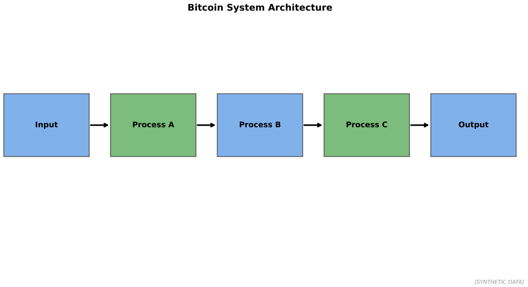
# Lesson 18: Bitcoin Architecture

## 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

**Bitcoin remains the largest cryptocurrency by market cap and network security.**

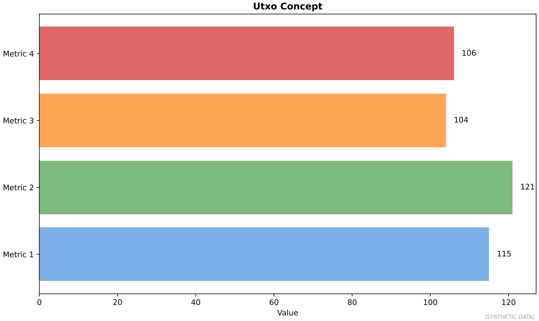
# UTXO Model: Digital Cash Analogy

**Physical Cash:**

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

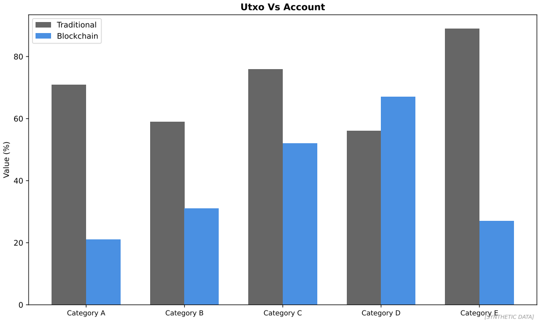
**UTXO Model:**

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



**Key concepts from this slide inform practical applications in finance.**

# UTXO vs Account Model



**UTXO (Bitcoin):**

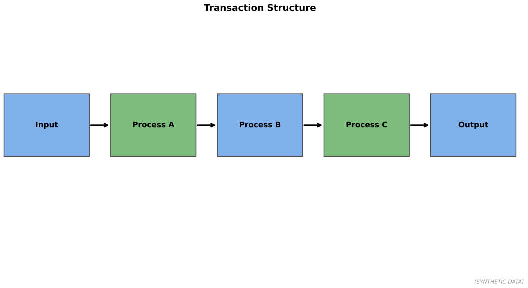
- Stateless
- Better privacy (addresses change)
- Parallel transaction validation
- No account balances

**Account (Ethereum):**

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

**Comparative analysis helps identify the right tool for specific requirements.**

# 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)

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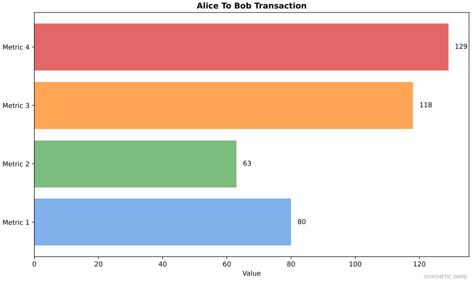
# Example Transaction: Alice Pays Bob

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

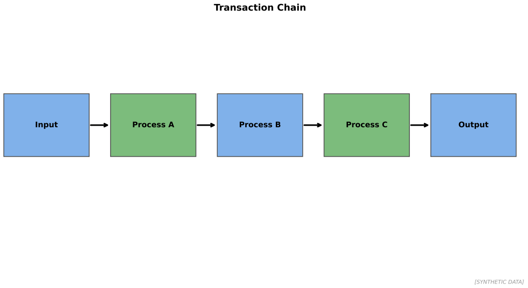
**Transaction:**

- **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)



