Blockchain System Design Overview

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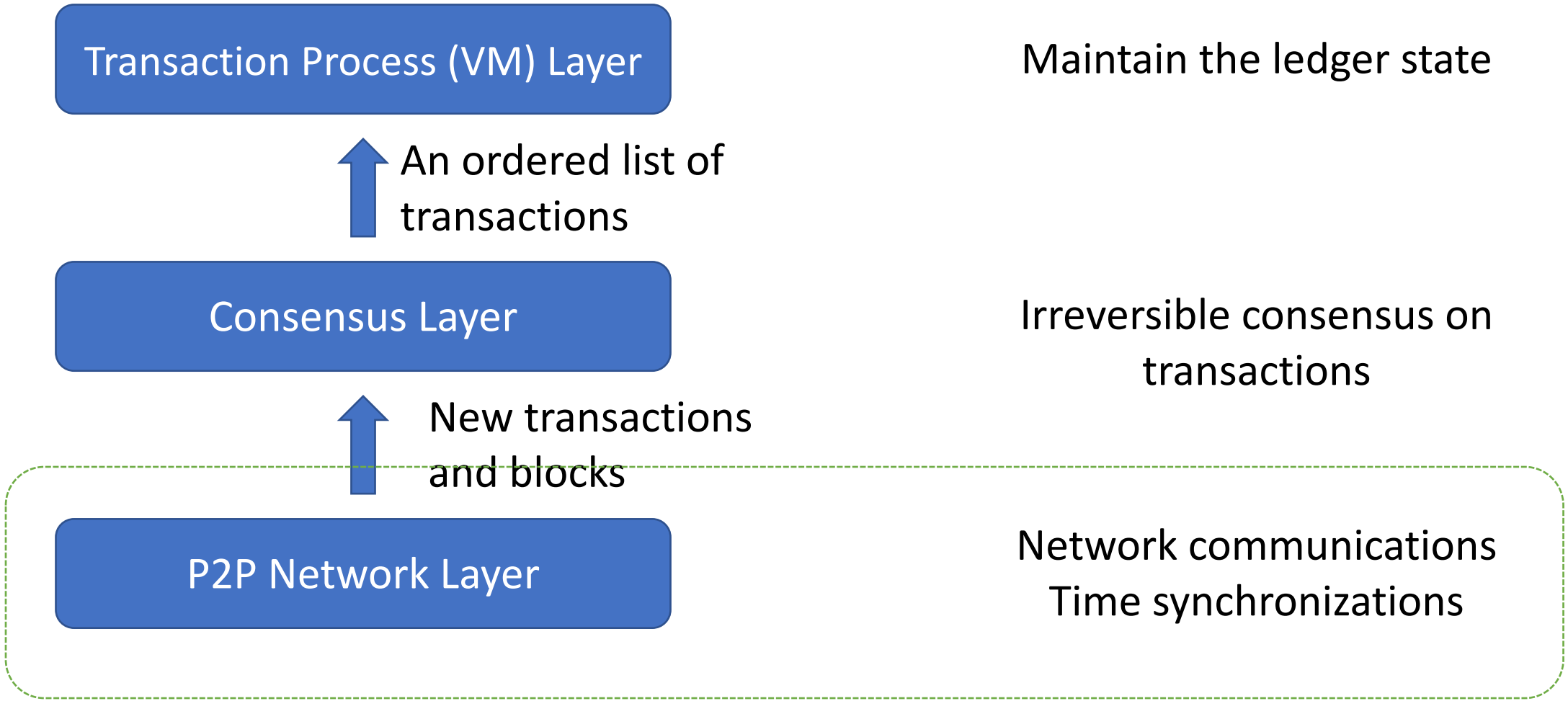
Components in Blockchain Systems

- Let’s think about what a blockchain system must do
- Propagate transaction and block information → **P2P Network**
- Determine transaction orders → **Distributed Consensus**
  - Proof-of-Work and Mining
  - Stop double spending!
- Process transactions → **Virtual Machine**

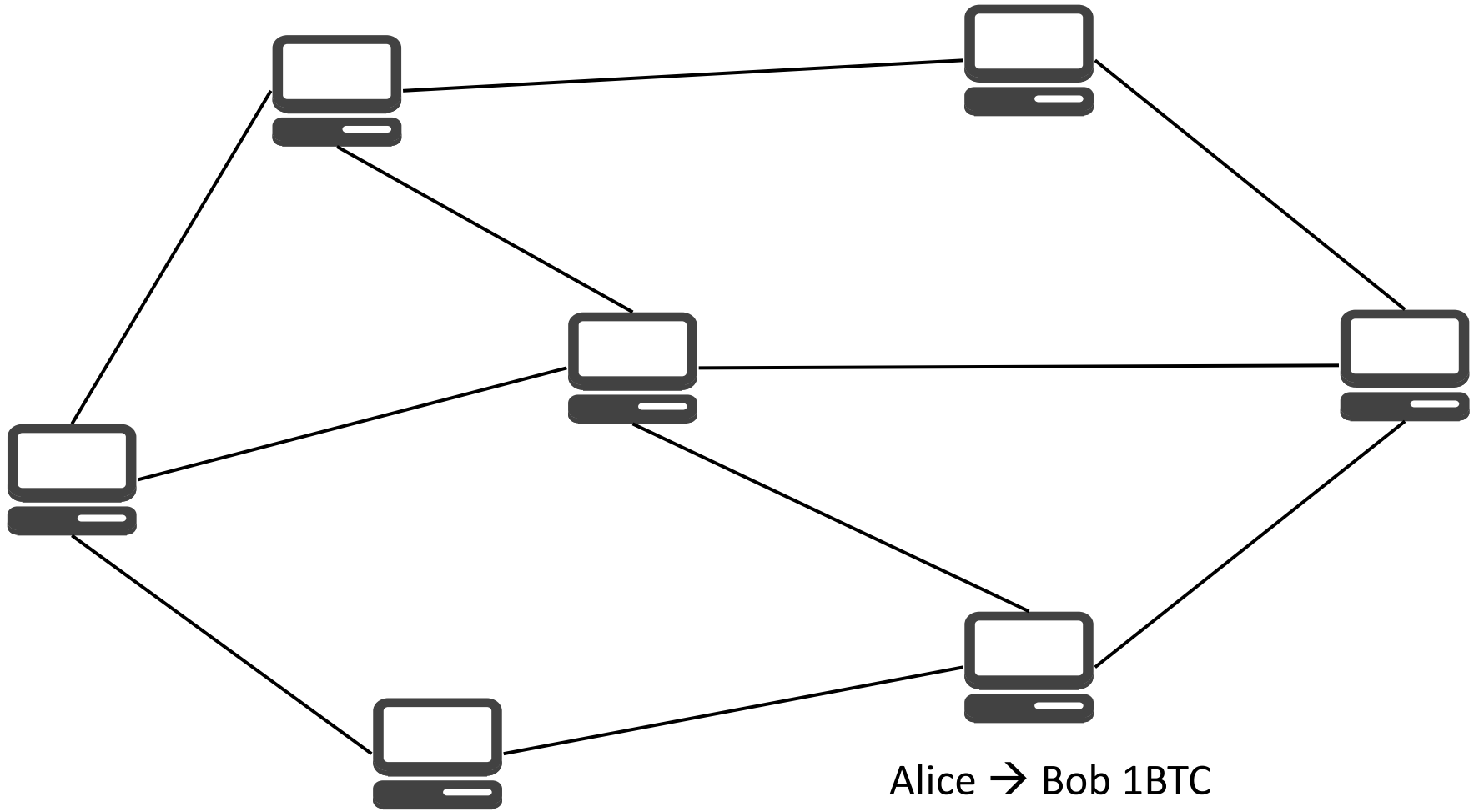
Layers in Blockchain Systems



P2P Network in Blockchain

- Each node connects to a number of peers
  - 32 peers in Bitcoin
- Nodes relay transactions and blocks to all peers recursively
  - Gossip around information
  - Therefore P2P Network is also called Gossip Network
- New nodes can join and leave the network at any time

