Bitcoin Protocol Deep Dive

BSc Blockchain, Crypto Economy & NFTs

Course Instructor

Module A: Blockchain Foundations

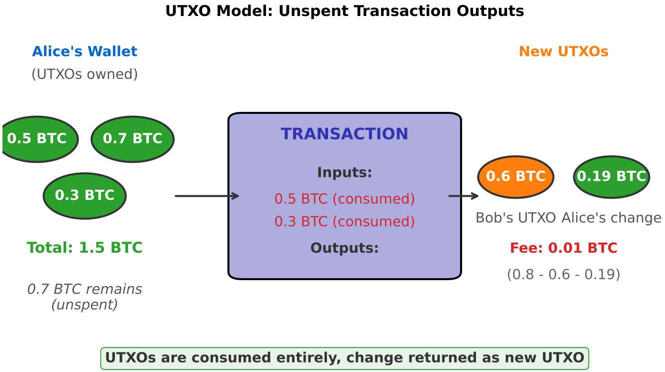
Learning Objectives

By the end of this lesson, you will be able to:

- Explain the UTXO (Unspent Transaction Output) model
- Describe the structure of a Bitcoin transaction
- Understand transaction inputs and outputs
- Recognize different Bitcoin Script types
- Trace the lifecycle of a transaction from creation to confirmation
- Distinguish between legacy and SegWit transaction formats

What is a UTXO?

- Unspent Transaction Output = a chunk of bitcoin that can be spent
- Bitcoin does not track account balances (unlike Ethereum)
- Instead, tracks individual “coins” (UTXOs)



UTXO Properties and Cash Analogy

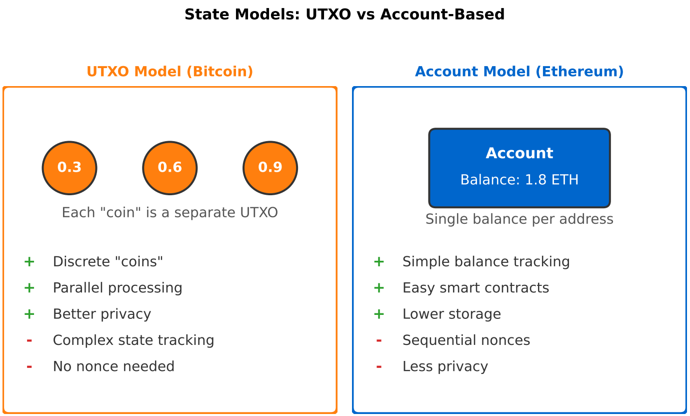
Analogy: Physical Cash

- UTXOs are like bills in your wallet
- You do not have "100 EUR balance" – you have five 20 EUR bills
- To pay 30 EUR: give one 20 EUR bill + one 10 EUR bill
- To pay 25 EUR with a 50 EUR bill: receive 25 EUR change

Key Principles:

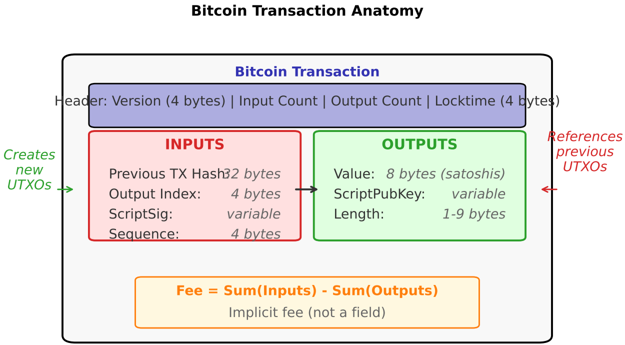
- Each UTXO can only be spent once (consumed entirely)
- Spending a UTXO creates new UTXOs
- Blockchain tracks which UTXOs are unspent
- Your wallet balance = sum of all UTXOs you can spend

UTXO Model vs. Account Model



Why Bitcoin Uses UTXO: Easier to verify (check UTXO existence), no global state needed, natural double-spend prevention.

