Blockchains & Distributed Ledgers

Lecture 02

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Slide credits: AK, Dionysis Zindros, Christos Nasikas

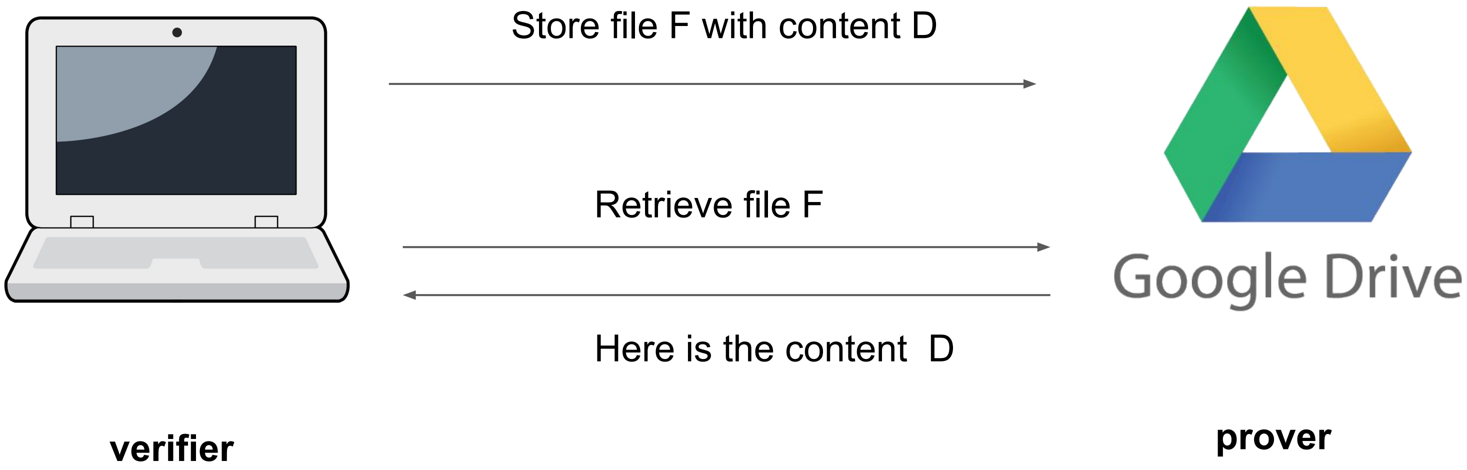
Overview

- Motivation: Server file storage
- Merkle trees to store lists
- Proofs-of-inclusion
- Merkle trees to store sets
- Proofs-of-non-inclusion
- Merkle–Patricia tries to store key:value pairs
- Blocks and blockchains

Authenticated Data Structures

- Like regular data structures, but cryptographically authenticated
- Allows a **verifier** to store, retrieve and operate on data with an untrusted **prover**

The authenticated file storage problem



The file storage problem

- Client wants to store a file on a server
- File has a name F and content D
- Clients wants to retrieve file F later

File storage: Basic protocol

- Client sends file F with content D to server
- Server stores (F, D)
- Client deletes D
- Client requests F from server
- Server returns D
- Client has recovered D

File storage: Protocol against adversaries

- What if **server is adversarial** and returns D’ != D?

File storage: Protocol against adversaries

Trivial solution:

- Client does not delete D
- When server returns D’, client compares D and D’

...what if client doesn’t have enough memory to store D for a long time?