**UTXO model: Alice's UTXO consumed, new UTXOs created for Bob and change.**

# Transaction Chaining



**Key Properties:**

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

**AI and ML are transforming financial services through automation and prediction.**

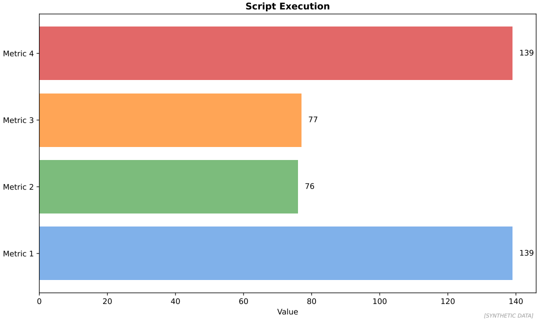
# Bitcoin Script: Programmable Conditions

**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



**Bitcoin remains the largest cryptocurrency by market cap and network security.**

# 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

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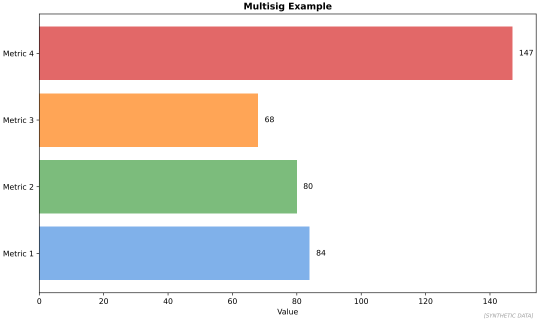
# Multisig: M-of-N Signatures

**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`

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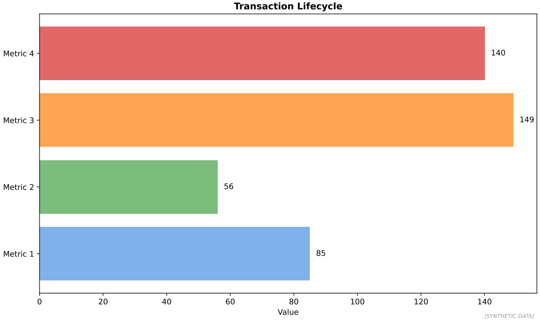
# Transaction Lifecycle



**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 (∼1 hour)

**Technology adoption follows predictable patterns—timing matters for investment decisions.**

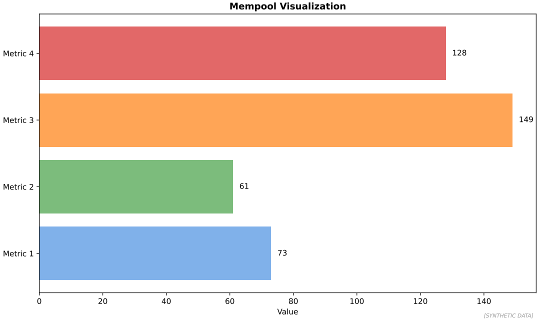
# Mempool: Waiting Room for Transactions

**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



**AI and ML are transforming financial services through automation and prediction.**

# Transaction Fees: Mechanics

**Fee Calculation:**

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

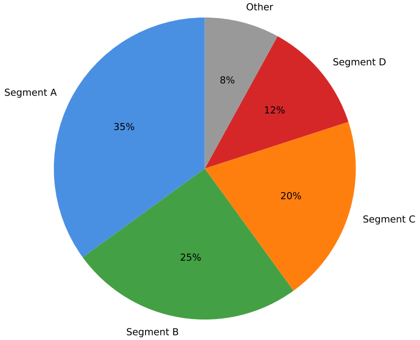
**Fee Rate:**

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

**Example:**

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

**Fee Distribution**



[SYNTHETIC DATA]

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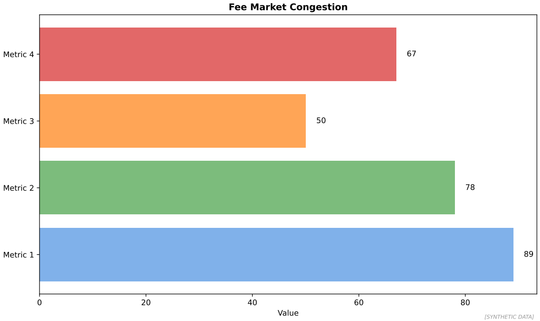
# Fee Dynamics During Congestion



**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

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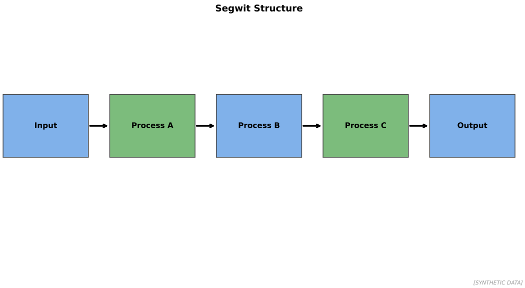
# SegWit: Segregated Witness (2017)