Bitcoin Transaction Structure



Transaction Hash (txid):

- Double SHA-256 of entire transaction – unique identifier
- Used to reference transaction in inputs

Transaction Inputs

Each Input Contains:

1. **Previous Transaction Hash:** txid of transaction containing UTXO
2. **Output Index:** which output from previous transaction (0, 1, 2, ...)
3. **ScriptSig (Unlocking Script):** provides signature and public key
4. **Sequence Number:** originally for transaction replacement

Example Input:

- Previous tx: `5a3c7b...` (Alice received 3 BTC)
- Output index: 0 (first output of that transaction)
- ScriptSig: signature proving Alice owns the UTXO

Multiple Inputs:

- Transaction can have many inputs (combining UTXOs)
- Each input must be signed separately

Each Output Contains:

1. **Value:** Amount of satoshis (1 BTC = 100,000,000 satoshis)
2. **ScriptPubKey (Locking Script):** conditions to spend this output

Change Outputs:

- When input value ¿ payment amount, create change output
- Change goes back to sender (usually new address for privacy)
- Example: Spend 5 BTC UTXO to send 3 BTC $\rightarrow$ 3 BTC to recipient + 1.999 BTC change

Transaction Fee:

- Fee = Sum of inputs − Sum of outputs
- Not explicitly stated in transaction (implicit)
- Miner collects the difference

Bitcoin Script: A Stack-Based Language

What is Bitcoin Script?

- Simple, stack-based programming language
- Not Turing-complete (no loops, limited expressiveness)
- Executed during transaction validation
- Determines whether transaction is valid

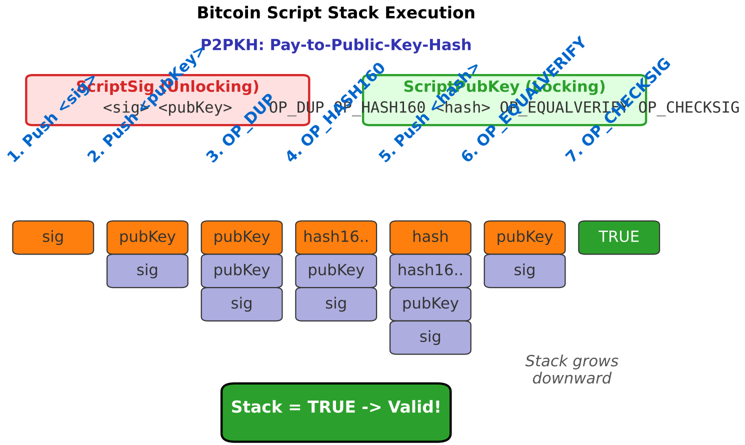
How It Works:

1. Combine ScriptSig (from input) + ScriptPubKey (from previous output)
2. Execute script operations left to right
3. Use a stack (LIFO data structure)
4. Transaction valid if final stack value is TRUE

Basic Operations:

- `OP_DUP`: duplicate top stack item
- `OP_HASH160`: hash with SHA-256 then RIPEMD-160
- `OP_EQUALVERIFY`: check equality, fail if not
- `OP_CHECKSIG`: verify signature against public key

P2PKH Script Execution



Why Public Key Hash? Shorter addresses (20 vs 33 bytes), extra security (quantum resistance until spending).

P2SH: Pay-to-Script-Hash

Purpose:

- Allows complex spending conditions (multi-signature, time-locks)
- Hides complexity until spending time
- Sender only needs recipient's P2SH address

ScriptPubKey:

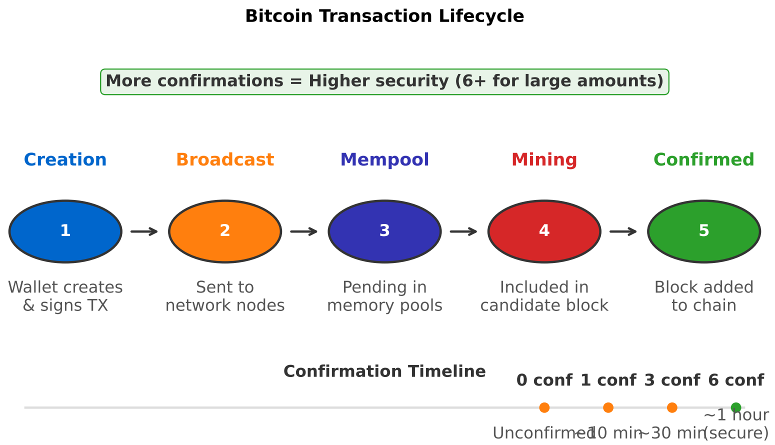
```
OP_HASH160 <ScriptHash> OP_EQUAL
```