File storage: Hash-based protocol

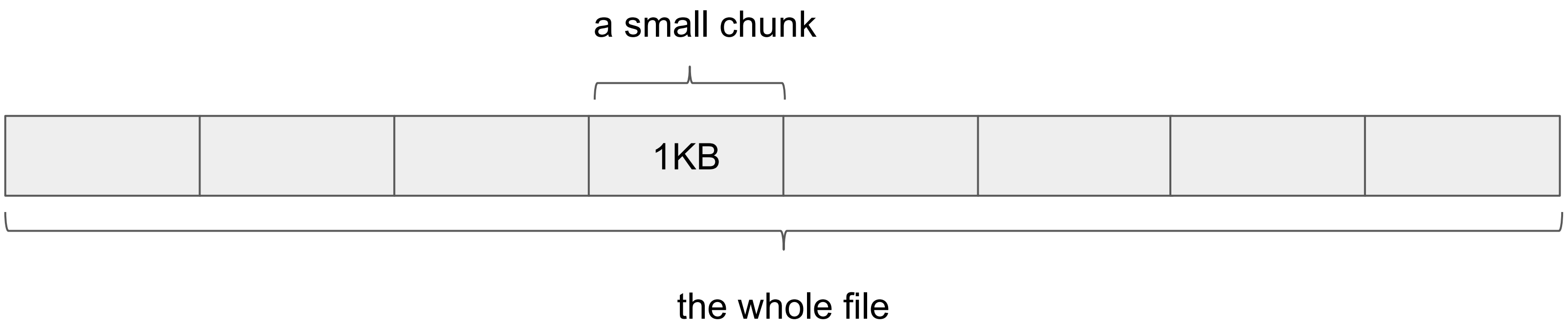
- Client sends file F with data D to server
- Server stores (F, D)
- Client stores H(D), deletes D
- Client requests F from server
- Server returns D’
- Client compares H(D’) = H(D)

File storage: File chunks

- What if client wants to retrieve the 200,019th byte of the file?
- Must download the whole file…
- Merkle trees to the rescue!

