Announcement

You should have a team!

Project 1 will be released end of week.

Introduction to Bitcoin

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Slides from Dan Boneh

Recap

SHA256: a collision resistant hash function
that outputs 32-byte hash values

Applications:

- a binding commitment to one value: commit(m) → H(m)
  or to a list of values: commit($m_1, \ldots, m_n$) → Merkle($m_1, \ldots, m_n$)

- Proof of work with difficulty D:
  given x find y s.t. $H(x, y) < 2^{256}/D$ takes time $O(D)$

Recap

<u>**Def**</u>: a signature scheme is a triple of algorithms:

- **Gen**(): outputs a key pair (pk, sk)
- **Sign**(sk, msg) outputs sig. σ
- **Verify**(pk, msg, σ) outputs 'accept' or 'reject'

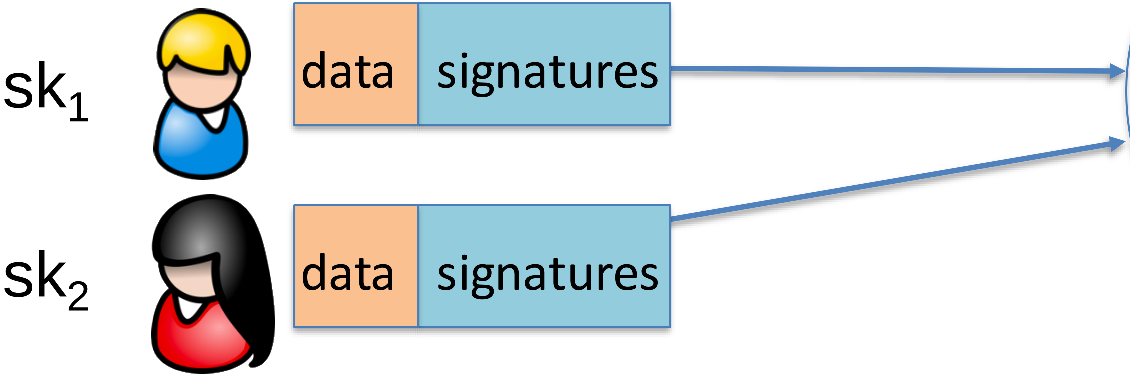
<u>**Secure signatures**</u>: (informal)

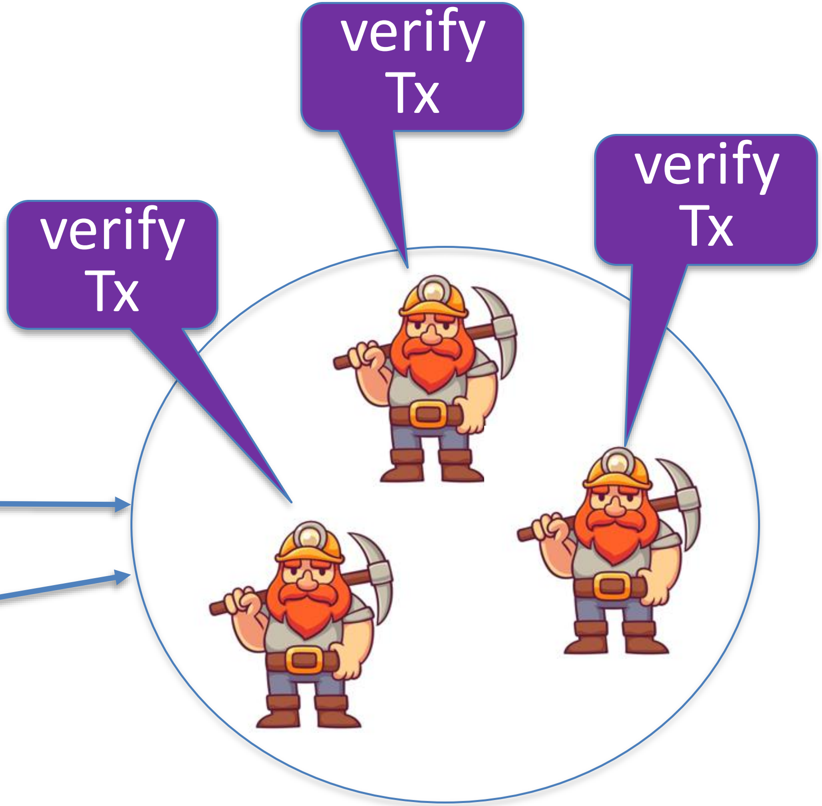
Adversary who sees signatures **on many messages** of their choice, cannot forge a signature on a new message.

Signatures on the blockchain

Signatures are used everywhere:

- ensure Tx authorization,
- governance votes,
- consensus protocol votes.





In summary …

Digital signatures: (Gen, Sign, Verify)

Gen() → (pk, sk),

Sign(sk, m) → σ,   Verify(pk, m, σ) → accept/reject

signing key

verification key

Today

Understand:

1. What is a block
2. What's in a transaction
3. What a coin is
4. How we spend coins (bitcoin scripts)
   - P2PKH
   - P2SH
   - more advanced scripts

This lecture: Bitcoin mechanics

user facing tools (cloud servers)

applications (DAPPs, smart contracts)

Execution engine (blockchain computer)