ScriptSig:

```
<Signature1> <Signature2> ... <RedeemScript>
```

Verification Process:

1. Hash the redeem script
2. Verify hash matches ScriptHash in ScriptPubKey
3. Execute redeem script with provided signatures
4. Transaction valid if redeem script evaluates to TRUE



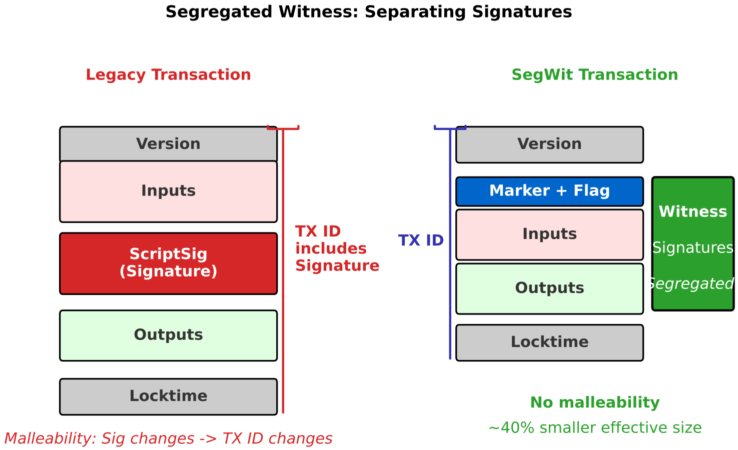
Key Stages:

- Creation → Signing → Broadcast → Mempool → Mining → Confirmation

Transaction Lifecycle: Details

1. **Creation and Signing:**
   - Wallet selects UTXOs, constructs inputs/outputs, calculates fee
   - Signs each input with corresponding private key
2. **Broadcast and Mempool:**
   - Transaction sent to connected nodes, validated, added to mempool
   - Nodes relay to peers (propagation across network)
   - Transactions sorted by fee rate in mempool
3. **Mining and Confirmation:**
   - Miner includes transaction in candidate block
   - Block mined, broadcast, validated by network
   - Each new block adds one confirmation
   - 6 confirmations typically considered final ($\sim$1 hour)

SegWit: Segregated Witness



Problem with Legacy: Signature in TX hash → malleability
SegWit Solution (BIP 141, 2017): Separate witness data from TX ID

SegWit Benefits

Block Capacity Increase:

- Legacy: 1 MB block size limit
- SegWit: measured in "weight units" (max 4 million)
- Witness data: 1 byte = 1 weight unit; Non-witness: 1 byte = 4 weight units
- Effective capacity: ~2-2.7 MB per block

Lower Transaction Fees:

- Witness data discounted by 75%
- Same transaction costs less with SegWit

Address Formats:

- P2WPKH (native SegWit): starts with "bc1q" (Bech32 encoding)
- P2SH-wrapped SegWit: starts with "3" (backward compatible)

Enables Lightning Network: Fixes malleability for secure payment channels

Taproot: SegWit v1 (Activated 2021)

Key Improvements:

- **Schnorr Signatures:** More efficient, enable signature aggregation
- **MAST:** Complex scripts hidden until execution, only reveal used branch
- **Privacy:** All transactions look similar on-chain

Benefits:

- Multi-sig indistinguishable from single-sig
- Complex smart contracts look like simple payments
- Smaller transaction size for complex scripts

Address Format:

- Starts with "bc1p" (Bech32m encoding)
- Example: `bc1p5d7rjq7g6rdk2yhzks9smlaqtedr4dekq08ge8...`

Transaction Validation Rules

Syntax Validation:

- Transaction size within limits
- Output values non-negative, do not exceed input values
- No duplicate inputs (double-spend within transaction)

