script C_4

Output 1: Amount y_2 Challenge Script C_5

Input Format

- hash
- n
- scriptSigLen
- scriptSig
- nSequence

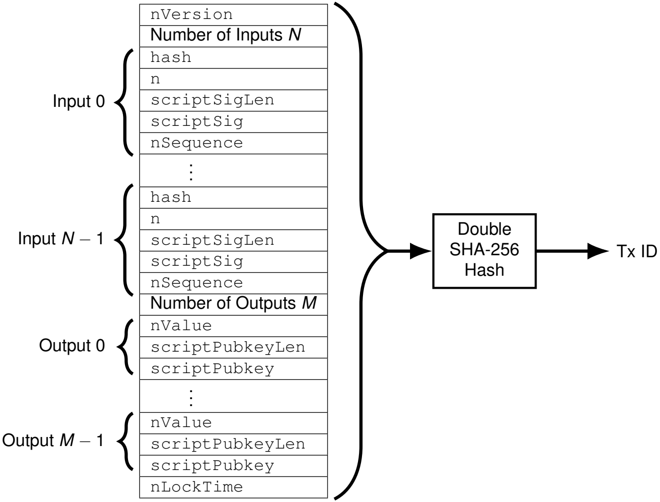
Output Format

- nValue
- scriptPubkeyLen
- scriptPubkey

- hash and n identify output being unlocked
- scriptSig contains the response script

Transaction ID

Regular Transaction



`nVersion`
Number of Inputs N

Input 0
`hash`
`n`
`scriptSigLen`
`scriptSig`
`nSequence`

⋮

Input $N-1$
`hash`
`n`
`scriptSigLen`
`scriptSig`
`nSequence`

Number of Outputs M

Output 0
`nValue`
`scriptPubkeyLen`
`scriptPubkey`

⋮

Output $M-1$
`nValue`
`scriptPubkeyLen`
`scriptPubkey`

`nLockTime`

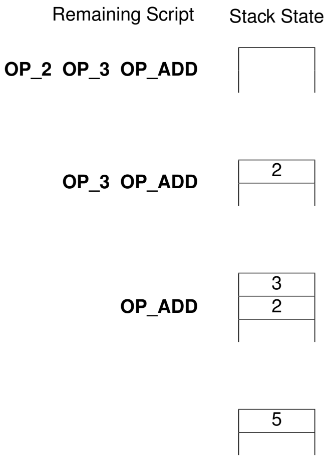
Double SHA-256 Hash

Tx ID

Bitcoin Scripting Language

Script

- Forth-like stack-based language
- One-byte opcodes



Remaining Script | Stack State

OP_2 OP_3 OP_ADD

OP_3 OP_ADD | 2

OP_ADD | 3, 2

5

Challenge/Response Script Execution

Remaining Script	Stack State
<Response Script> <Challenge Script>	
<Challenge Script>	x_1 x_2 $\vdots$ x_n
	y_1 y_2 $\vdots$ y_m

Response is valid if top element y_1 evaluates to True

Challenge Script Example

$$\textbf{OP\_HASH256}\quad\textbf{0x20}\quad\underbrace{\textbf{<256-bit string>}}_{\textbf{S}}\quad\textbf{OP\_EQUAL}$$

Remaining Script	Stack State
OP_HASH256 0x20 S OP_EQUAL	x
0x20 S OP_EQUAL	$H(x)$
OP_EQUAL	**S** $H(x)$
	0 or 1

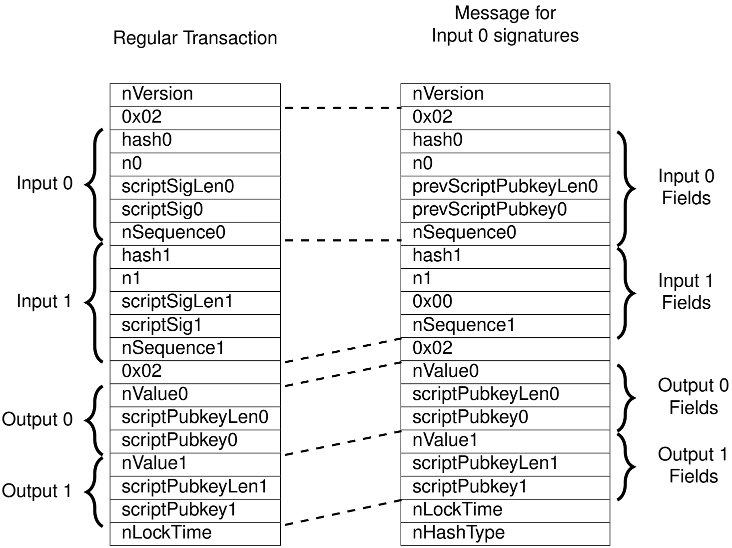
Unsafe challenge script! Guess why?