P2P Network in Blockchain



Alice → Bob 1BTC

Hey peers, I got a new transaction with id XXX

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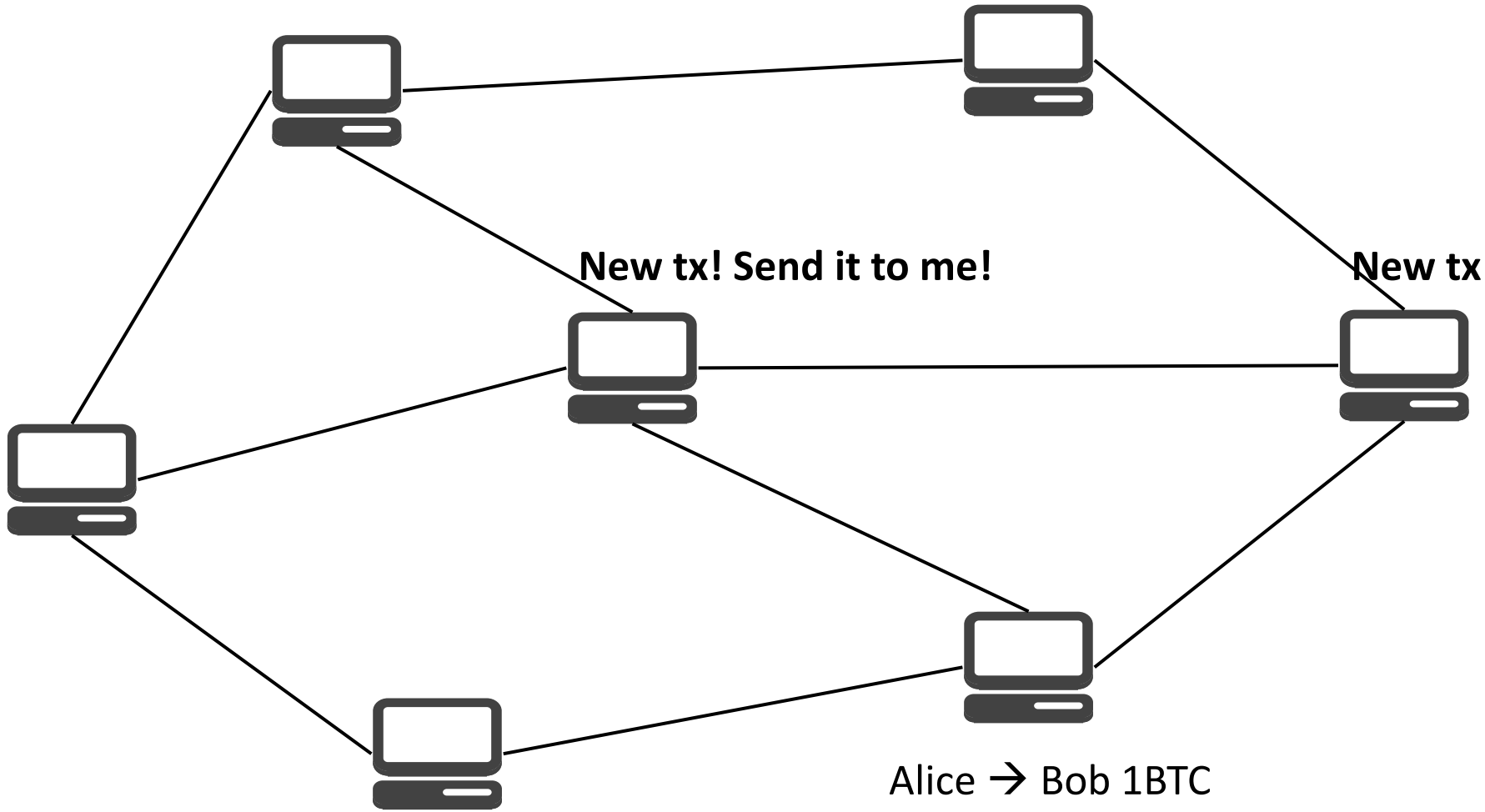

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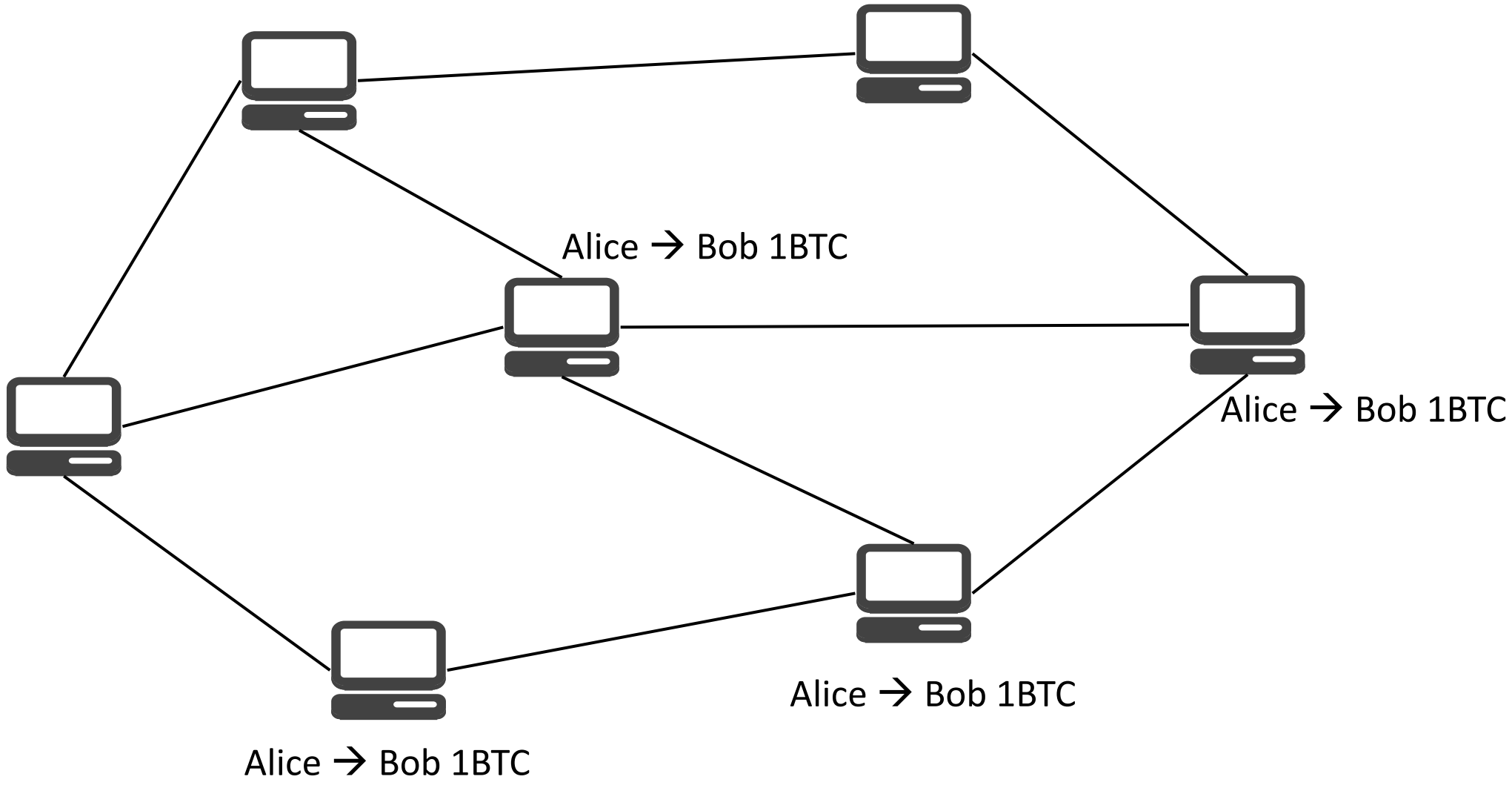

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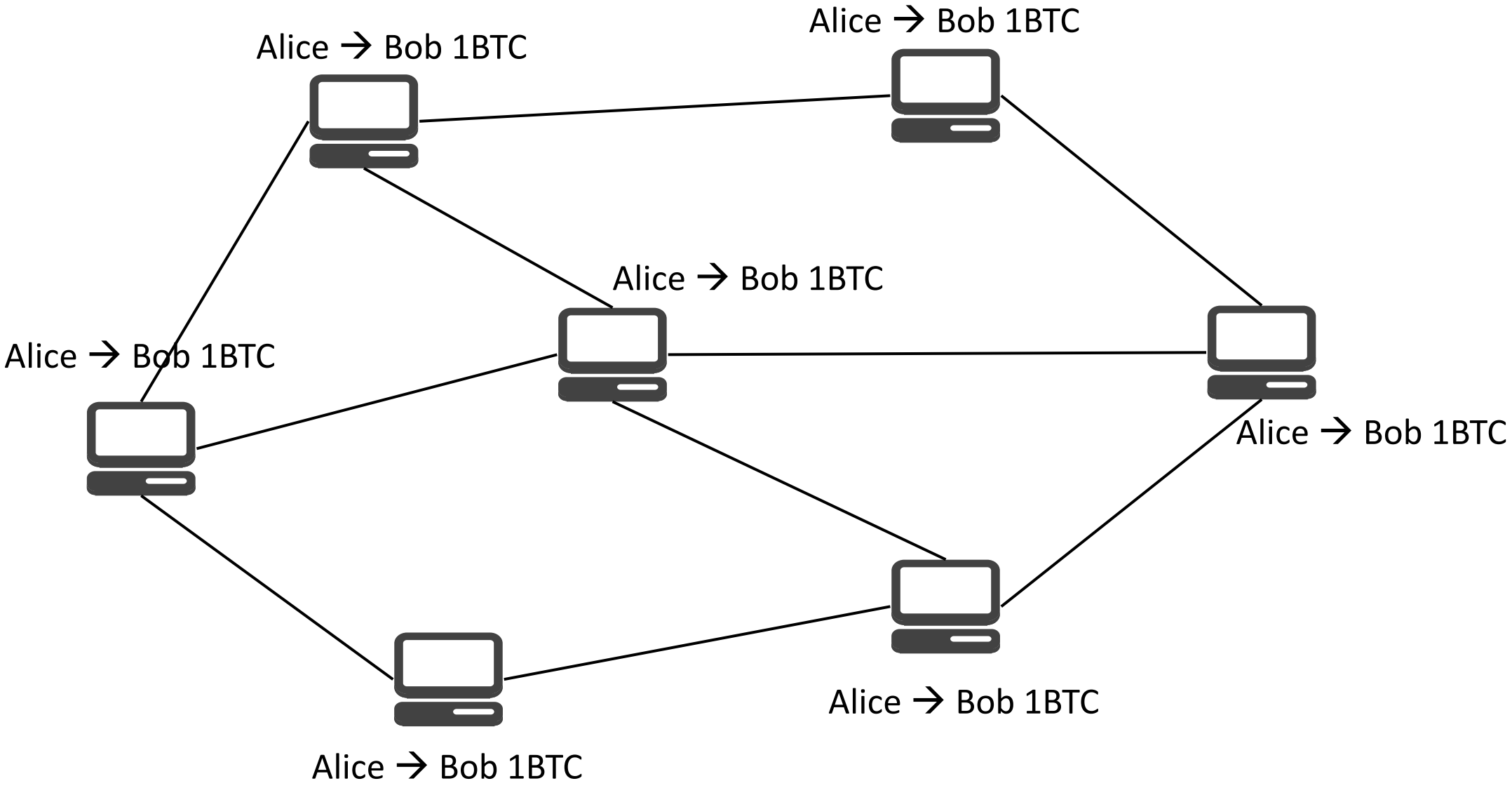