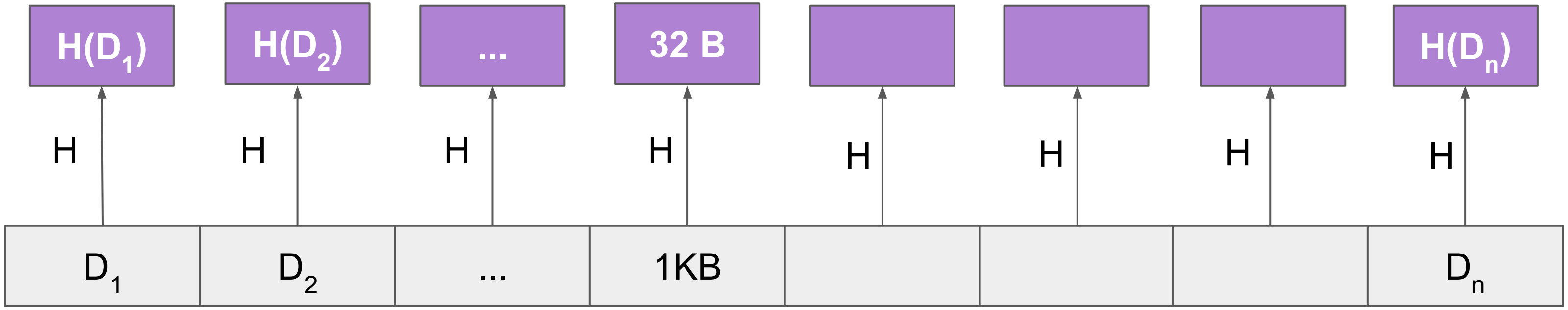
Merkle Tree

- An **authenticated** binary tree
- Split file into **chunks** of, say, 1KB



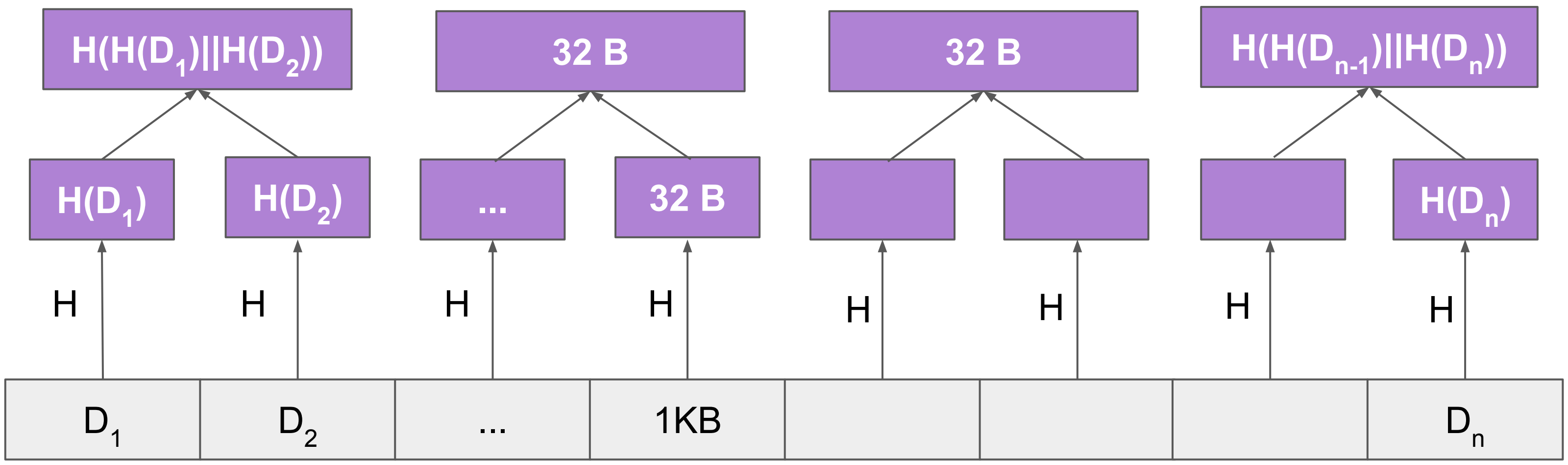
Merkle Tree

- **Hash** each chunk using a cryptographic hash function (SHA256)
- Convention: Arrows show direction of hash function application