**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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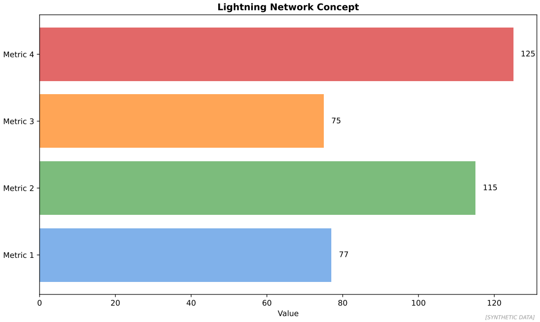
# Lightning Network: Layer 2 Scaling



**Problem:** Bitcoin throughput ∼7 tx/s, expensive fees, slow confirmations

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

**Network metrics provide objective measures of adoption and ecosystem health.**

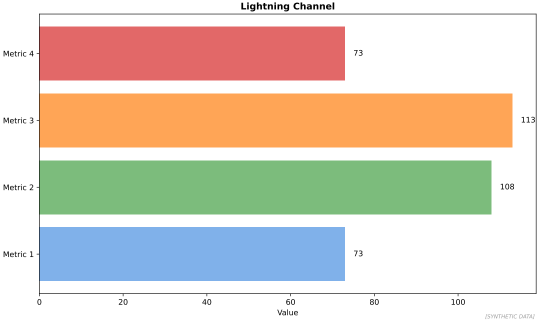
# Lightning Payment Channel Mechanics

**Opening Channel:**

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

**Off-Chain Payments:**

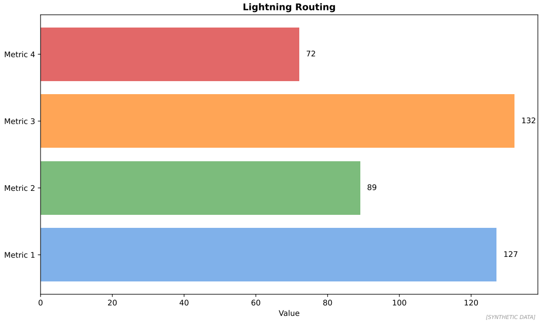
- Exchange signed commitment transactions
- Update balances instantly
- No on-chain transactions
- Unlimited throughput



**Closing Channel:** Broadcast final state to blockchain

**Payment systems are critical infrastructure for economic activity.**

# Lightning Network Routing



**Multi-Hop Payments:**

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

**Network metrics provide objective measures of adoption and ecosystem health.**

# 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 |

**Comparative analysis helps identify the right tool for specific requirements.**

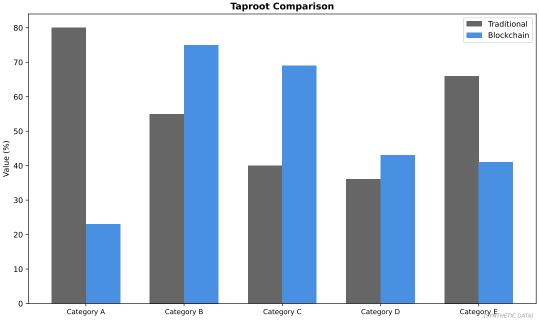
# Taproot Upgrade (2021)

**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)



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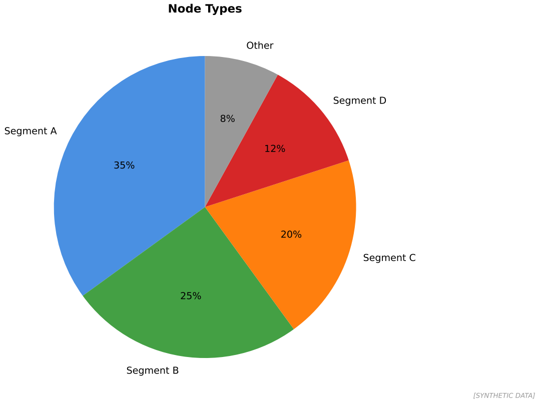
# Bitcoin Full Node

**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