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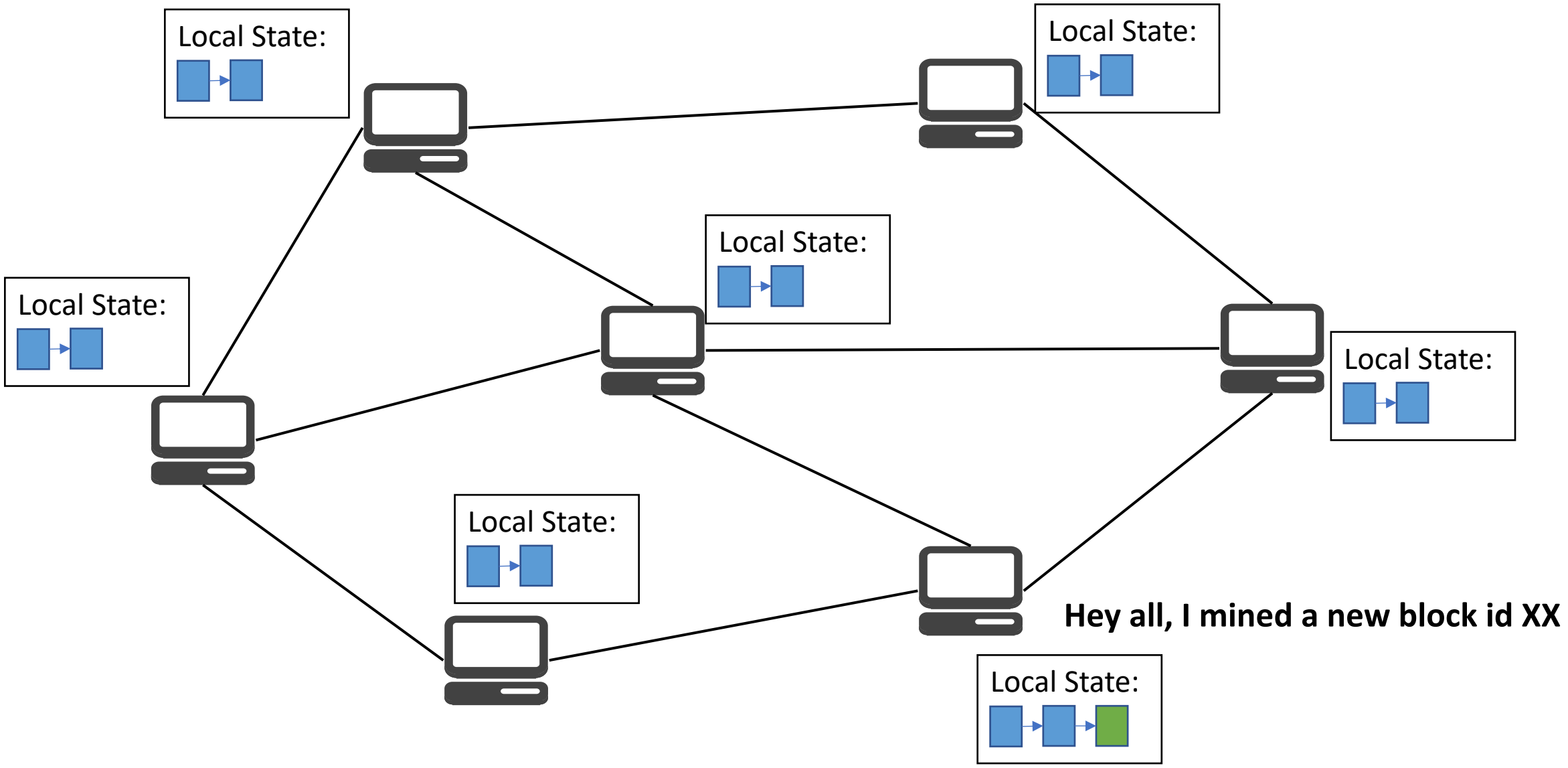

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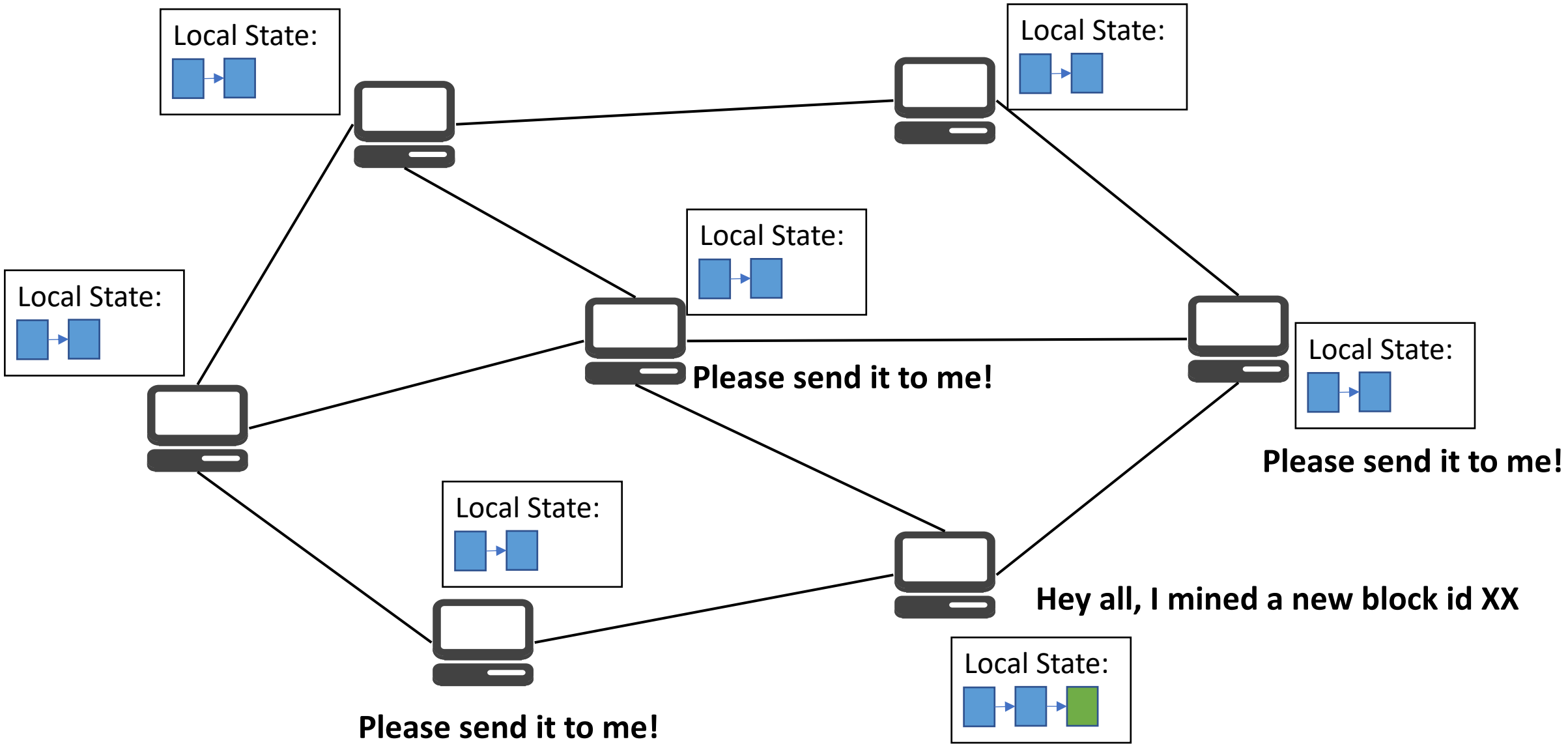

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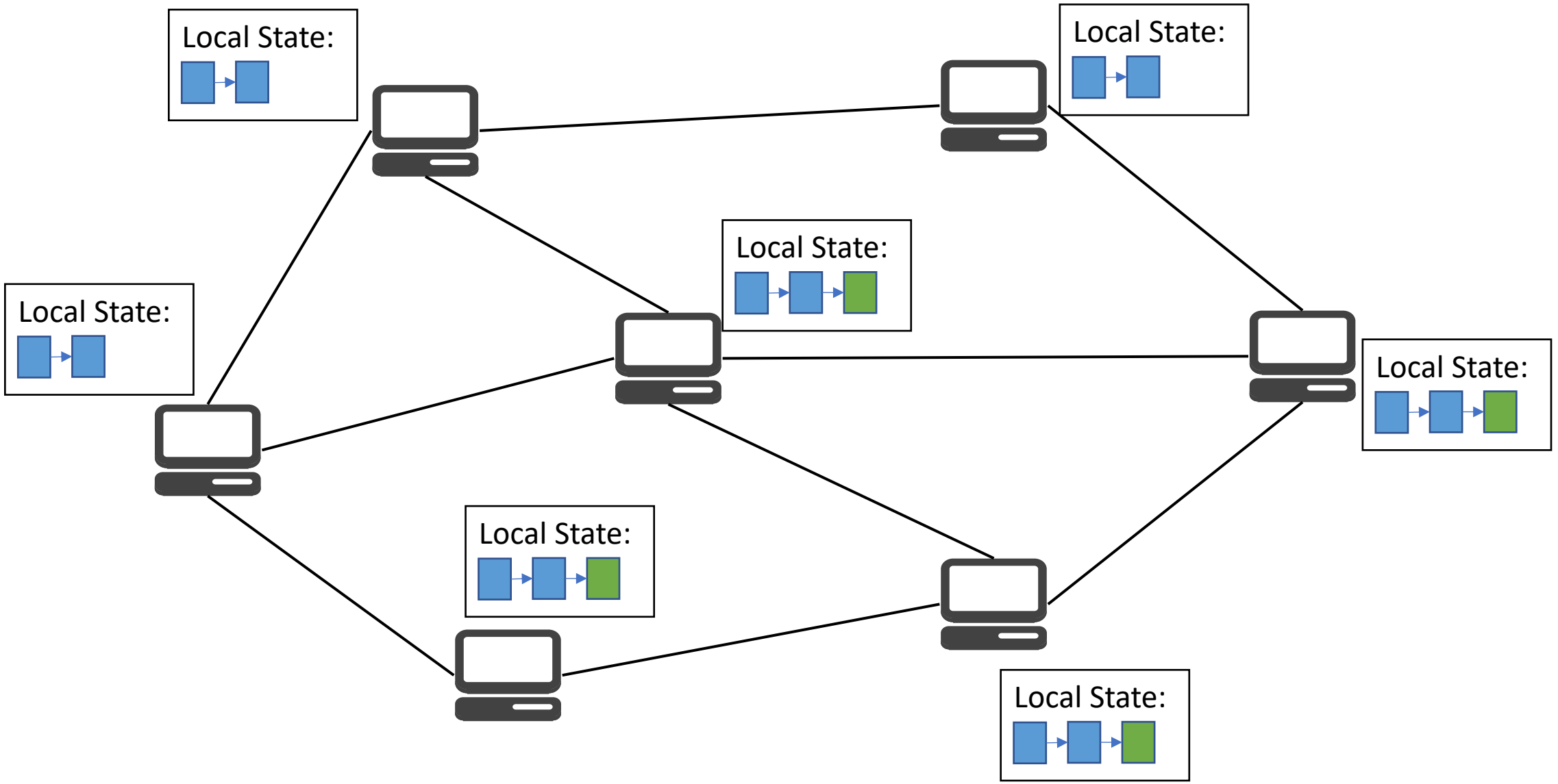