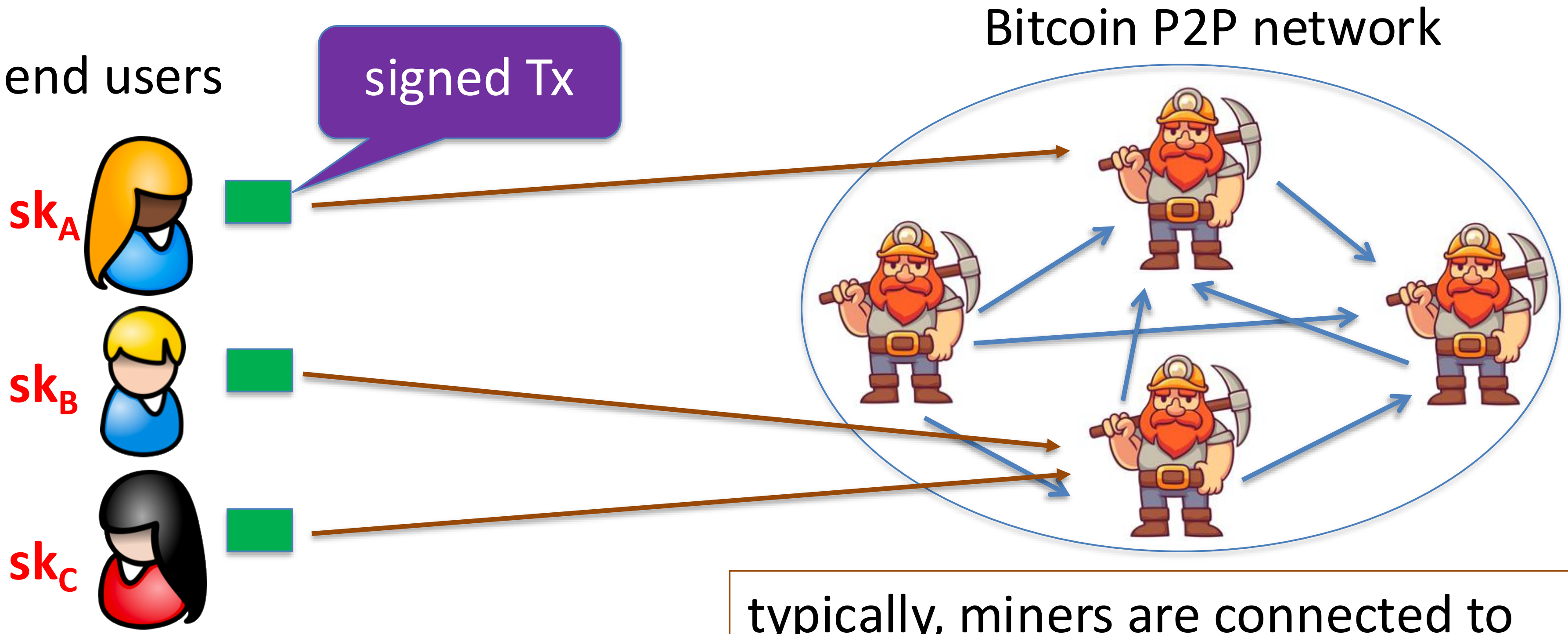
start today

Sequencer: orders transactions

Data Availability / Consensus Layer

next class

First: overview of the Bitcoin consensus layer



typically, miners are connected to eight other peers (anyone can join)

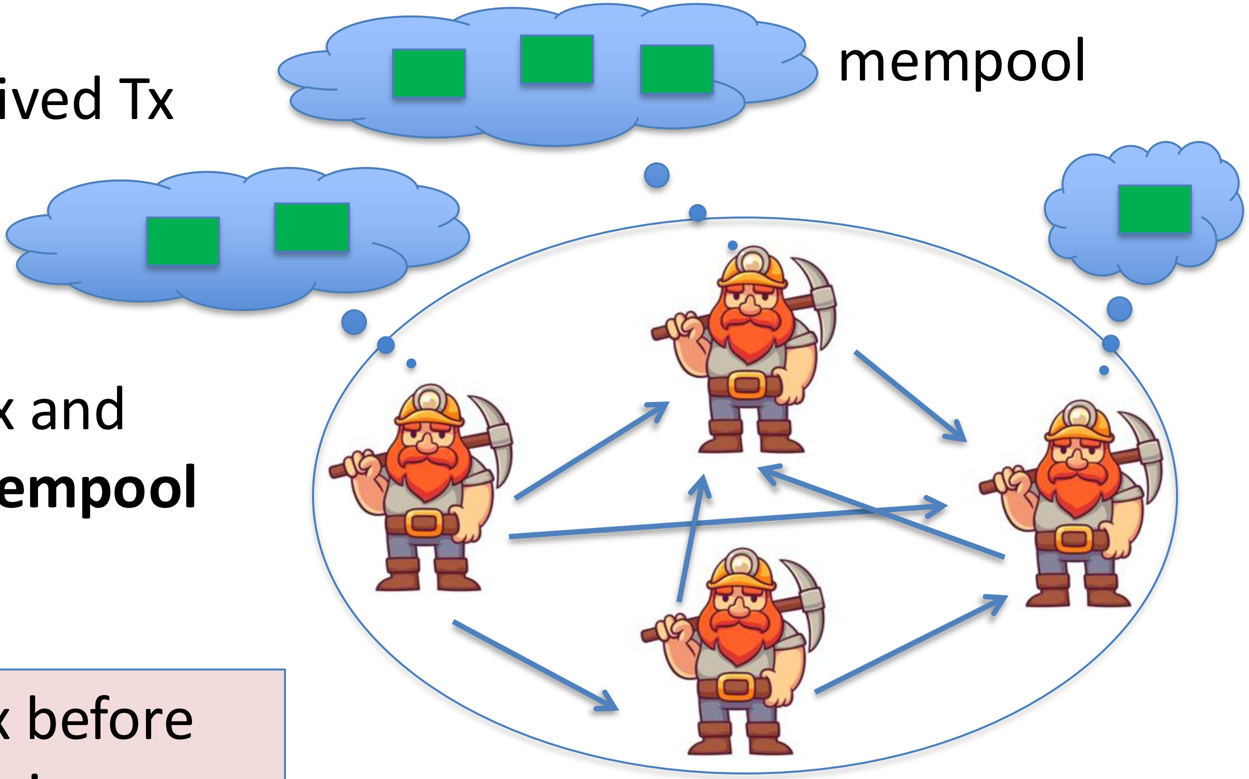
First: overview of the Bitcoin consensus layer

miners broadcast received Tx
to the P2P network

every miner:

validates received Tx and
stores them in its **mempool**
(unconfirmed Tx)

note: miners see all Tx before
they are posted on chain



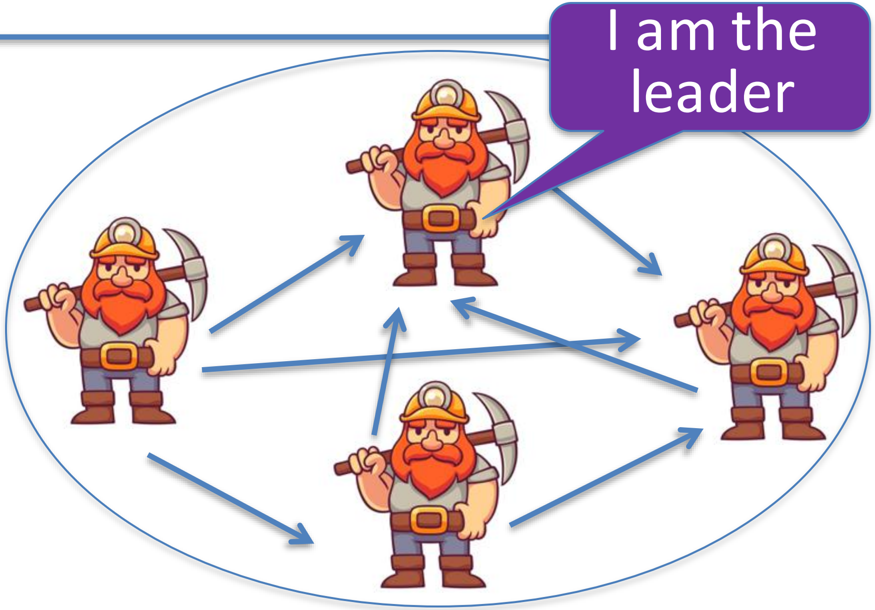
Bitcoin P2P network

First: overview of the Bitcoin consensus layer

blockchain

<u>Every ≈**10 minutes**</u>:

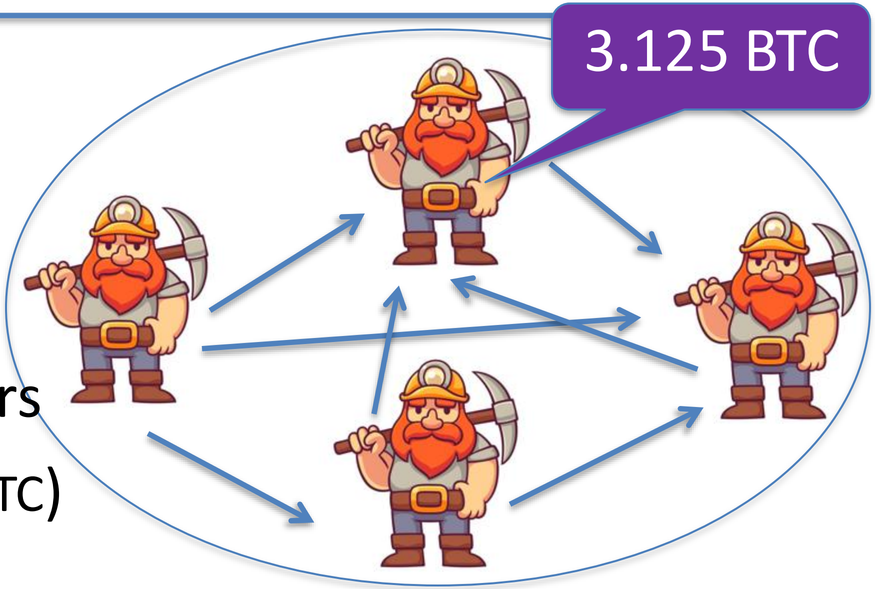
- Each miner creates a candidate block from Tx in its mempool
- a “random” miner is selected (how: next week), and broadcasts its block to P2P network
- all miners validate new block