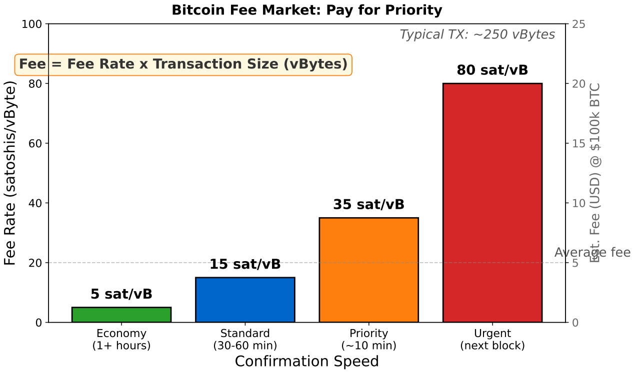
Semantic Validation:

- All referenced UTXOs exist and are unspent
- Signatures valid for all inputs
- Script execution succeeds for all inputs
- Locktime constraints satisfied

Rejection Reasons:

- Invalid signature $\rightarrow$ likely fraud attempt
- Double-spend $\rightarrow$ UTXO already spent
- Dust output $\rightarrow$ output value too small (spam prevention)

Transaction Fees: Economics



Fee Market Dynamics:

- Block space is scarce (∼4 MB weight per 10 minutes)
- Users compete for inclusion via fees
- Fee estimation based on mempool state and target confirmation time

Replace-by-Fee (RBF) and CPFP

RBF (BIP 125):

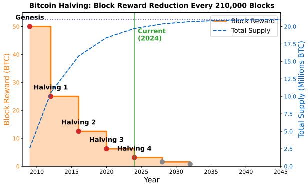
- Create replacement transaction with same inputs
- Increase fee by at least 1 satoshi per byte
- Signal RBF by setting sequence number ¡ 0xfffffffe
- Use cases: fee bump, output modification, cancel transaction

Child-Pays-for-Parent (CPFP):

- Recipient creates high-fee transaction spending unconfirmed output
- Miners must include parent to mine child
- Combined fee rate makes both transactions attractive

Comparison:

- RBF: sender bumps fee (requires signaling)
- CPFP: receiver bumps fee (works for any transaction)



Coinbase Properties:

- First transaction in every block, creates new bitcoins
- Miner collects block reward + all transaction fees
- Must wait 100 confirmations before spending (maturity rule)

2024 Milestone: Bitcoin ETFs and Institutional Adoption

January 10, 2024: Spot Bitcoin ETF Approval

- SEC approved 11 spot Bitcoin ETFs (first time in US)
- Major issuers: BlackRock (IBIT), Fidelity (FBTC), Grayscale (GBTC)
- Accumulated $50B+ in assets under management by end of 2024

Market Impact:

- Institutional legitimization of Bitcoin as asset class
- Daily trading volume rivals major commodity ETFs
- Custody handled by regulated institutions

Transaction Implications:

- ETF creation/redemption uses large on-chain transactions
- Institutional custody drives UTXO consolidation
- Increased demand for block space during high activity

Key Takeaways

- Bitcoin uses the UTXO model: transactions consume old outputs and create new ones
- Each transaction has inputs (UTXOs being spent) and outputs (new UTXOs)
- Bitcoin Script enables flexible spending conditions without Turing completeness
- P2PKH (legacy), P2SH (multi-sig), SegWit, and Taproot offer increasing efficiency
- Transaction lifecycle: creation → signing → broadcast → mempool → mining → confirmation
- Fees determined by market competition for block space
- SegWit and Taproot improve scalability and privacy

Design Philosophy: Bitcoin prioritizes security and decentralization over transaction throughput.

Discussion Questions

1. Why does Bitcoin use the UTXO model instead of the account model?
2. How does the fee market incentivize miners to include transactions?
3. What are the trade-offs between legacy addresses, SegWit, and Taproot?
4. How does transaction malleability affect second-layer solutions?
5. Why is the coinbase maturity rule (100 confirmations) necessary?
6. How could you design a transaction that can only be spent after a certain date?

Next Lesson Preview: L07 Proof of Work Consensus

Topics to be covered:

- Mining mechanics and the proof-of-work algorithm
- Nonce searching and difficulty adjustment
- Block header structure and hash rate
- 51% attacks and mining centralization risks
- Energy consumption and environmental concerns

Preparation:

- Review hash function properties (pre-image resistance)
- Explore Bitcoin mining pools and hash rate distribution
- Consider the economics of mining profitability