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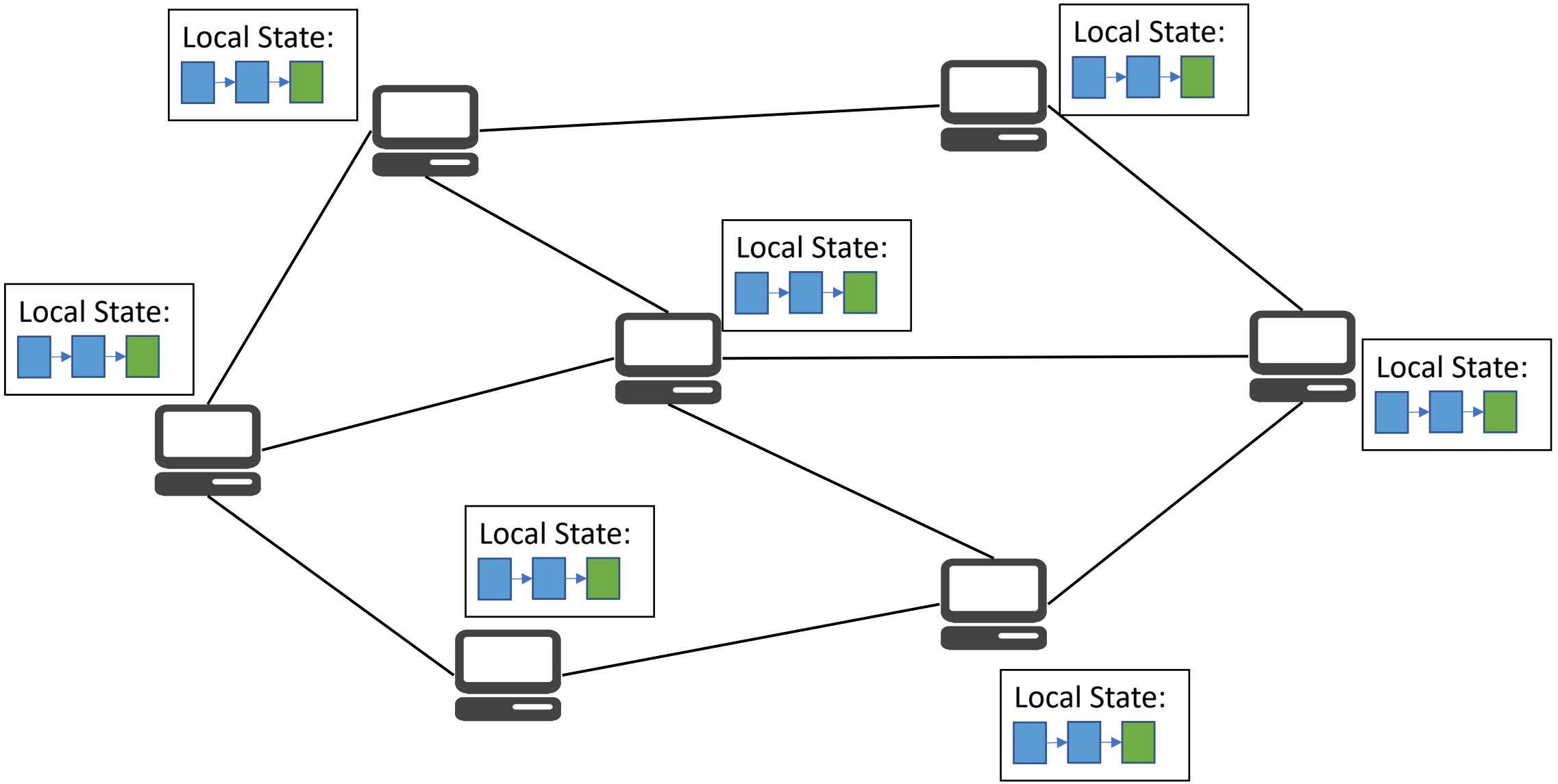
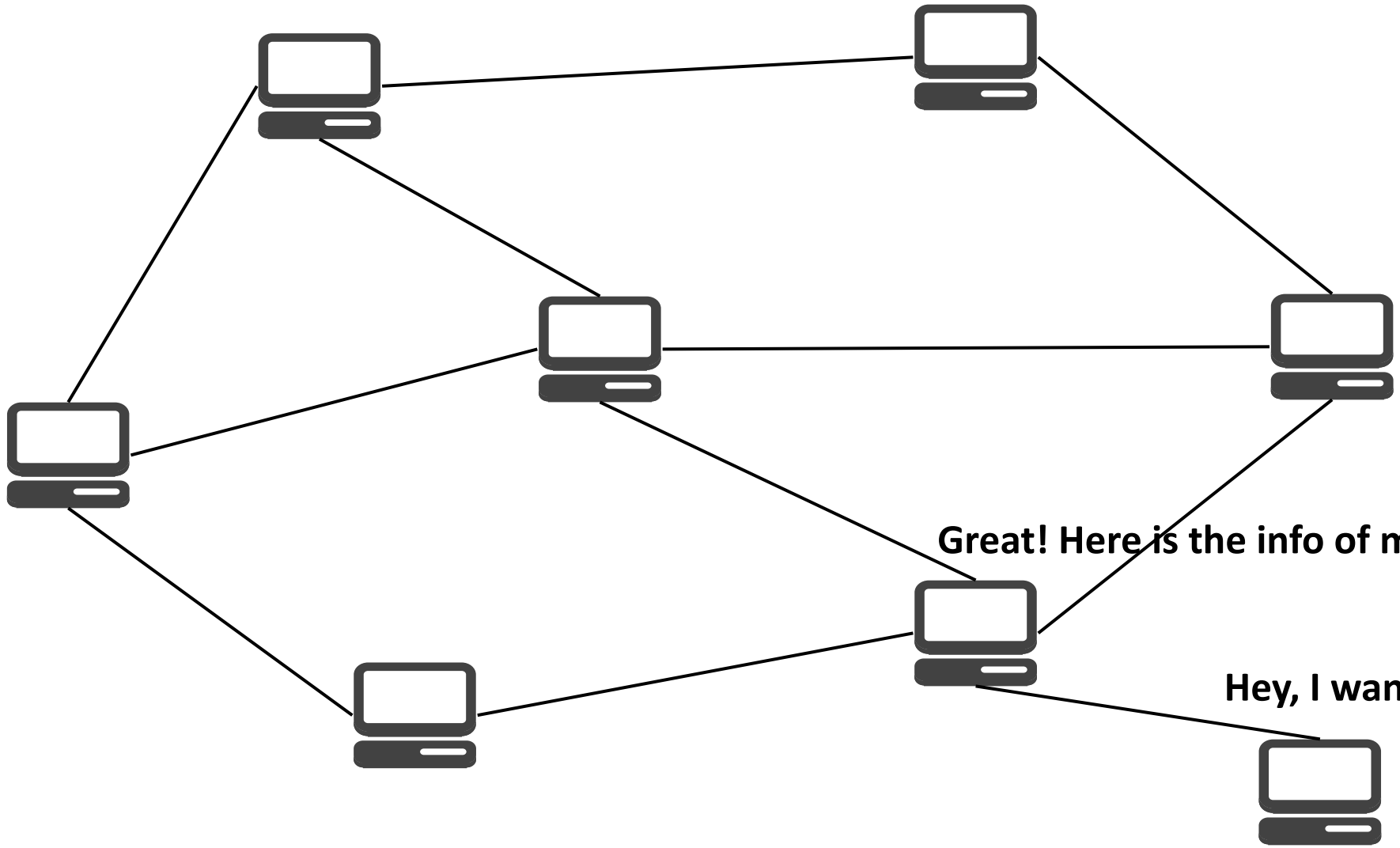