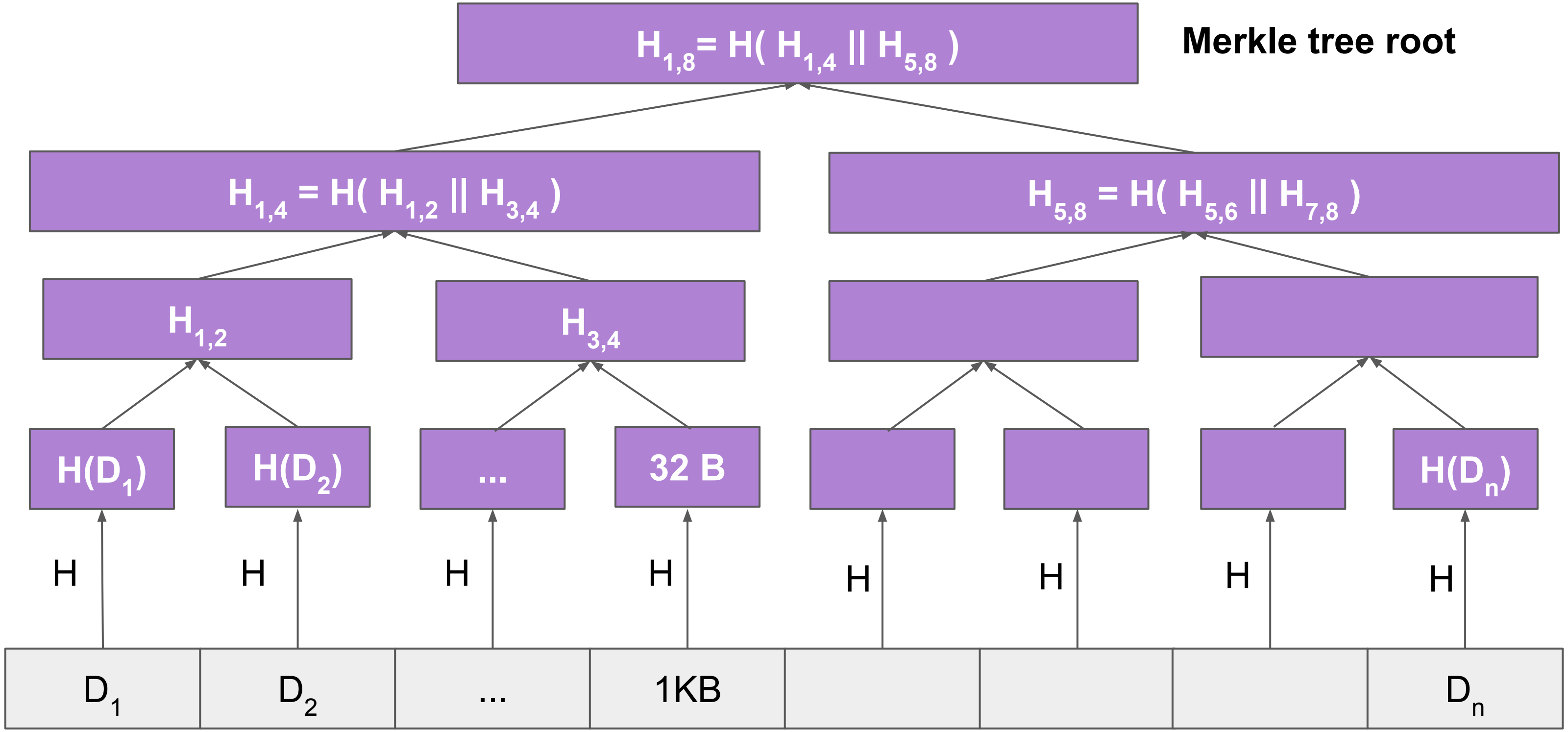


Merkle Tree

- **Combine** them by two to create a binary tree
- Each node stores the **hash** of the **concat** of its children