Bitcoin P2P network

First: overview of the Bitcoin consensus layer

blockchain



Selected miner is paid 3.125 BTC
in **coinbase Tx** (first Tx in the block)

- only way new BTC is created
- block reward halves every four years

  ⇒ max 21M BTC (currently 19.9M BTC)

note: miner chooses order of Tx in block

Properties (very informal)

Next week:

Safety / Persistence:

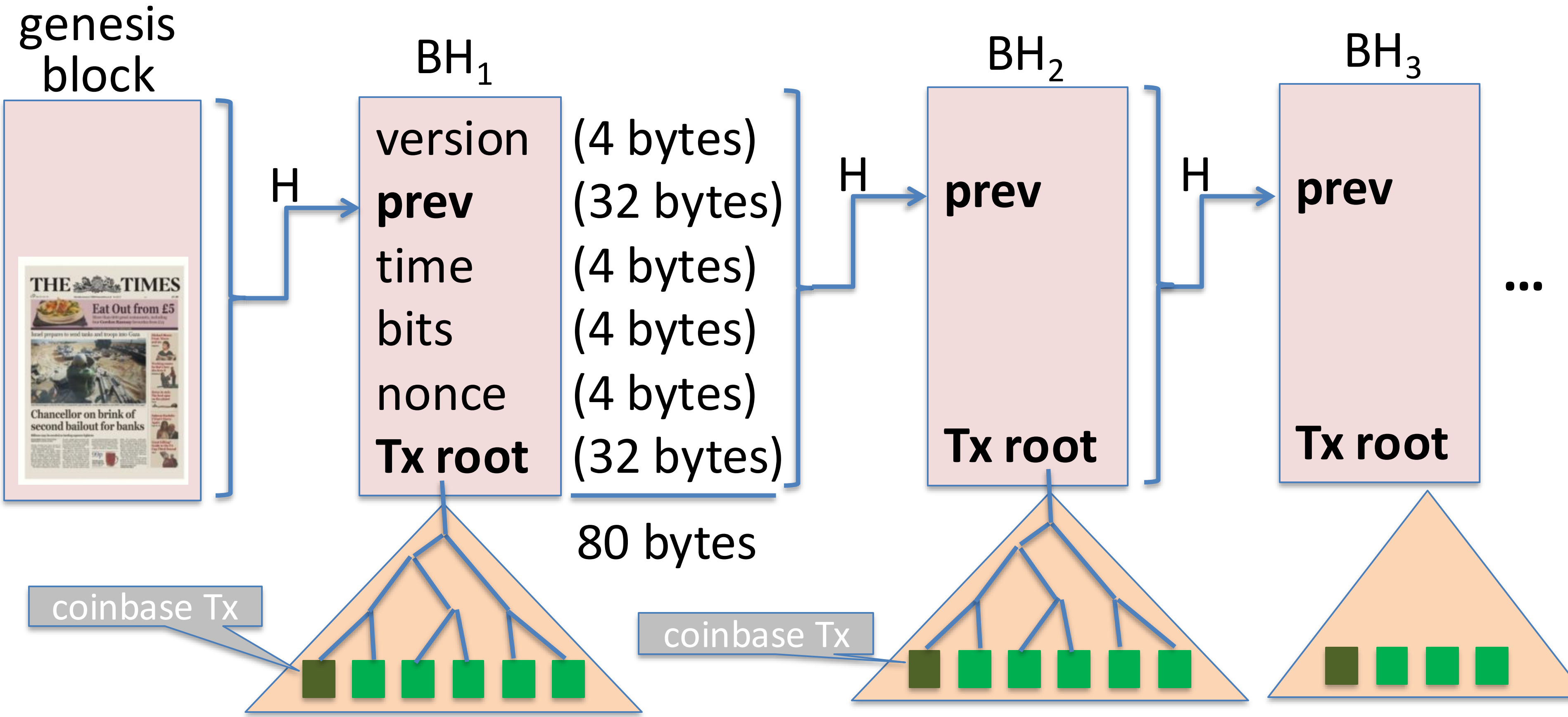
- to remove a block, need to convince 51% of mining power *

Liveness:

- to block a Tx from being posted, need to convince 51% of mining power **

(some sub 50% censorship attacks, such as feather forks)

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



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

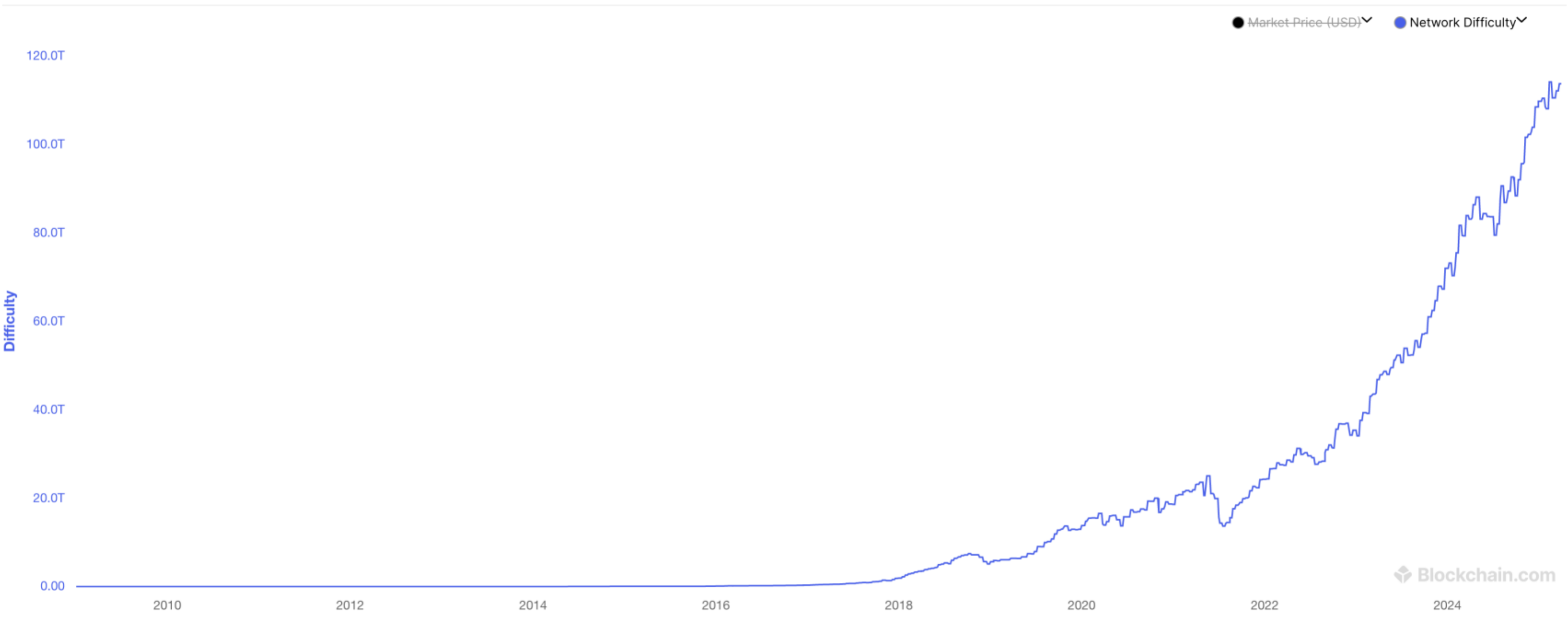
time: time miner assembled the block. Self reported.
(block rejected if too far in past or future)

bits: proof of work difficulty
nonce: proof of work solution
} for choosing a leader (next week)

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

new block every ≈10 minutes.