New Node Join



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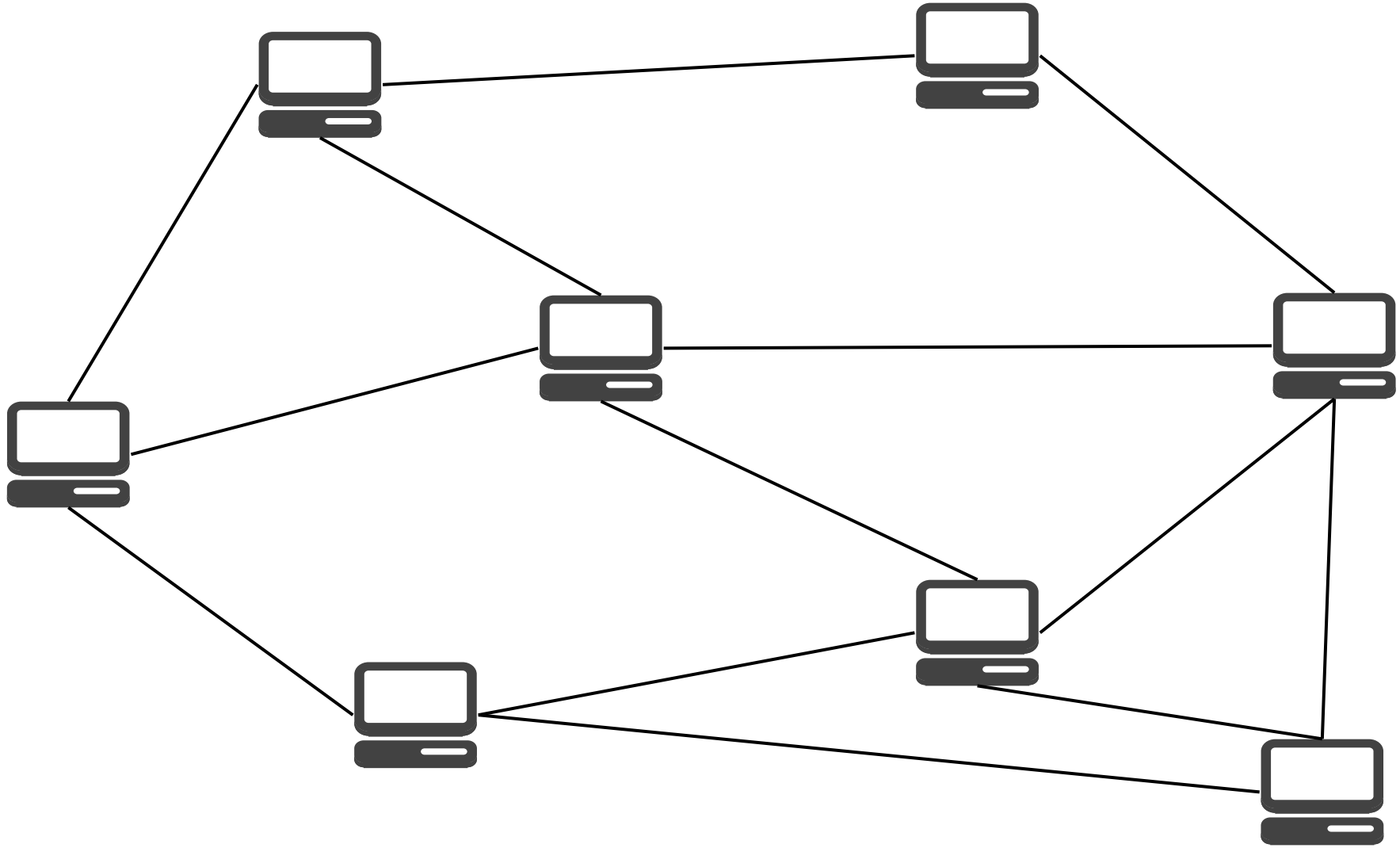


Defense against DoS Attacks

- Attackers send excessive amount of messages to flood the Network

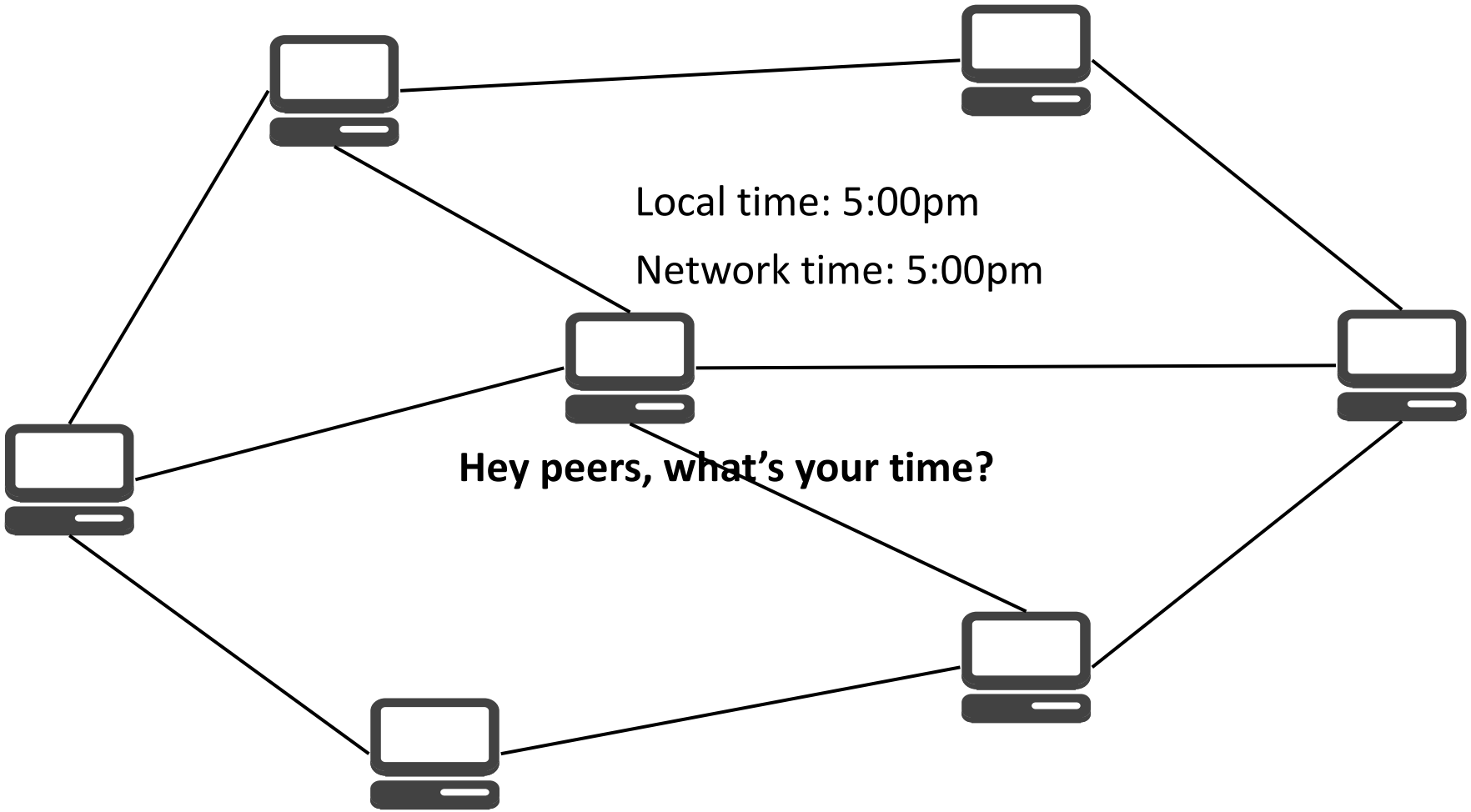
- Check validity of transactions / blocks before relaying
- Do not relay duplicate transactions / blocks
  - Remember hash ids of existing blocks and all pending transactions
  - Check whether a block/transaction id is duplicate
- Drop peers that constantly send invalid / duplicate messages

Network Adjusted Timestamp

- **Problem**: How to obtain a synchronized time in Blockchain
  - Timestamp each block/transaction
  - Adjust PoW difficulty based on timestamp (will talk about later)

- **A Solution**: Rely on centralized time service (e.g., time.apple.com)
- **Bitcoin Solution**: Use P2P Network to synchronize time between nodes
  - No single point of failure
  - Remain working even if centralized time service is down

Network Adjusted Time



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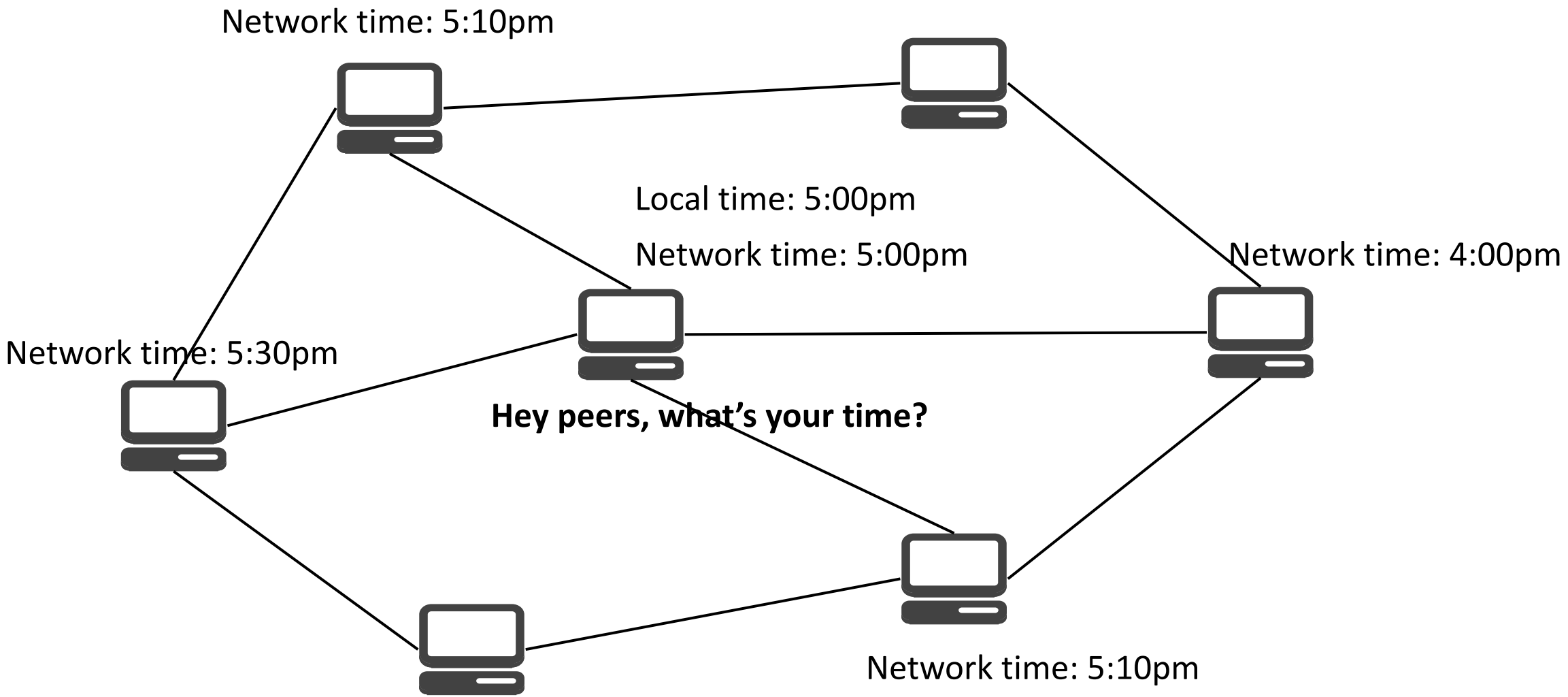