Pay to Public Key

- Challenge script: **0x21 <Public Key> OP_CHECKSIG**
- Response script: **<Signature>**

Remaining Script	Stack State
<Signature> <Public Key> OP_CHECKSIG	
<Public Key> OP_CHECKSIG	**<Signature>**
OP_CHECKSIG	**<Public Key>** **<Signature>**
	True/False

Signatures Protect Transactions



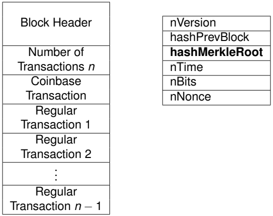
Regular Transaction

- nVersion
- 0x02
- Input 0
  - hash0
  - n0
  - scriptSigLen0
  - scriptSig0
  - nSequence0
- Input 1
  - hash1
  - n1
  - scriptSigLen1
  - scriptSig1
  - nSequence1
- 0x02
- Output 0
  - nValue0
  - scriptPubkeyLen0
  - scriptPubkey0
- Output 1
  - nValue1
  - scriptPubkeyLen1
  - scriptPubkey1
- nLockTime

Message for
Input 0 signatures

- nVersion
- 0x02
- Input 0 Fields
  - hash0
  - n0
  - prevScriptPubkeyLen0
  - prevScriptPubkey0
  - nSequence0
- Input 1 Fields
  - hash1
  - n1
  - 0x00
  - nSequence1
- 0x02
- Output 0 Fields
  - nValue0
  - scriptPubkeyLen0
  - scriptPubkey0
- Output 1 Fields
  - nValue1
  - scriptPubkeyLen1
  - scriptPubkey1
- nLockTime
- nHashType

Transaction Merkle Root



Block Header

Number of Transactions n

Coinbase Transaction

Regular Transaction 1

Regular Transaction 2

⋮

Regular Transaction $n-1$

nVersion

hashPrevBlock

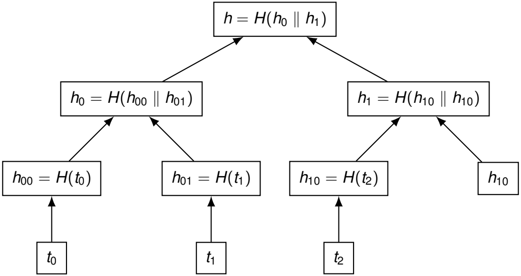
hashMerkleRoot

nTime

nBits

nNonce

- hashMerkleRoot contains root hash of transaction Merkle tree
- Modifying any transaction will modify the block header



$h = H(h_0 \parallel h_1)$

$h_0 = H(h_{00} \parallel h_{01})$

$h_1 = H(h_{10} \parallel h_{10})$

$h_{00} = H(t_0)$

$h_{01} = H(t_1)$

$h_{10} = H(t_2)$

h_{10}

t_0

t_1

t_2

Key Takeaways

- Coinbase transactions have no inputs; outputs have challenge scripts
- Regular transaction inputs unlock previous outputs; outputs again have challenge scripts
- Scripts are expressed in a stack-based language
- Signatures prevent tampering of unconfirmed transactions

Bitcoin Addresses

Bitcoin Addresses

- To receive bitcoins, a challenge script needs to be specified
- Bitcoin addresses encode challenge scripts
- Example: 1EHNa6Q4Jz2uvNExL497mE43ikXhwF6kZm

- Bitcoin payment workflow (recap)
    - Merchant shares address out of band (not using Bitcoin P2P network)
    - Customer transmits transaction which pays the address
    - Merchant waits for transaction confirmations before providing goods/service

