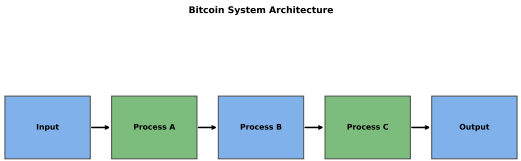
Lesson 18: Bitcoin Architecture

Module 2: Blockchain Fundamentals

Digital Finance

Bitcoin System Overview



Core Components:

- **P2P Network:** Decentralized node communication
- **Blockchain:** Immutable ledger of transactions
- **UTXO Model:** Unspent transaction outputs (like digital cash)
- **Script System:** Programmable transaction validation

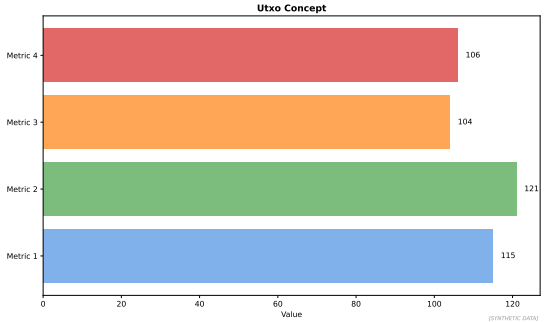
UTXO Model: Digital Cash Analogy

Physical Cash:

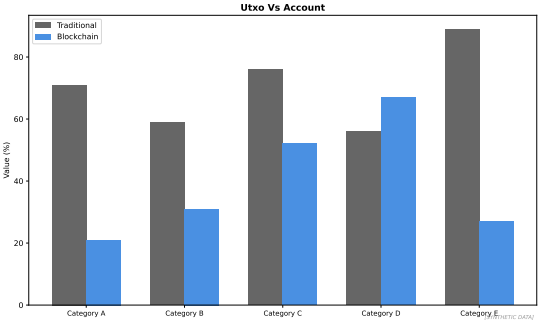
- Discrete bills and coins
- Cannot split a $20 bill
- Give exact amount or get change
- Destroyed when spent

UTXO Model:

- Discrete chunks of bitcoin
- Cannot partially spend UTXO
- Consume entirely, create change UTXO
- Marked as spent, new UTXO created



UTXO vs Account Model



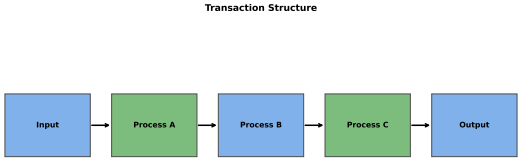
UTXO (Bitcoin):

- Stateless
- Better privacy (addresses change)
- Parallel transaction validation
- No account balances

Account (Ethereum):

- Stateful (balance stored)
- Simple mental model
- Sequential nonces
- Easier for smart contracts

Transaction Structure: Inputs and Outputs



Components:

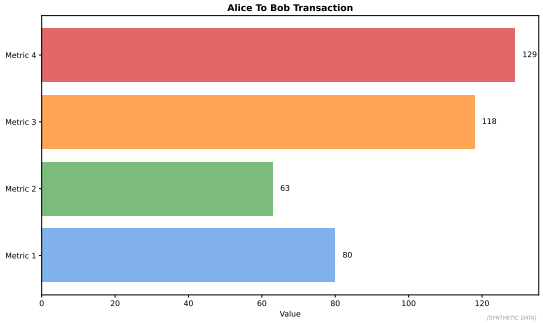
- **Inputs:** References to previous UTXOs (txid + output index) + signature
- **Outputs:** New UTXOs with amounts and locking scripts
- **Fee:** Sum(inputs) – Sum(outputs)

Example Transaction: Alice Pays Bob

Scenario: Alice has 0.5 BTC UTXO, wants to pay Bob 0.3 BTC

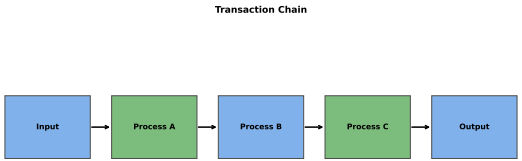
Transaction:

- **Input:** Alice's 0.5 BTC UTXO + Alice's signature
- **Output 1:** 0.3 BTC to Bob's address
- **Output 2:** 0.19 BTC change to Alice's new address
- **Fee:** 0.01 BTC (0.5 – 0.3 – 0.19)