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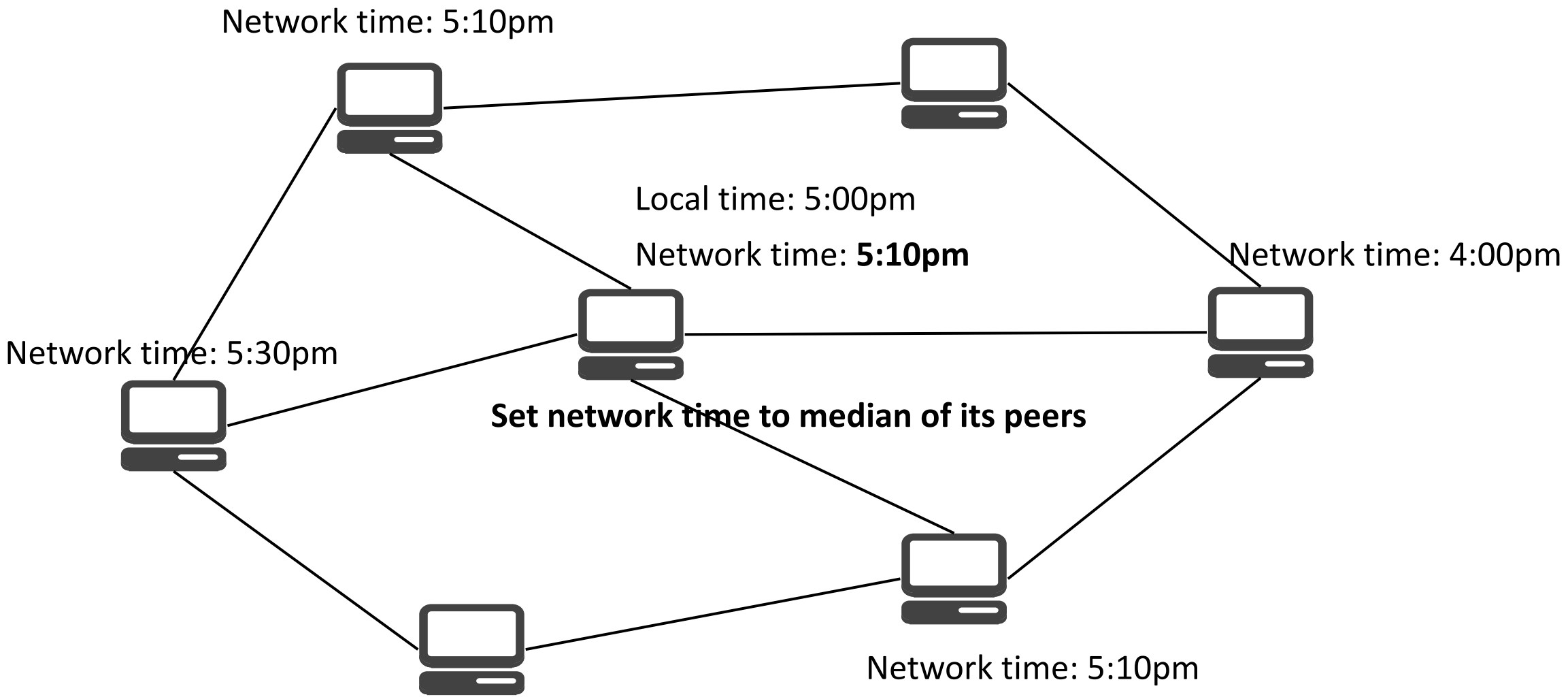
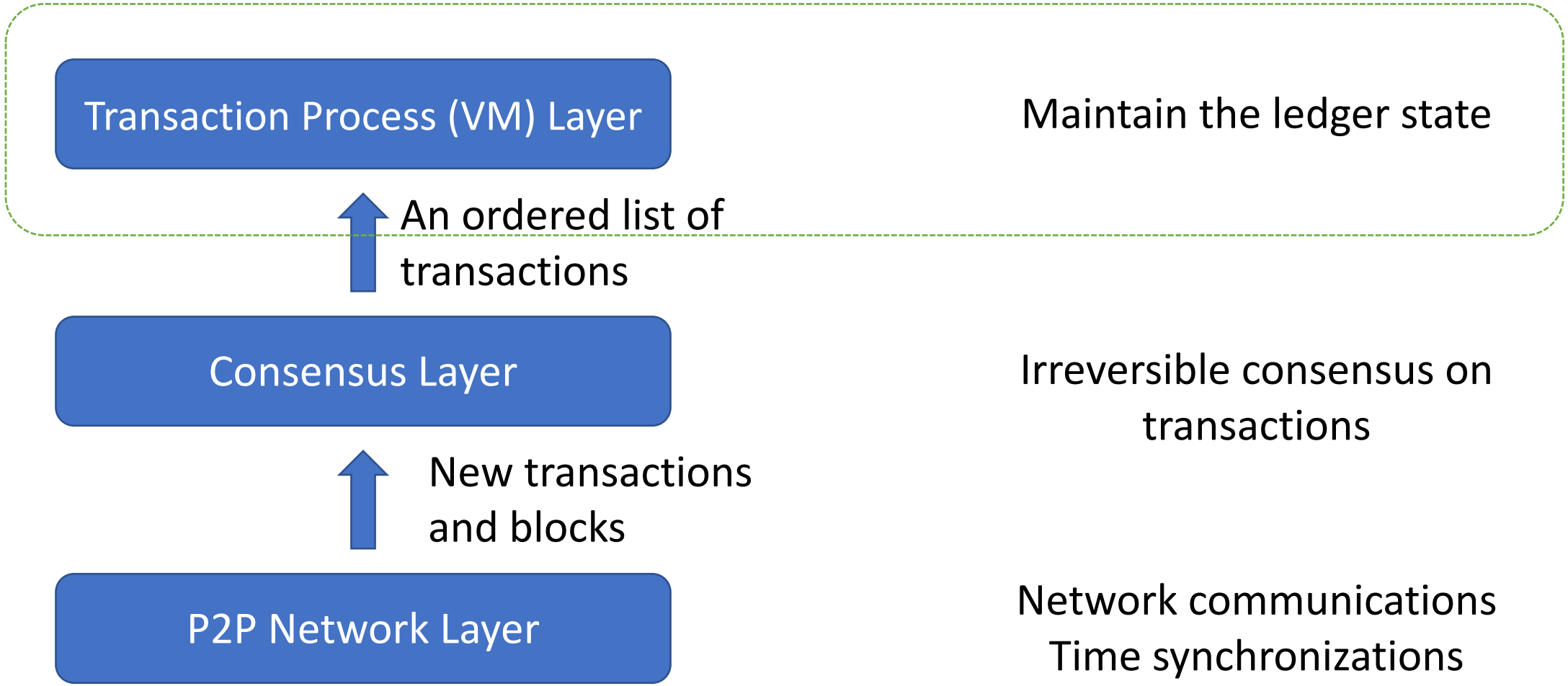


Network Adjusted Time

- Each node collects timestamps from all of its peers periodically
- Set its own network adjusted time to the median of its peers
- The largest difference between network adjusted time and local time can be 70 minutes
  - If the difference is larger than 70 minutes, adjust 70 minutes only

- Is it possible to attack this protocol and control timestamps?
- Why use median not average?

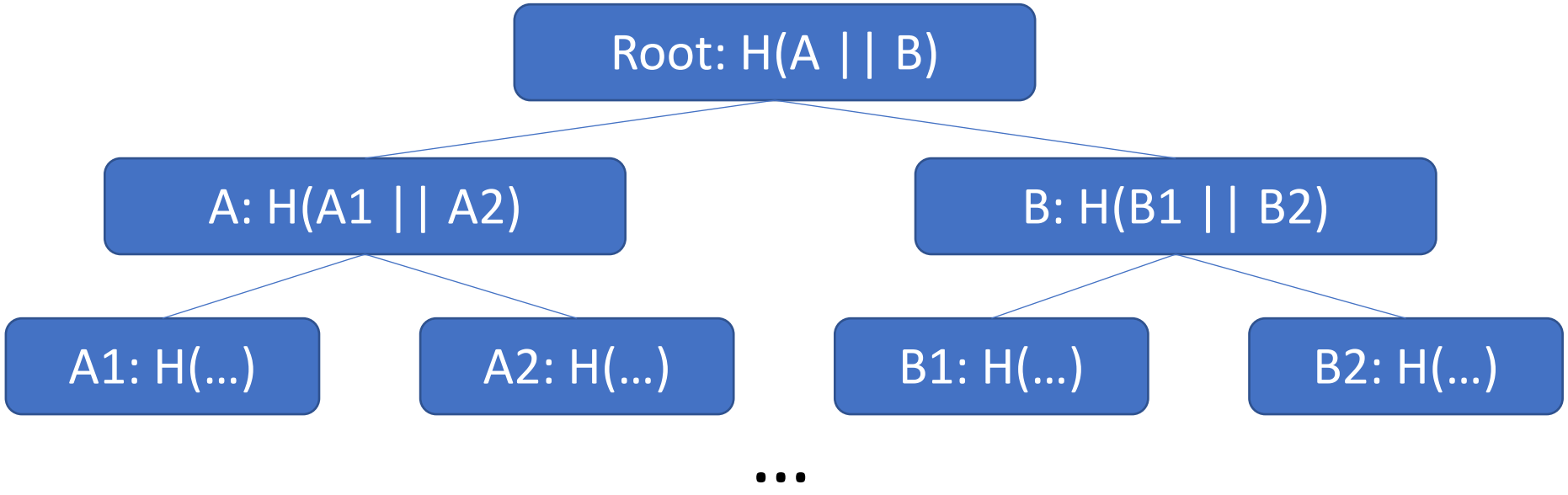
Layers in Blockchain Systems



How Information in Blockchain is Organized?