Difficulty over time



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

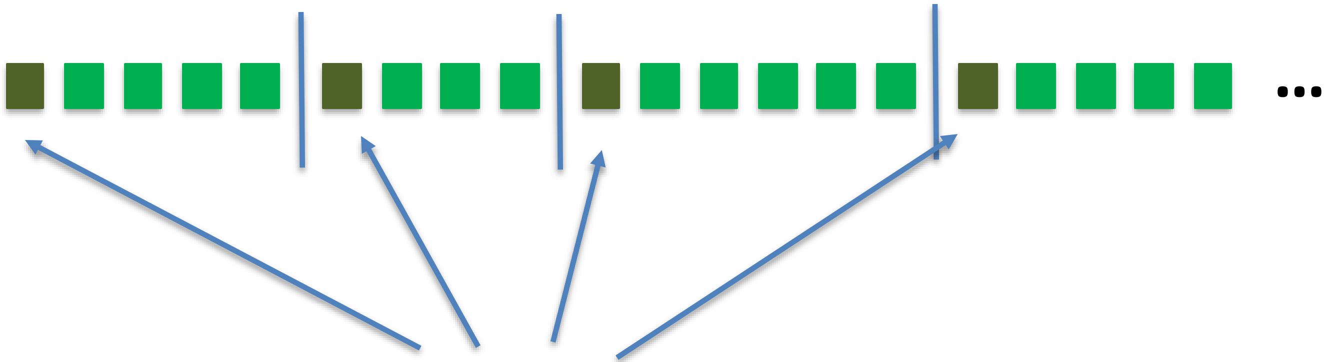
Block 648493

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 was 2020

This lecture

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



coinbase Tx

Tx structure (non-coinbase)

inputs
input[0]
input[1]
input[2]

outputs
output[0]
output[1]

(segwit)
witnesses
(part of input)

(4 bytes)
locktime

earliest block # that can include Tx

TxID = H(Tx)
(excluding witnesses)

input:

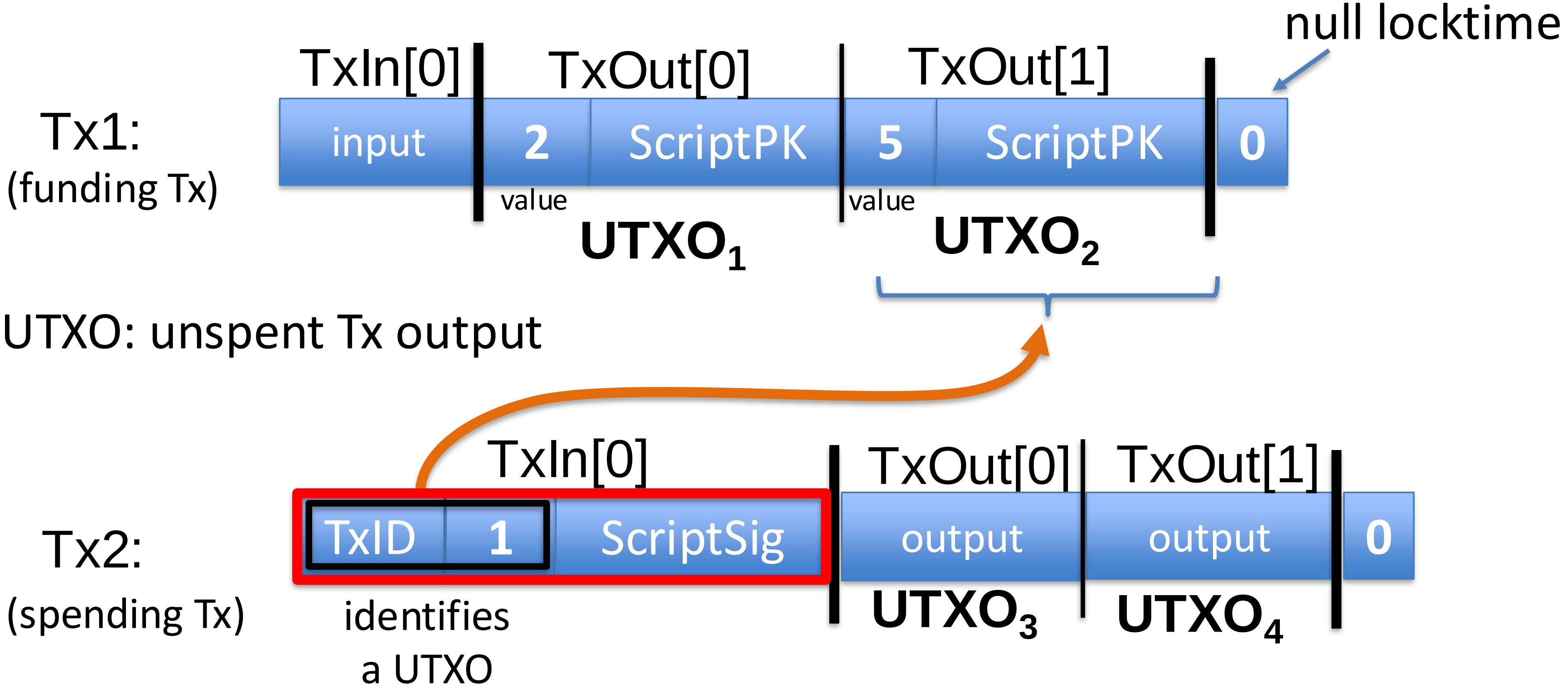
TxID	32 byte hash
out-index	4 byte index
ScriptSig	program
seq	ignore

output:

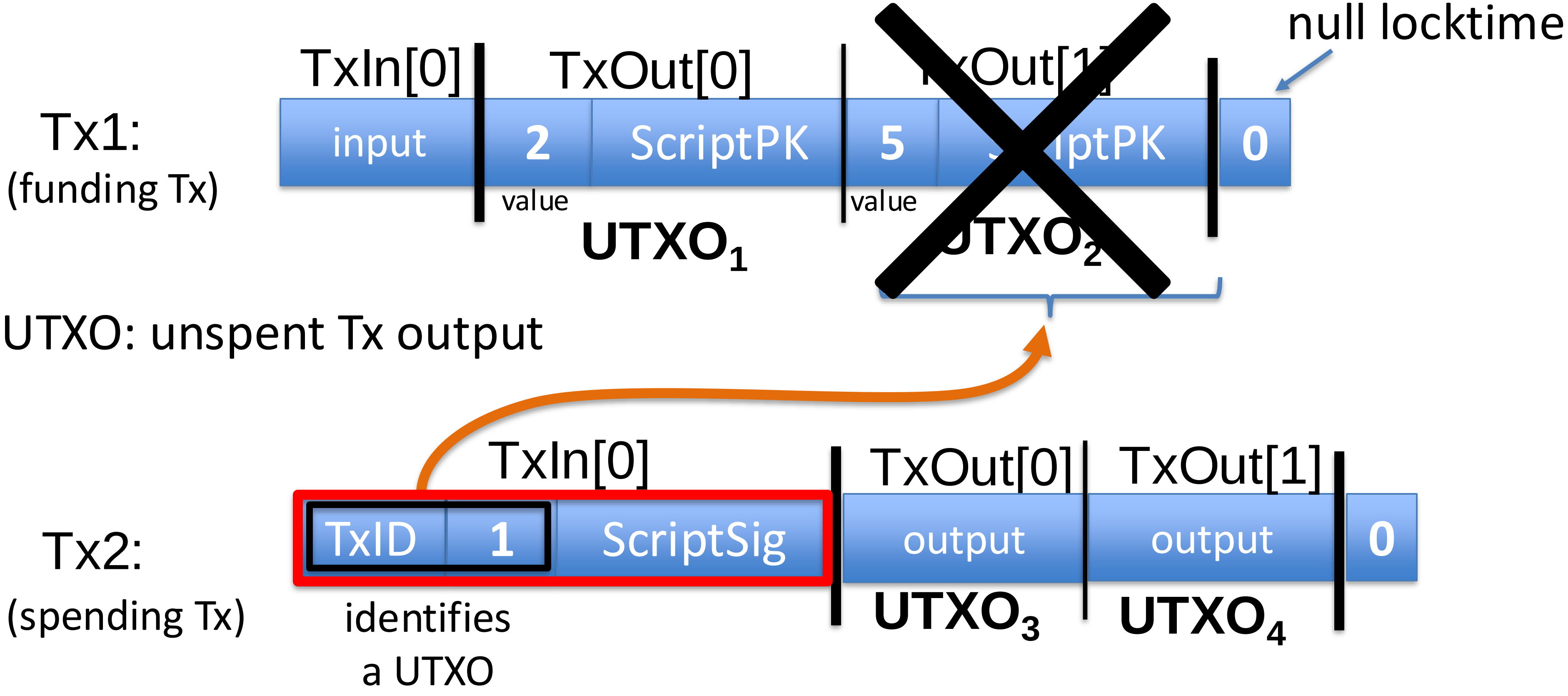
value	8 bytes
ScriptPK	program

$\#BTC = value/10^8$

Example


null locktime
TxIn[0]
TxOut[0]
TxOut[1]
Tx1:
(funding Tx)
input
2
ScriptPK
5
ScriptPK
0
value
value
UTXO$_1$
UTXO$_2$
UTXO: unspent Tx output
TxIn[0]
TxOut[0]
TxOut[1]
Tx2:
(spending Tx)
TxID
1
ScriptSig
output
output
0
identifies
a UTXO
UTXO$_3$
UTXO$_4$

Example



null locktime
TxIn[0]
TxOut[0]
~~TxOut[1]~~
Tx1:
(funding Tx)
input
2
ScriptPK
5
~~ScriptPK~~
0
value
value
UTXO$_1$
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output
0
identifies
a UTXO
UTXO$_3$
UTXO$_4$

Validating Tx2

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

Miners check (for each input):

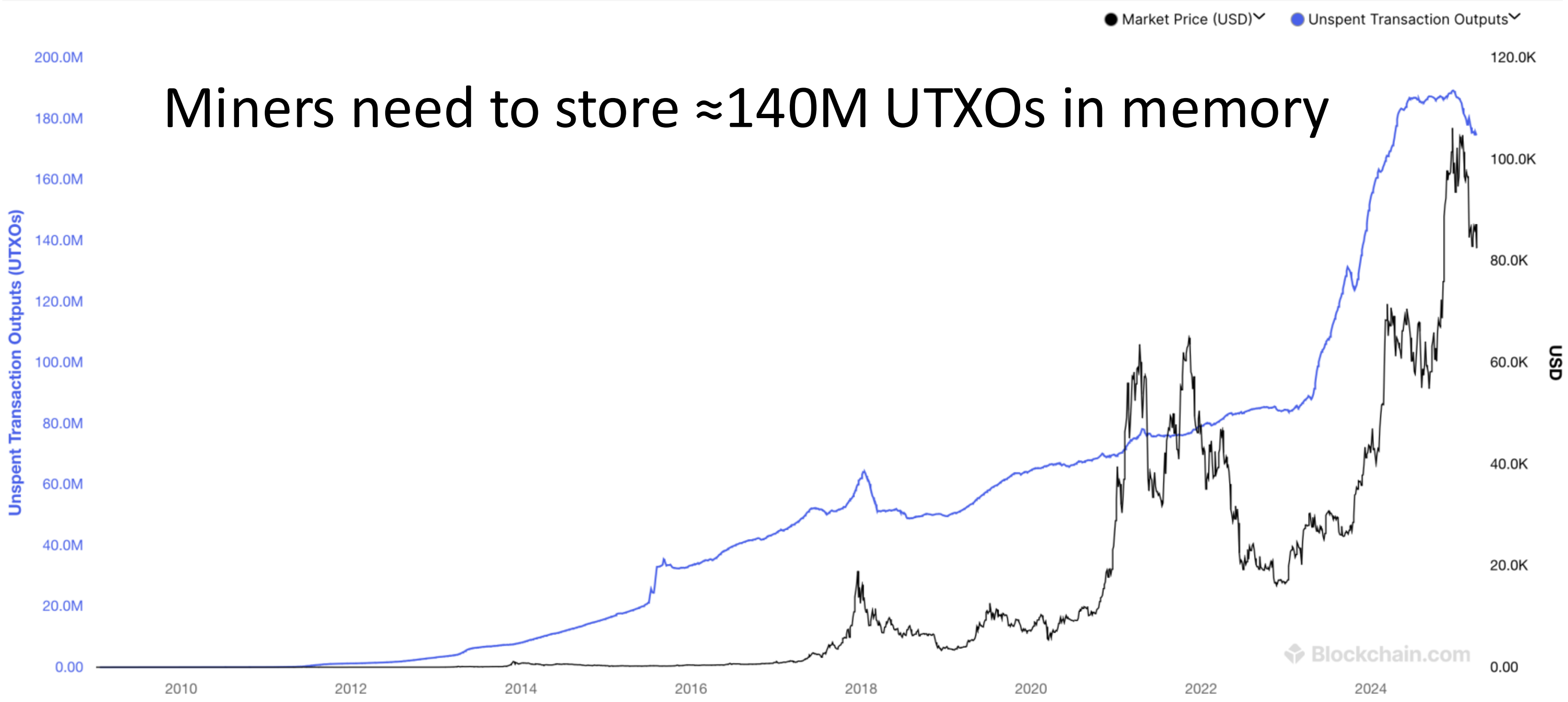
1. The program $\boxed{\text{ScriptSig | ScriptPK}}$ returns true

2. $\boxed{\text{TxID | index}}$ is in the current UTXO set

3. sum input values $\geq$ sum output values

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

All value in Bitcoin is held in UTXOs



An example (block 648493) [2826 Tx]