Merkle Tree

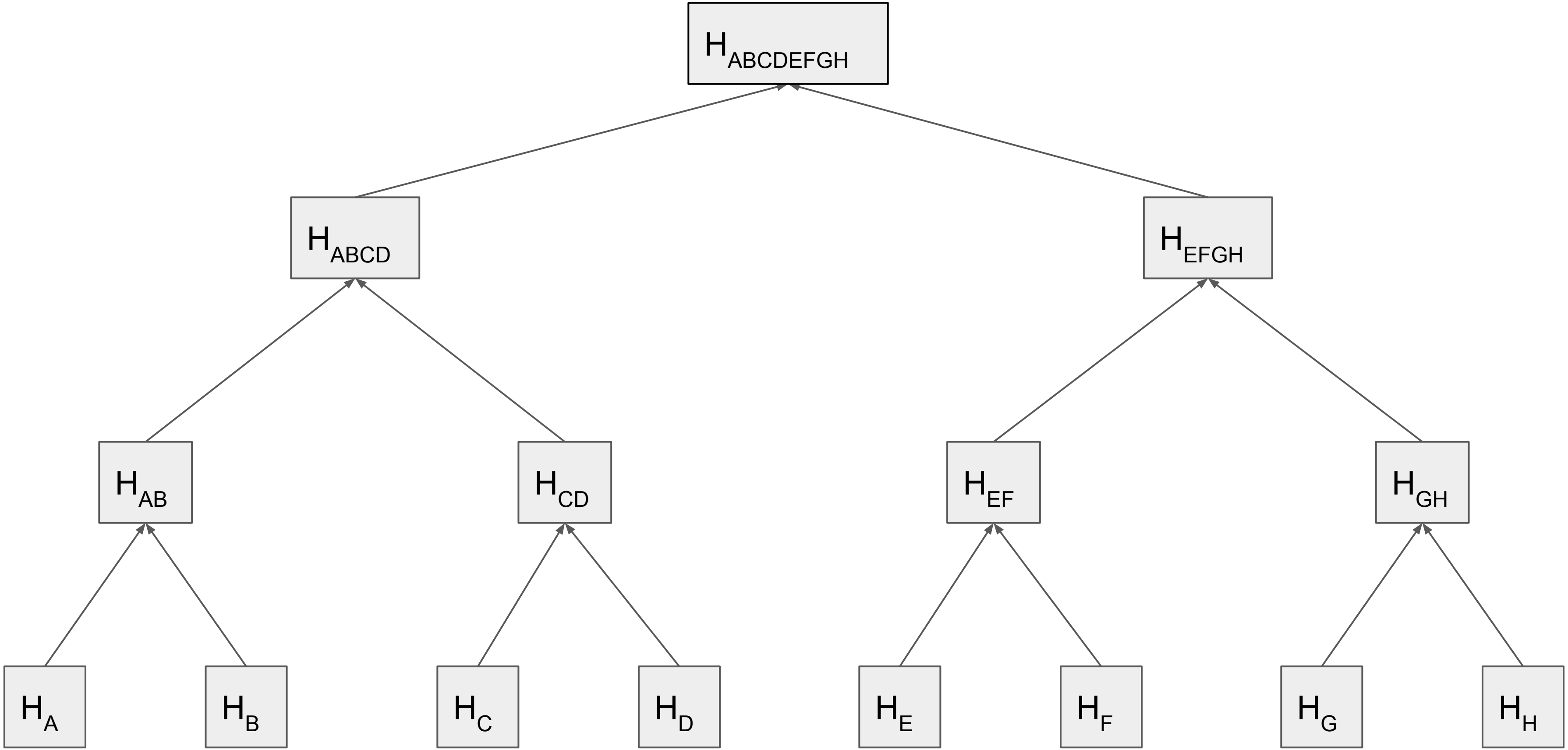


Merkle tree root
$H_{1,8} = H(H_{1,4} \| H_{5,8})$
$H_{1,4} = H(H_{1,2} \| H_{3,4})$
$H_{5,8} = H(H_{5,6} \| H_{7,8})$
$H_{1,2}$
$H_{3,4}$
$H(D_1)$
$H(D_2)$
...
32 B
$H(D_n)$
H
H
H
H
H
H
H
H
D_1
D_2
...
1KB
D_n

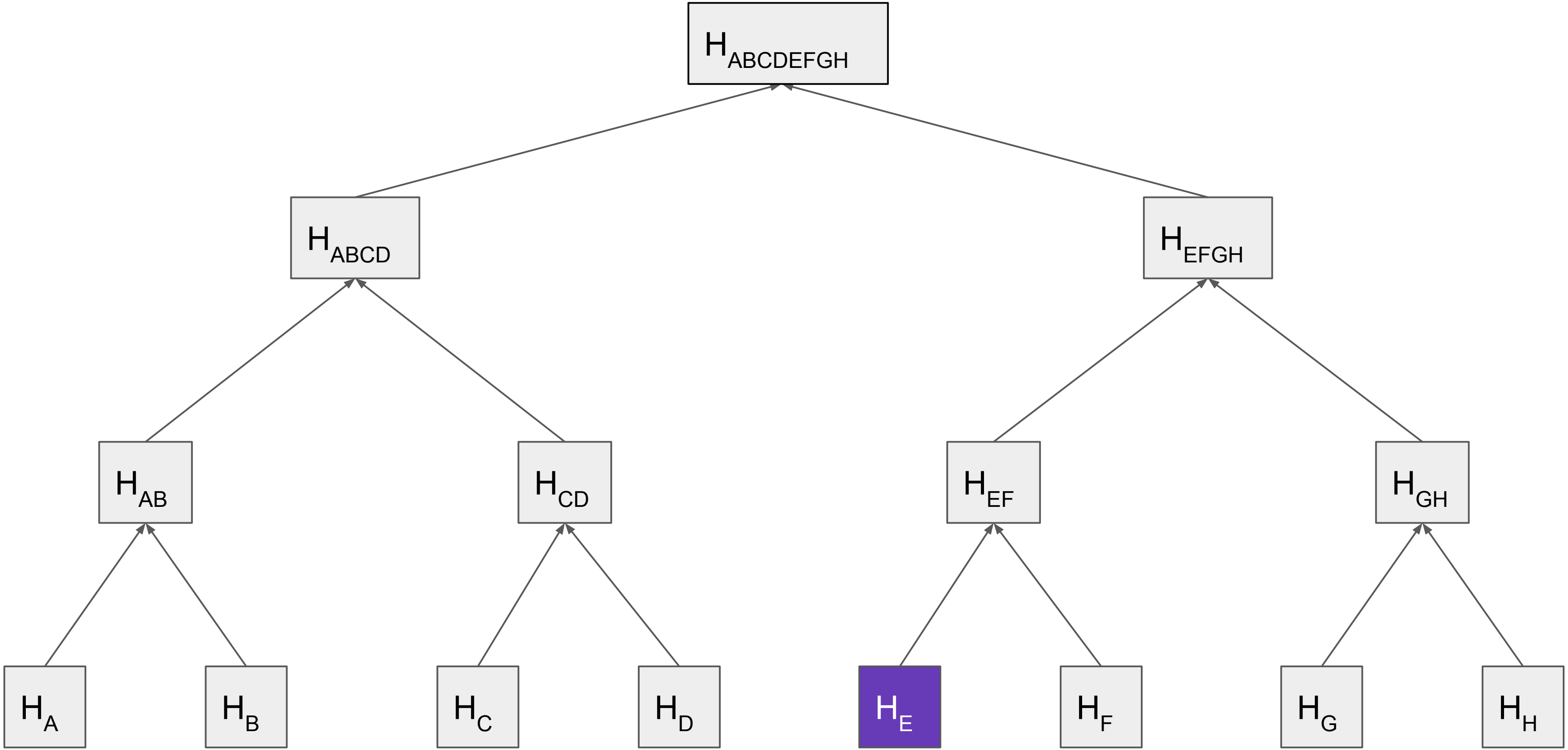
Proofs-of-inclusion

- Client creates Merkle Tree root **MTR** from initial file data D
- Client sends file data D to server
- Client deletes data D, but stores MTR (32 bytes)
- Client requests chunk x from server
- Server returns chunk x and short proof-of-inclusion π
- Client checks that chunk x is included in MTR using proof π