Authenticated Data Structure: Merkel Tree

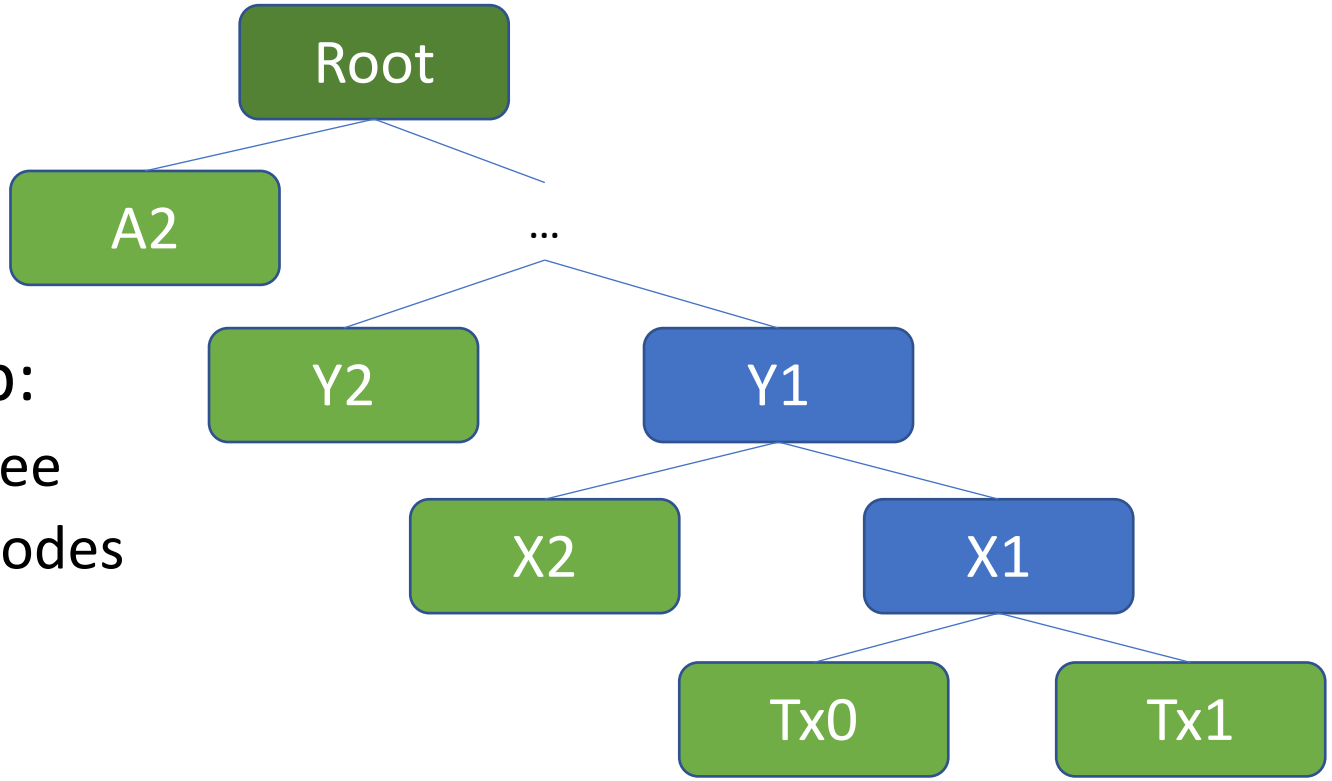
- Each node stores one-way crypto-hash of its children



- Leaf nodes store data
  - The root (merkel root) ensures the data integrity
  - O(Log n) proof for authenticated read

Merkel Tree: Authenticated Read

- Suppose transactions stored in a Merkel tree.
- Alice knows the whole tree. Bob only knows the root



- Alice proves to Bob:
  - Tx0 exists in the tree
  - Only send green nodes
- Why?

Applications of Merkel Tree in Blockchains

- Transactions in a block
  - Merkel root stored in the header
- Unspent transactions at a block height
  - In Bitcoin, Unspent transactions defines the current account state
- Account state in Ethereum
  - Use a special Merkel tree called Merkel Patricia Tree

- **Key Advantage**: Enable light nodes that only store block header to reliably retrieve information from full nodes with proof
  - A light node does not need to trust full nodes to interact with the blockchain

How Blockchain States are Represented?

Account State in Blockchain

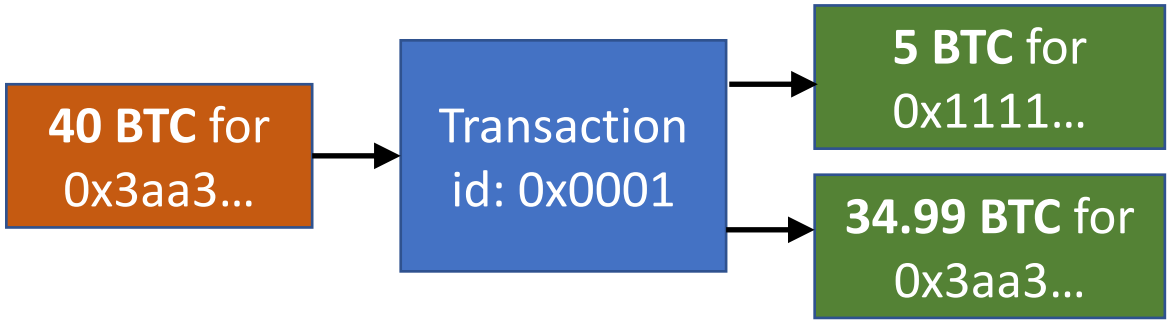
- An address to balance mapping, for example:

Address	Balance
0x2222…	10
0x1111…	20
…	…

- Replay Attack:
  - Alice sign and send ”Alice will pay Bob 1BTC”
  - Bob recorded this signed message
  - One year later, Bob resend recorded message to steal another 1BTC
- **Caveat**: Need to remember all history transactions

Bitcoin: Unspent Transaction Output (UTXO)

- Each transaction can have multiple inputs and outputs:



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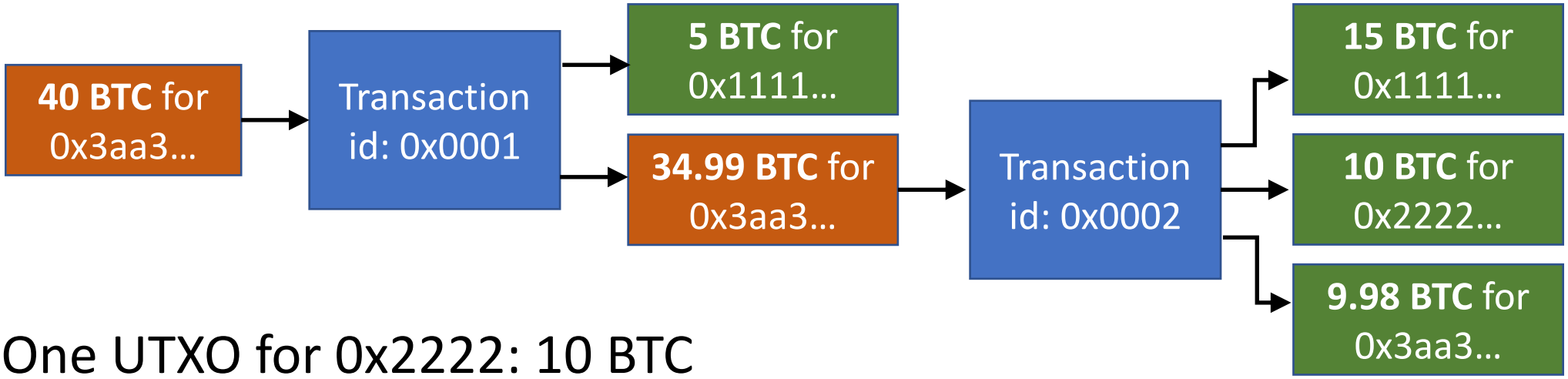


- One UTXO for 0x2222: 10 BTC
- Two UTXOs for 0x1111: 5 BTC + 15 BTC
- Transaction fees are implicit
- Only need to remember UTXOs now

Discussion: Pros and Cons of UTXO Model

- Simplified conflict definition:
  - Two transactions should not share the same UTXO
- Parallel transaction processing
- Encourage the usage of different addresses: better anonymity

- Counter-intuitive
- Hard to build smart contracts on top of it
  - Will cover more when we talk about Ethereum

How to Process Transactions?