Base58 Encoding

1EHNa6Q4Jz2uvNExL497mE43ikXhwF6kZm

$$\updownarrow$$

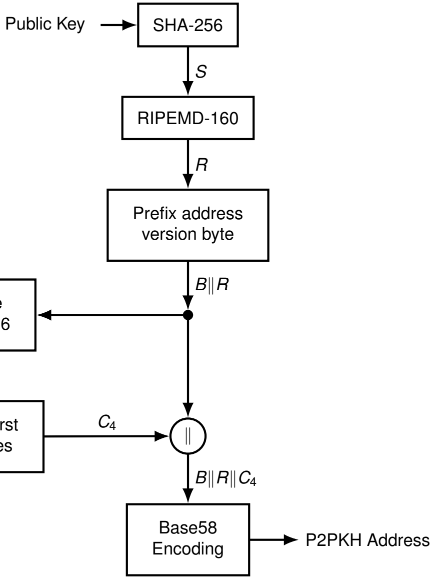
0091B24BF9F5288532960AC687ABB035127B1D28A50074FFE0

- Alphanumeric representation of bytestrings
- From 62 alphanumeric characters 0, O, I, l are excluded

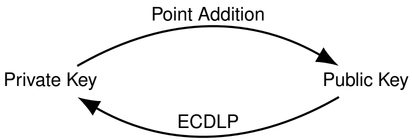
Ch	Int	Ch	Int	Ch	Int	Ch	Int	Ch	Int	Ch	Int	Ch	Int
1	0	A	9	K	18	U	27	d	36	n	45	w	54
2	1	B	10	L	19	V	28	e	37	o	46	x	55
3	2	C	11	M	20	W	29	f	38	p	47	y	56
4	3	D	12	N	21	X	30	g	39	q	48	z	57
5	4	E	13	P	22	Y	31	h	40	r	49		
6	5	F	14	Q	23	Z	32	i	41	s	50		
7	6	G	15	R	24	a	33	j	42	t	51		
8	7	H	16	S	25	b	34	k	43	u	52		
9	8	J	17	T	26	c	35	m	44	v	53		

- Given a bytestring $b_n b_{n-1} \cdots b_0$
  - Encode each leading zero byte as a 1
  - Get integer $N = \sum_{i=0}^{n-m} b_i 256^i$
  - Get $a_k a_{k-1} \cdots a_0$ where $N = \sum_{i=0}^{k} a_i 58^i$
  - Map each integer a_i to a Base58 character

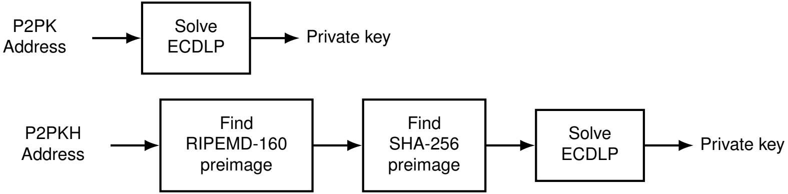
Pay to Public Key Hash Address



Why Hash the Public Key?

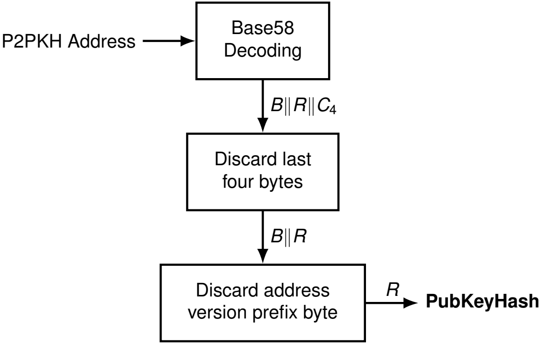


- ECDLP = Elliptic Curve Discrete Logarithm Problem
- ECDLP currently hard but no future guarantees
- Hashing the public key gives extra protection



P2PKH Transaction

- Challenge script
  OP_DUP OP_HASH160 <PubKeyHash> OP_EQUALVERIFY OP_CHECKSIG



- Response script: **<Signature> <Public Key>**

P2PKH Script Execution (1/2)

Remaining Script	Stack State
<Signature> <Public Key> OP_DUP OP_HASH160 <PubKeyHash> OP_EQUALVERIFY OP_CHECKSIG	
<Public Key> OP_DUP OP_HASH160 <PubKeyHash> OP_EQUALVERIFY OP_CHECKSIG	**<Signature>**
OP_DUP OP_HASH160 <PubKeyHash> OP_EQUALVERIFY OP_CHECKSIG	**<Public Key>** **<Signature>**
OP_HASH160 <PubKeyHash> OP_EQUALVERIFY OP_CHECKSIG	**<Public Key>** **<Public Key>** **<Signature>**