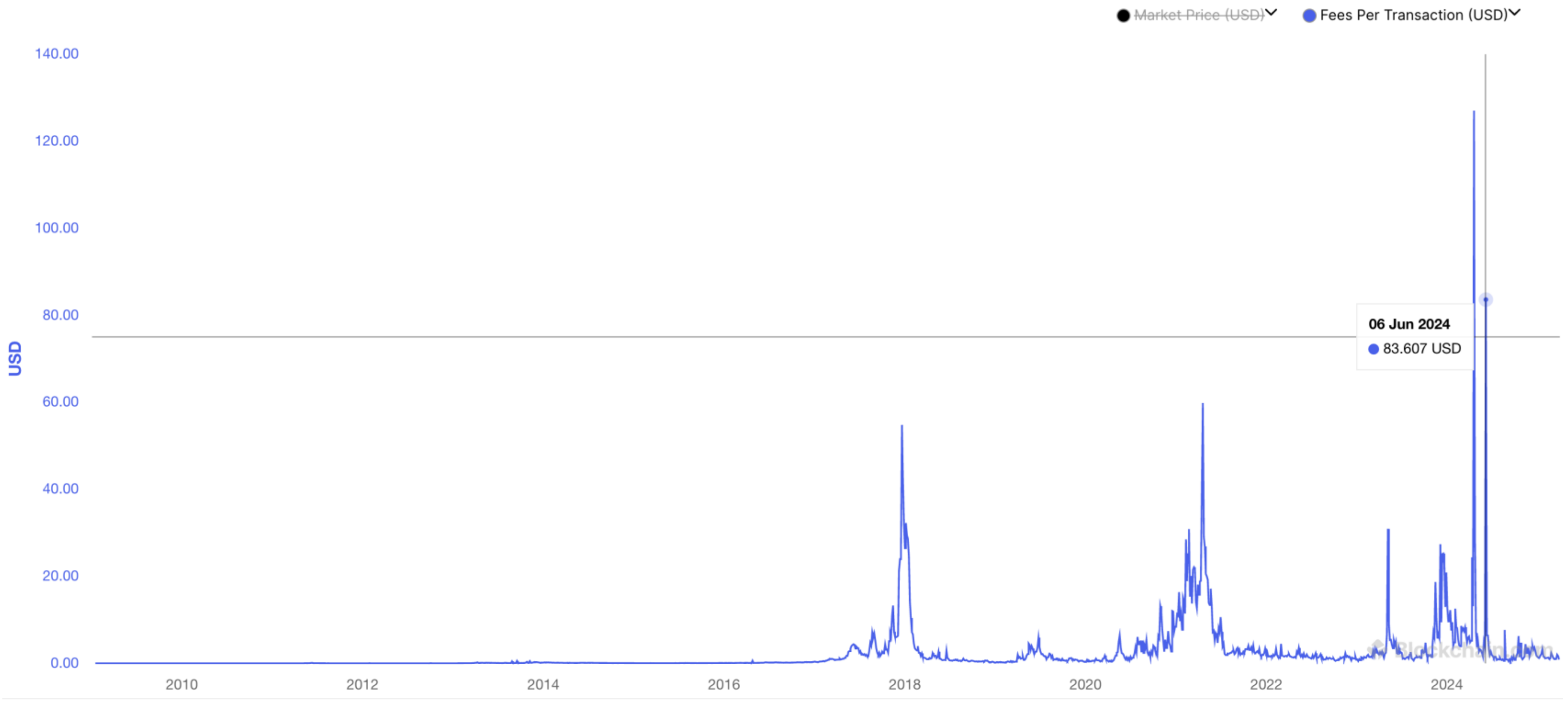
COINBASE (Newly Generated Coins)		→	1CK6KHY6MHgYvmRQ4PAafKYDrg1ejbH1cE	7.14047154 BTC
			OP_RETURN	0.00000000 BTC
			OP_RETURN	0.00000000 BTC
Tx0				
0.00000000 BTC			6.25 + Tx fees =	7.14047154 BTC

3PuJbxJS1pKxf8EdVR18yBkD1fPAbgUtyw	0.72333974 BTC	→	1E5Ao1VUnA5BhffvXf2Xmud6avUgwkFnJv	0.00917379 BTC
input	(input UTXO value)		bc1qr8k3e0vx06lpu3j7m858pa2ak9tyr56ttwvefk	0.61504199 BTC
			bc1qdrxve8kua3yz5dgx6wf3u95ngh0d3e648...	0.09290152 BTC
Tx1			14ZhjuXpQ5jCDjtAy7ZMu3hfEQCWewzLw7	0.00616444 BTC
0.00005800 BTC (Tx fee)			outputs	0.72328174 BTC

17MWze4Z1uP1jnvqvj7SAnGtxcoVq11H8A	0.05000000 BTC	→	3G3C2RFQ8gsf77EQpdR4ZReChWFKEHhxVU	0.04808000 BTC
Tx2				
0.00192000 BTC (Tx fee)				0.04808000 BTC

sum of fees in block added to coinbase Tx

Tx fees (all time)



Focusing on Tx2: TxIn[0]

from UTXO
(Bitcoin script)

Value	0.05000000 BTC
Pkscript	OP_DUP OP_HASH160 45b21c8a0cb687d563342b6c729d31dab58e3a4e OP_EQUALVERIFY OP_CHECKSIG
Sigscript	304402205846cace0d73de82dfbdeba4d65b9856d7c1b1730eb401cf4906b2401a69b dc90220589d36d36be64e774c8796b96c011f29768191abeb7f56ba20ffb0351280860 c01 03557c228b080703d52d72ead1bd93fc72f45c4ddb4c2b7a20c458e2d069c8dd9e

from TxIn[0]

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

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)

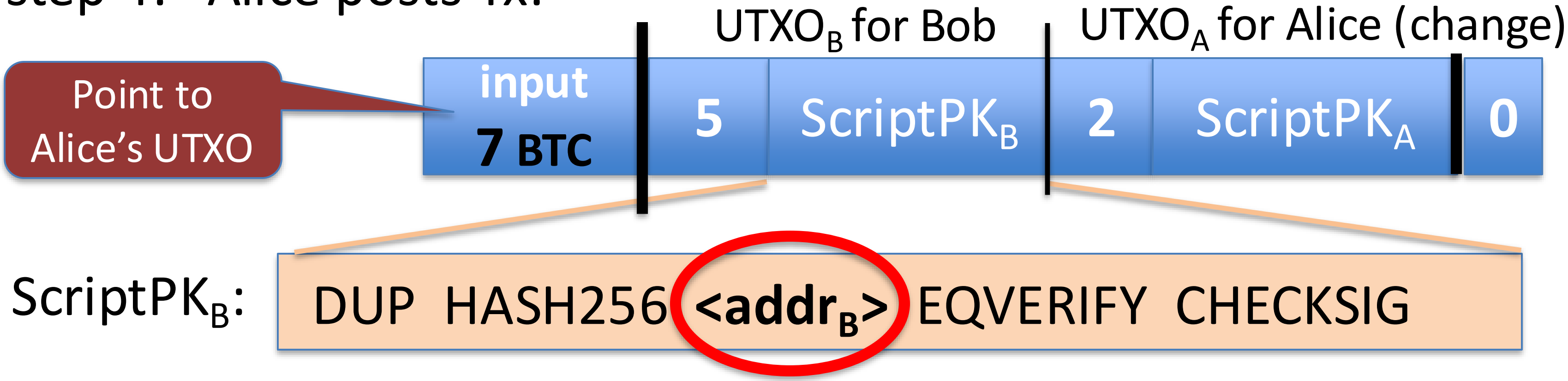
⇒ successful termination

Transaction types: (1) P2PKH

pay to public key hash

Alice want to pay Bob 5 BTC:

- step 1: Bob generates sig key pair $(pk_B, sk_B) \leftarrow \text{Gen}()$
- 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:



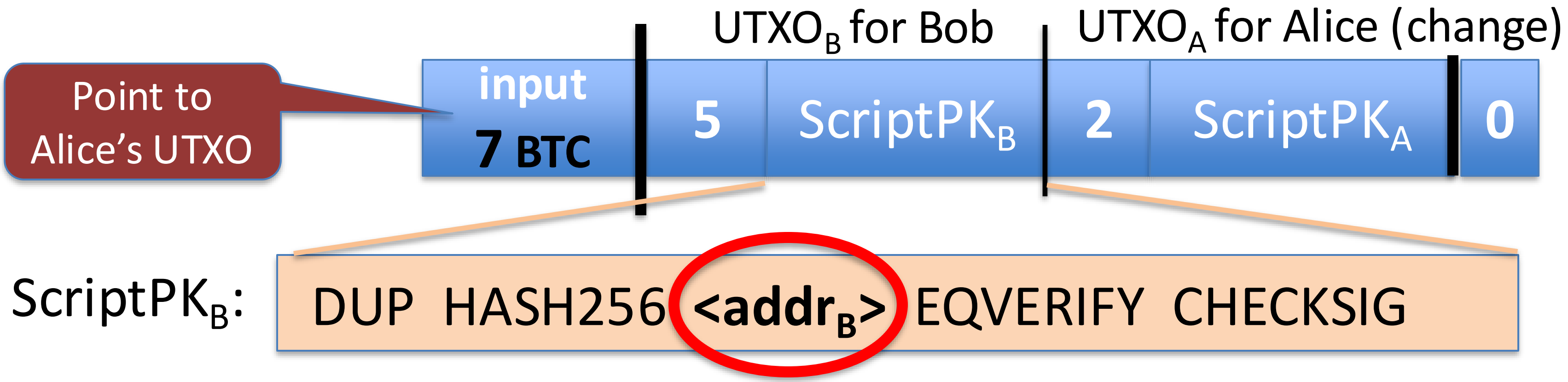
Transaction types: (1) P2PKH

pay to public key hash

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

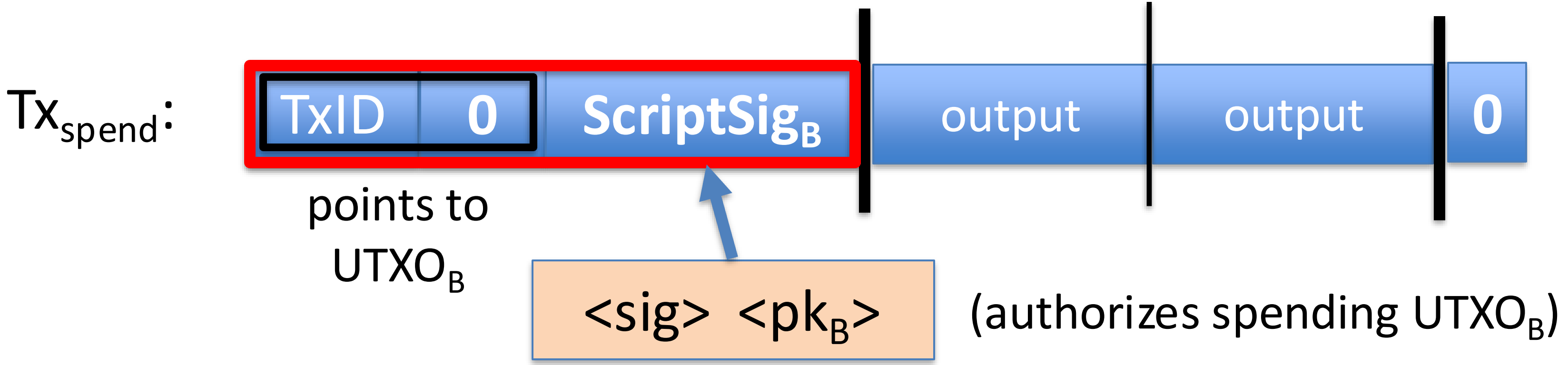
- example: ScriptSig contains Alice's signature on Tx

  $\Longrightarrow$ 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)

We've actually been looking at P2WPKH

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)

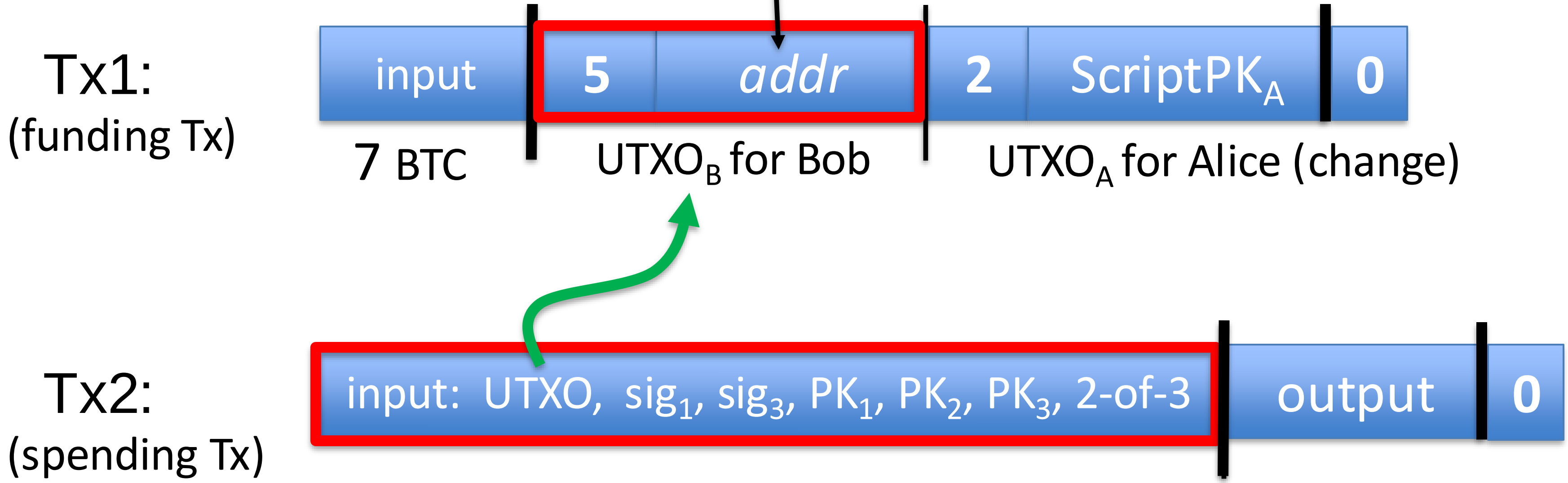
<2> <PK$_1$> <PK$_2$> <PK$_3$> <3> CHECKMULTISIG

hash gives P2SH address

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

Abstractly …

Multisig address: $addr = H(PK_1, PK_2, PK_3, \text{2-of-3})$



Transaction types: (3) P2TR: pay to Taproot

Let’s payer specify complex spending conditions:

A. Public key (similar to P2WPKH) but using Schnorr signatures

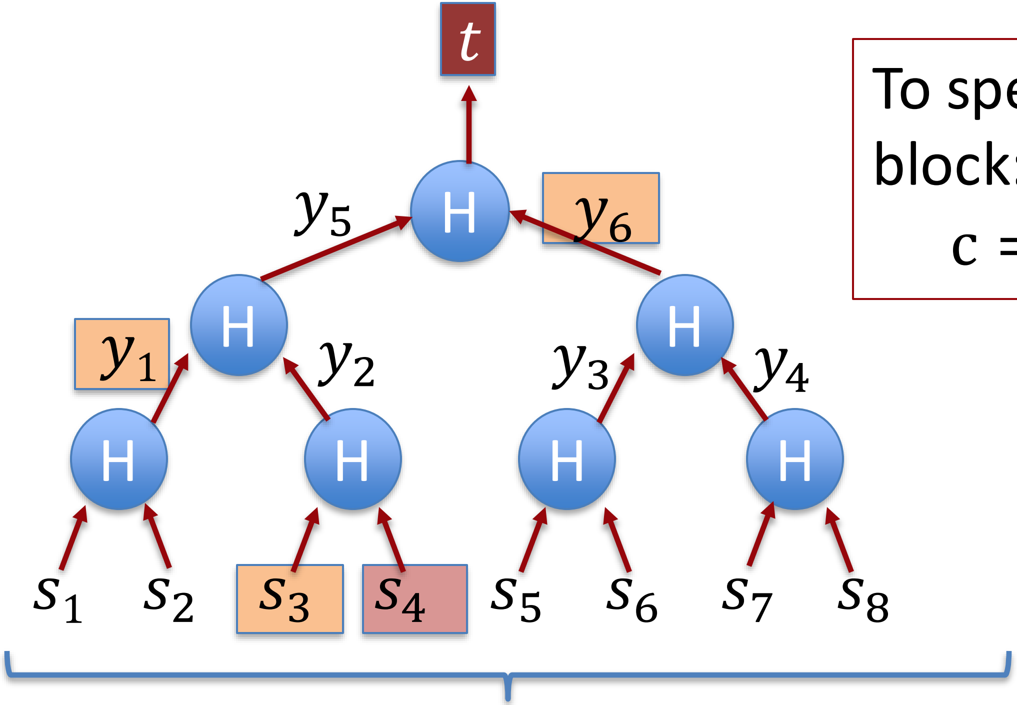
   - Aggregate and threshold signing is easy

B. Some script (similar to P2SH)

   - Can have many script spending conditions

Idea: Can’t distinguish between A or B + don’t need to reveal script until you spend.

Transaction types: (3) P2TR: pay to Taproot



list of (version, script)

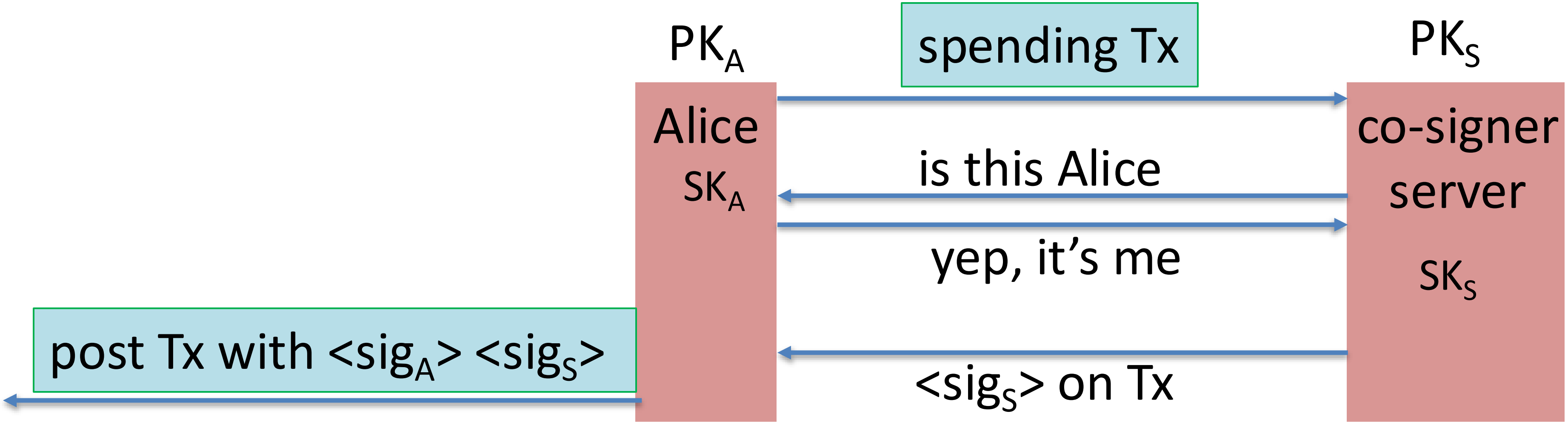
To spend with s_4, provide control block:

$$c = (internal\ pk, s_4, y_1, y_6)$$

Using Bitcoin scripts

Protecting assets with a co-signer

Alice stores her funds in UTXOs for $\mathit{addr} = \textbf{2-of-2}(\mathbf{PK_A}, \mathbf{PK_S})$



$\Rightarrow$ theft of Alice's SK_A does not compromise BTC

Escrow service

Alice wants to buy a backpack for 0.1Ƀ from merchant Bob

Goal: Alice only pays after backpack arrives, but can't not pay

addr = **2-of-3(PK_A, PK_B, PK_J)**

post payment of 0.11Ƀ to *addr*

(creates $UTXO_{ABJ}$)

Alice

PK_A

want backpack for 0.1Ƀ

once see Tx on chain

mail backpack

backpack arrives

send <sig$_A$> on Tx:

$UTXO_{ABJ} \rightarrow (PK_B{:}0.1,\ PK_A{:}0.01)$

Bob

PK_B

redeem using <sig$_A$> <sig$_B$> on Tx

Judge

PK_J

Escrow service: a dispute

(1) Backpack never arrives: (Bob at fault)

Alice gets her funds back with help of Judge and a Tx:

Tx: $(\mathbf{UTXO_{ABJ}} \rightarrow \mathbf{PK_A}\ ,\ \mathbf{sig_A},\ \mathbf{sig_{Judge}})$ [2-out-of-3]

(2) Alice never sends sig_A: (Alice at fault)

Bob gets paid with help of Judge and a Tx:

Tx: $(\mathbf{UTXO_{ABJ}} \rightarrow \mathbf{PK_B}\ ,\ \mathbf{sig_B},\ \mathbf{sig_{Judge}})$ [2-out-of-3]

(3) Both are at fault: Judge publishes $<sig_{Judge}>$ on Tx:

Tx: $(\mathbf{UTXO_{ABJ}} \rightarrow \mathbf{PK_A: 0.05,\ PK_B: 0.05,\ PK_J: 0.01})$

Now either Alice or Bob can execute this Tx.

Cross Chain Atomic Swap

Alice has 5 BTC, Bob has 2 LTC (LiteCoin). They want to swap.

Want a sequence of Tx on the Bitcoin and Litecoin chains s.t.:

- either success: Alice has 2 LTC and Bob has 5 BTX,
- or failure: no funds move.

Swap cannot get stuck halfway.

Goal: design a sequence of Tx to do this.

solution: programming proj #1 ex 4.