Verify a Transaction in Bitcoin

- To spend an unspent transaction, sender provides:
  - Public key
  - Signature generated with the private key
- To verify the input of an unspent transaction:
  - Check the public key matches the sender's address
  - Check the signature is correct

- Bitcoin defines a stack-based script language to check transactions

Bitcoin Scripts

- The locking script defines how to spend a UTXO
- Sender provides an unlocking script
- Concatenate two scripts to run
- The script passes if the execution ends with no error and no input left
  - Reject the transaction if the execution fails

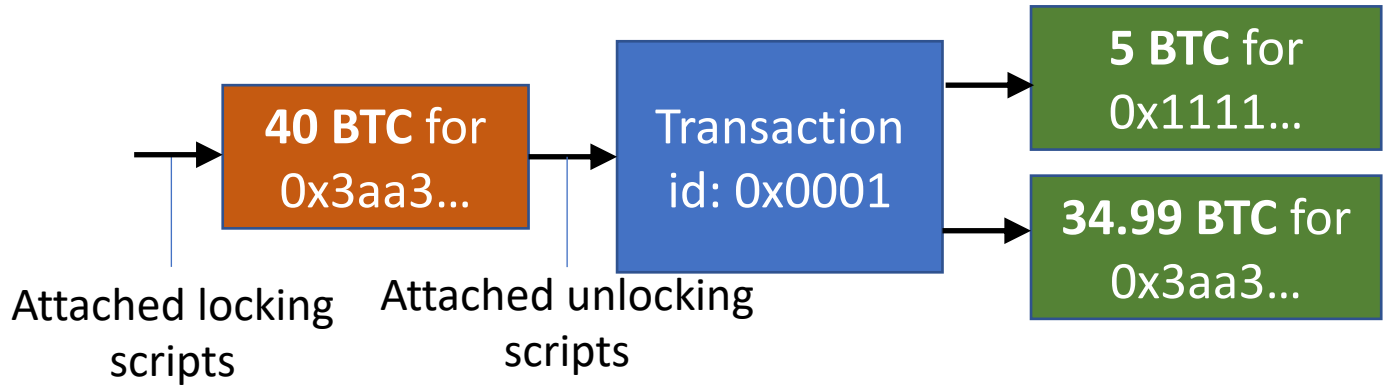
<signature>
<public key>

Sender unlocking scripts

OP_DUP
OP_HASH160
<bitcoin address (hash of public key)>
OP_EQUALVERIFY
OP_CHECKSIG

The standard
UTXO locking script

Bitcoin Scripts



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Sender unlocking scripts

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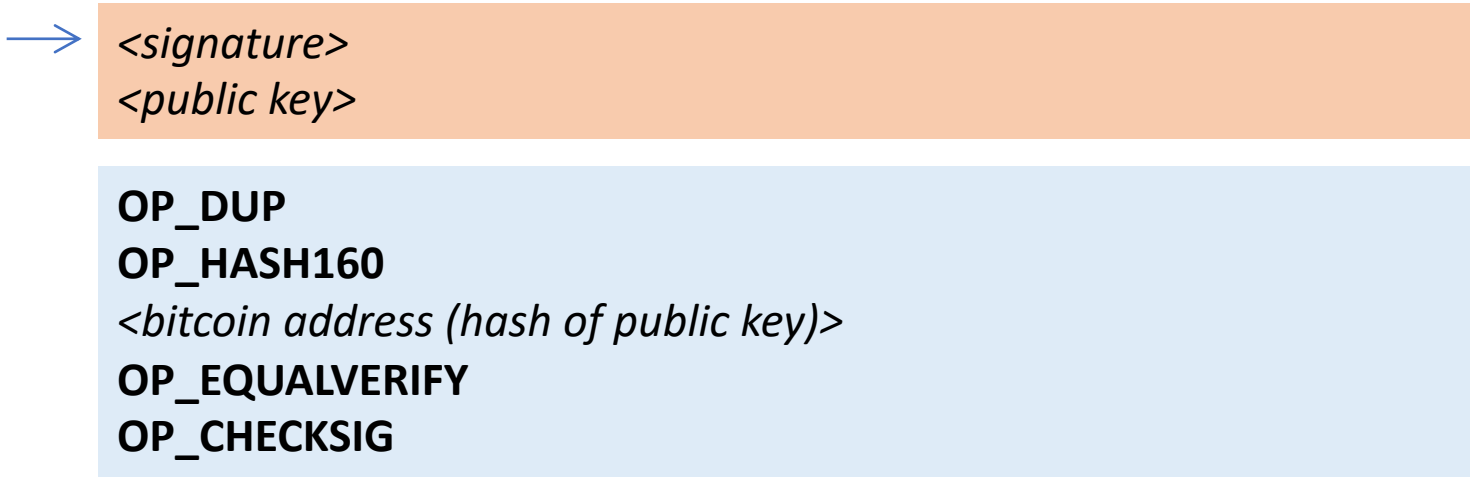
Example: Bitcoin Script Execution



Execution Stack

For data token, just push it into the stack!

Example: Bitcoin Script Execution

<signature>
<public key>

OP_DUP
OP_HASH160
<bitcoin address (hash of public key)>
OP_EQUALVERIFY
OP_CHECKSIG

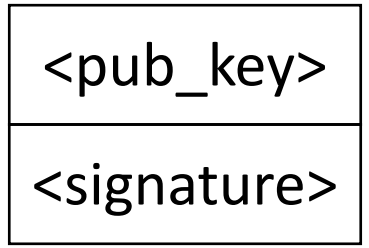
<signature>

Execution Stack

Example: Bitcoin Script Execution

<signature>
<public key>

→ **OP_DUP**
OP_HASH160
<bitcoin address (hash of public key)>
OP_EQUALVERIFY
OP_CHECKSIG



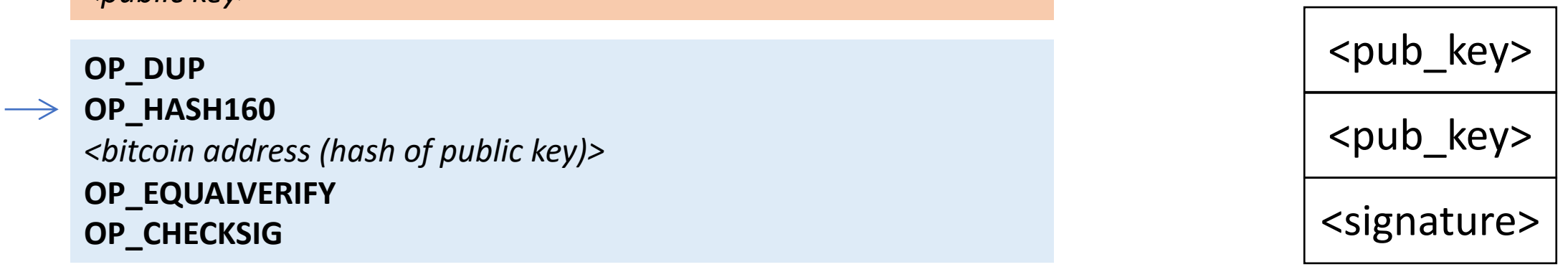
Execution Stack

OP_DUP duplicates the top entry of the stack

Example: Bitcoin Script Execution

<signature>
<public key>

OP_DUP
OP_HASH160
<bitcoin address (hash of public key)>
OP_EQUALVERIFY
OP_CHECKSIG



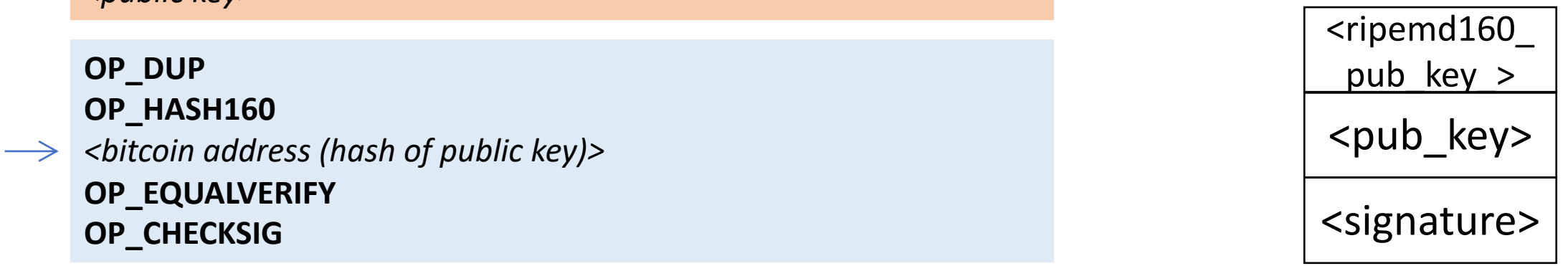
Execution Stack

OP_HASH160 computes RIPEMD160 of the top item and replaces it

Example: Bitcoin Script Execution

<signature>
<public key>

OP_DUP
OP_HASH160
<bitcoin address (hash of public key)>
OP_EQUALVERIFY
OP_CHECKSIG



Execution Stack

Example: Bitcoin Script Execution

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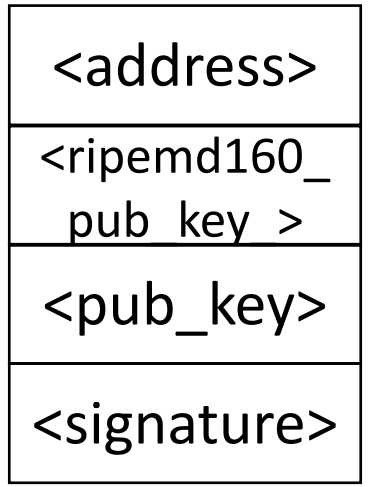


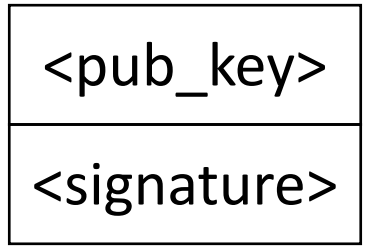
Execution Stack

OP_EQUIALVERIFY pops the top two items and compares them, terminate with error if they do not equal

Example: Bitcoin Script Execution

<signature>
<public key>

OP_DUP
OP_HASH160
<bitcoin address (hash of public key)>
OP_EQUALVERIFY
→ **OP_CHECKSIG**



Execution Stack

OP_CHECKSIG pops the top two items and checks whether they correspond to a correct public_key-signature pair. If not, terminate with error.

Example: Bitcoin Script Execution

<signature>
<public key>

OP_DUP
OP_HASH160
<bitcoin address (hash of public key)>
OP_EQUALVERIFY
OP_CHECKSIG

Execution Stack

Execution ends without error. The unspent fund is unlocked successfully!

Bitcoin Script Language

- Support arithmetic and cryptographic primitives
- Stack-based language with more than one hundred opcodes
  - Not Turing complete though
- Why define a language for transaction validation?
- To support complicated transaction logic:
  - Multi-signature transactions
  - Hash-locked transactions
  - Time-lock
- Ethereum instead defines a more powerful Turing complete language