Result: Alice's UTXO consumed, two new UTXOs created

Transaction Chaining



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Key Properties:

- Each transaction references previous outputs
- Creates directed acyclic graph (DAG)
- Double-spending prevented by UTXO tracking
- Validation traces back to coinbase transactions

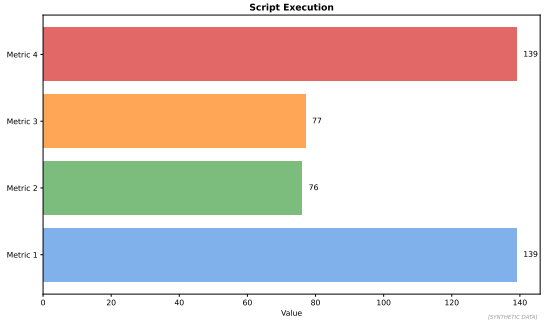
Bitcoin Script: Programmable Conditions

What is Script?

- Stack-based language
- Turing-incomplete (no loops)
- Defines spending conditions
- Executed by all nodes

Script Types:

- Pay-to-Public-Key-Hash (P2PKH)
- Pay-to-Script-Hash (P2SH)
- Pay-to-Witness-Public-Key-Hash (P2WPKH)
- Multisig



P2PKH: Standard Bitcoin Transaction

Locking Script (scriptPubKey):

```
OP_DUP OP_HASH160 <PubKeyHash> OP_EQUALVERIFY OP_CHECKSIG
```

Unlocking Script (scriptSig):

```
<Signature> <PublicKey>
```

Execution:

1. Push signature and public key to stack
2. Duplicate public key
3. Hash duplicated public key
4. Compare hash to stored hash (EQUALVERIFY)
5. Verify signature with public key (CHECKSIG)
6. Success if top of stack is TRUE

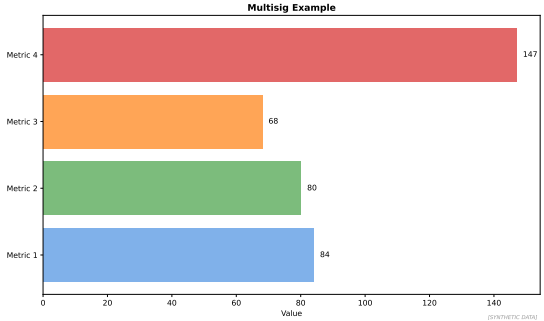
Multisig: M-of-N Signatures

Use Case:

- Shared custody
- Corporate accounts
- Escrow services
- Enhanced security

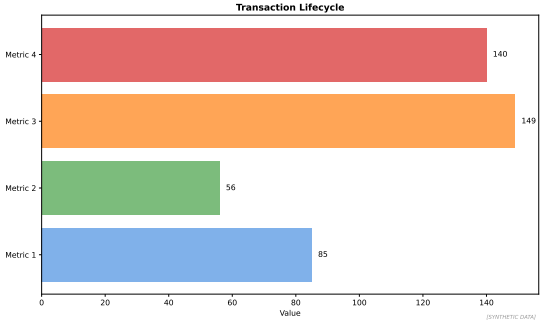
Example (2-of-3):

- 3 public keys
- Require any 2 signatures
- Escrow: buyer, seller, arbiter



Script: `OP_2 <PubKey1> <PubKey2> <PubKey3> OP_3 OP_CHECKMULTISIG`

Transaction Lifecycle



Stages:

1. **Creation:** User signs transaction
2. **Broadcast:** Sent to P2P network
3. **Mempool:** Unconfirmed transactions pool
4. **Mining:** Miner includes in block
5. **Confirmation:** Block added to chain
6. **Finality:** 6+ confirmations ($\sim$1 hour)

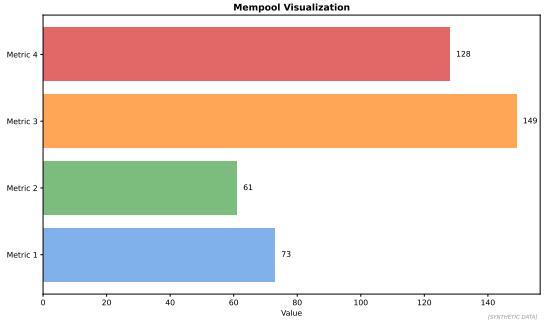
Mempool: Waiting Room for Transactions

Properties:

- Unconfirmed transactions
- Not consensus-critical (each node maintains own)
- Size varies by network congestion
- Transactions ranked by fee rate

Fee Market:

- Higher fee = faster inclusion
- Fee rate: satoshis per byte (sat/vB)
- Dynamic pricing based on demand



Transaction Fees: Mechanics

Fee Calculation:

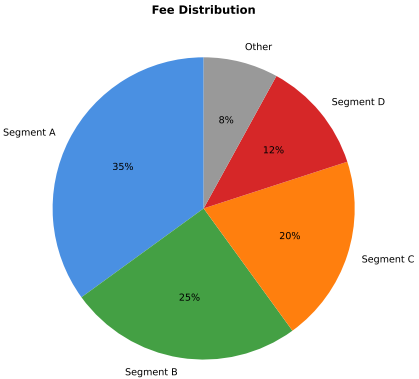
$$\text{Fee} = \sum \text{Inputs} - \sum \text{Outputs}$$

Fee Rate:

$$\text{Fee Rate} = \frac{\text{Fee}}{\text{Transaction Size (vB)}}$$

Example:

- Transaction size: 250 vB
- Target: 50 sat/vB
- Fee: $250 \times 50 = 12,500$ sat $= 0.000125$ BTC



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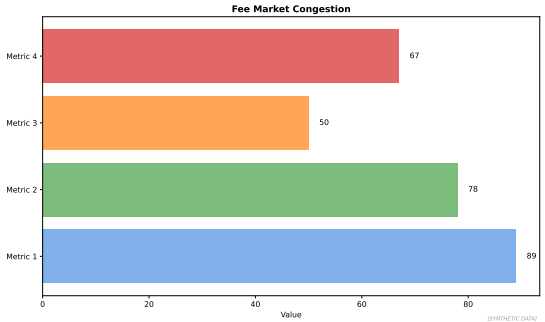
Fee Dynamics During Congestion



High Demand Periods:

- 2017 Bull Run: Fees >$50 per transaction
- 2021 NFT Craze: Ordinals inscriptions clog network
- 2024: Runes protocol launch, fees spike to >1000 sat/vB
- Replace-By-Fee (RBF) and Child-Pays-For-Parent (CPFP) for fee bumping

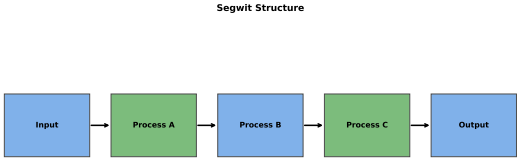
SegWit: Segregated Witness (2017)

Problem:

- Block size limit: 1 MB
- Signature data takes 60–70% of transaction
- Scalability bottleneck
- Transaction malleability

Solution:

- Separate signature data (witness)
- Witness data not counted toward 1 MB limit
- Effective block size: ∼2–2.5 MB
- Fixes malleability



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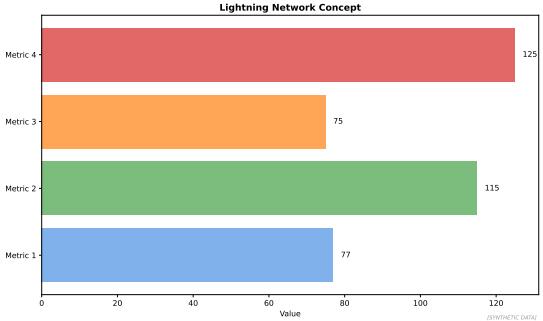
Lightning Network: Layer 2 Scaling



Problem: Bitcoin throughput $\sim$7 tx/s, expensive fees, slow confirmations

Solution: Off-chain payment channels, only settle on-chain when closing

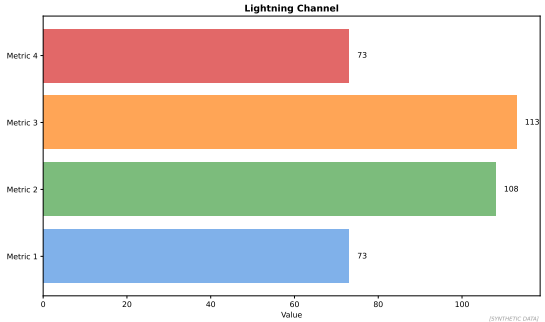
Lightning Payment Channel Mechanics

Opening Channel:

1. Alice and Bob create 2-of-2 multisig
2. Deposit funds (funding transaction)
3. On-chain confirmation

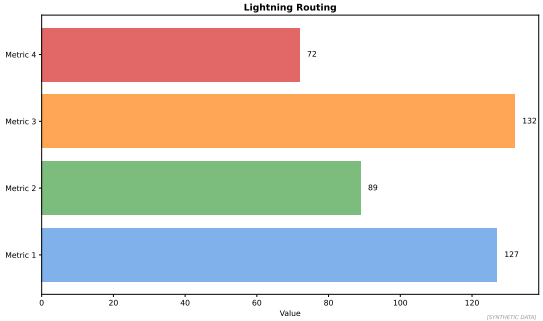
Off-Chain Payments:

- Exchange signed commitment transactions
- Update balances instantly
- No on-chain transactions
- Unlimited throughput



Closing Channel: Broadcast final state to blockchain

Lightning Network Routing



Multi-Hop Payments:

- Alice wants to pay Dave, no direct channel
- Route: Alice $\rightarrow$ Bob $\rightarrow$ Carol $\rightarrow$ Dave
- Hash Time-Locked Contracts (HTLCs) ensure atomicity
- Routing fees: $\sim$1 satoshi per hop

Lightning vs On-Chain Comparison

Aspect	On-Chain (Layer 1)	Lightning (Layer 2)
Speed	10 min average	Instant (milliseconds)
Throughput	$\sim$7 tx/s	Millions of tx/s
Fees	\$1–\$50 (variable)	$<$\$0.01
Finality	6 confirmations (1 hour)	Instant (with channel counterparty)
Trust	Fully trustless	Counterparty risk (can close unilaterally)
Use Case	Large settlements, savings	Micropayments, retail

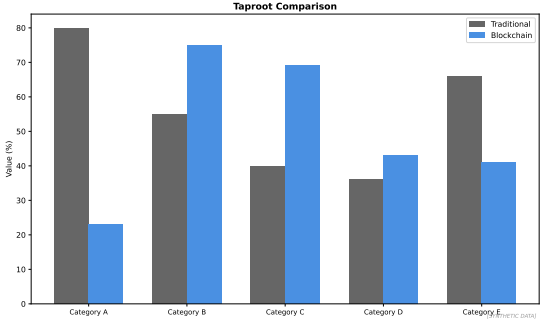
Taproot Upgrade (2021)

Improvements:

- Schnorr signatures (batch verification)
- MAST (Merklized Alternative Script Trees)
- Enhanced privacy (multisig looks like single-sig)
- More efficient smart contracts

Benefits:

- Lower fees for complex scripts
- Better privacy
- Enables new use cases (DLCs, multi-party protocols)



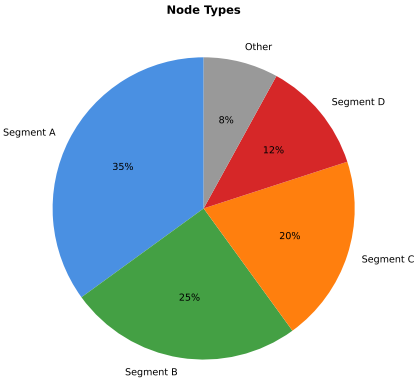
Bitcoin Full Node

Responsibilities:

- Download entire blockchain
- Validate all transactions
- Relay transactions and blocks
- Enforce consensus rules

Requirements (2024):

- Disk: ∼600 GB (growing ∼50 GB/year)
- Bandwidth: ∼500 GB/month
- RAM: 4+ GB
- CPU: Modest (validation not mining)



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Summary

- **UTXO Model:** Discrete outputs, like digital cash, stateless validation
- **Transactions:** Inputs (previous UTXOs) + Outputs (new UTXOs) + Fee
- **Script:** Stack-based language defines spending conditions (P2PKH, multisig)
- **Mempool:** Unconfirmed transactions, fee market determines priority
- **SegWit:** Separated witness data, increased capacity, fixed malleability
- **Lightning:** Layer 2, instant payments, millions tx/s, minimal fees

Next Lesson: Ethereum and Smart Contracts – from currency to computation