P2PKH Script Execution (2/2)

Remaining Script	Stack State
<PubKeyHash> OP_EQUALVERIFY OP_CHECKSIG	**<PubKeyHashCalc>** **<Public Key>** **<Signature>**
OP_EQUALVERIFY OP_CHECKSIG	**<PubKeyHash>** **<PubKeyHashCalc>** **<Public Key>** **<Signature>**
OP_CHECKSIG	**<Public Key>** **<Signature>**
	True/False

m-of-*n* Multi-Signature Scripts

- *m*-of-*n* multisig challenge script specifies *n* public keys

  m <Public Key 1> $\cdots$ <Public Key n> n OP_CHECKMULTISIG

- Response script provides signatures created using **any** *m* out of the *n* private keys

  OP_0 <Signature 1> $\cdots$ <Signature m>.

- Example: $m = 2$ and $n = 3$
  - Challenge script

    OP_2 <PubKey1> <PubKey2> <PubKey3> OP_3 OP_CHECKMULTISIG

  - Response script

    OP_0 <Sig1> <Sig2>

2-of-3 Multisig Script Execution

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

Pay to Script Hash Script

- Specify arbitrary scripts as payment destinations
- Challenge script

OP_HASH160 <RedeemScriptHash> OP_EQUAL

- Response script

<Response To Redeem Script> <Redeem Script>

- Example
  - 1-of-2 Multisig Challenge Script

    OP_1 <PubKey1> <PubKey2> OP_2 OP_CHECKMULTISIG
  - 1-of-2 Multisig Response Script

    OP_0 <Sig1> or **OP_0 <Sig2>**
  - P2SH Multisig challenge script

    OP_HASH160 <RedeemScriptHash> OP_EQUAL
  - P2SH Multisig response script

$$\underbrace{\textbf{OP\_0 <Sig1>}}_{\substack{\text{Response to}\\ \text{Redeem Script}}} \quad \underbrace{\textbf{OP\_1 <PubKey1> <PubKey2> OP\_2 OP\_CHECKMULTISIG}}_{\text{Redeem Script}}$$

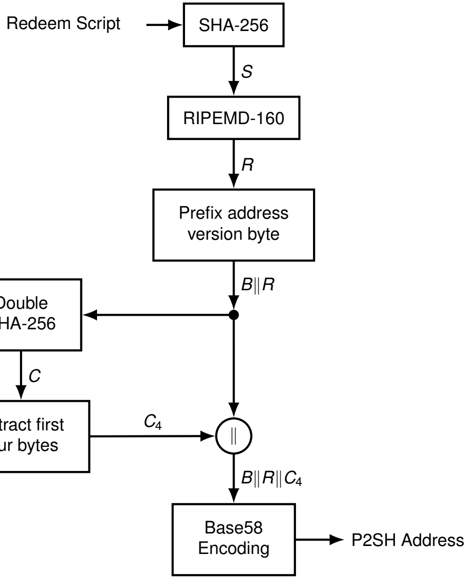
P2SH Multisig Script Execution (1/2)

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

P2SH Multisig Script Execution (2/2)

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

Pay to Script Hash Address



Null Data Script

- Challenge script

  `OP_RETURN <Data>`

  Length(**`<Data>`**) $\leq$ 80 bytes
- **`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
- Mainly used to timestamp data

Pre-SegWit Standard Scripts

- Pay to Public Key (P2PK)
- Pay to Public Key Hash (P2PKH)
- m-of-n Multi-Signature (Multisig)
- Pay to Script Hash (P2SH)
- Null Data

Key Takeaways

- Bitcoin addresses are shared over the Internet
- Transactions paying these addresses are broadcast on the Bitcoin network
- P2PKH addresses are obtained by hashing public keys
- Signatures created using private keys unlock P2PKH outputs
- P2SH addresses are obtained by hashing scripts
- Unlocking P2SH outputs requires both redeem script and valid response to it
- Null data scripts are for recording arbitrary data on the blockchain

References

- Chapter 5 of *An Introduction to Bitcoin*, S. Vijayakumaran, `www.ee.iitb.ac.in/~sarva/bitcoin.html`
- Bitcoin Script `https://en.bitcoin.it/wiki/Script`