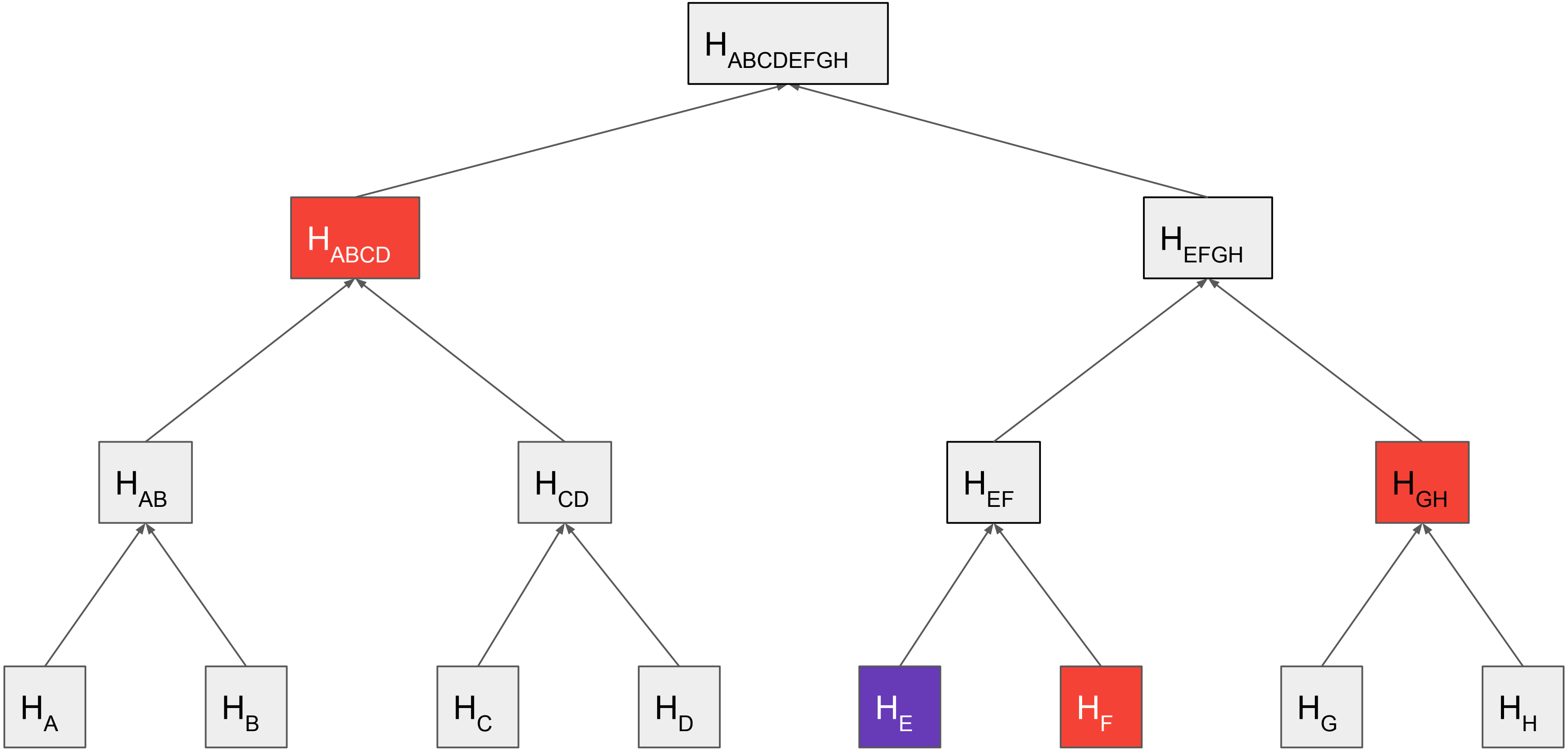
Merkle tree: proof of inclusion



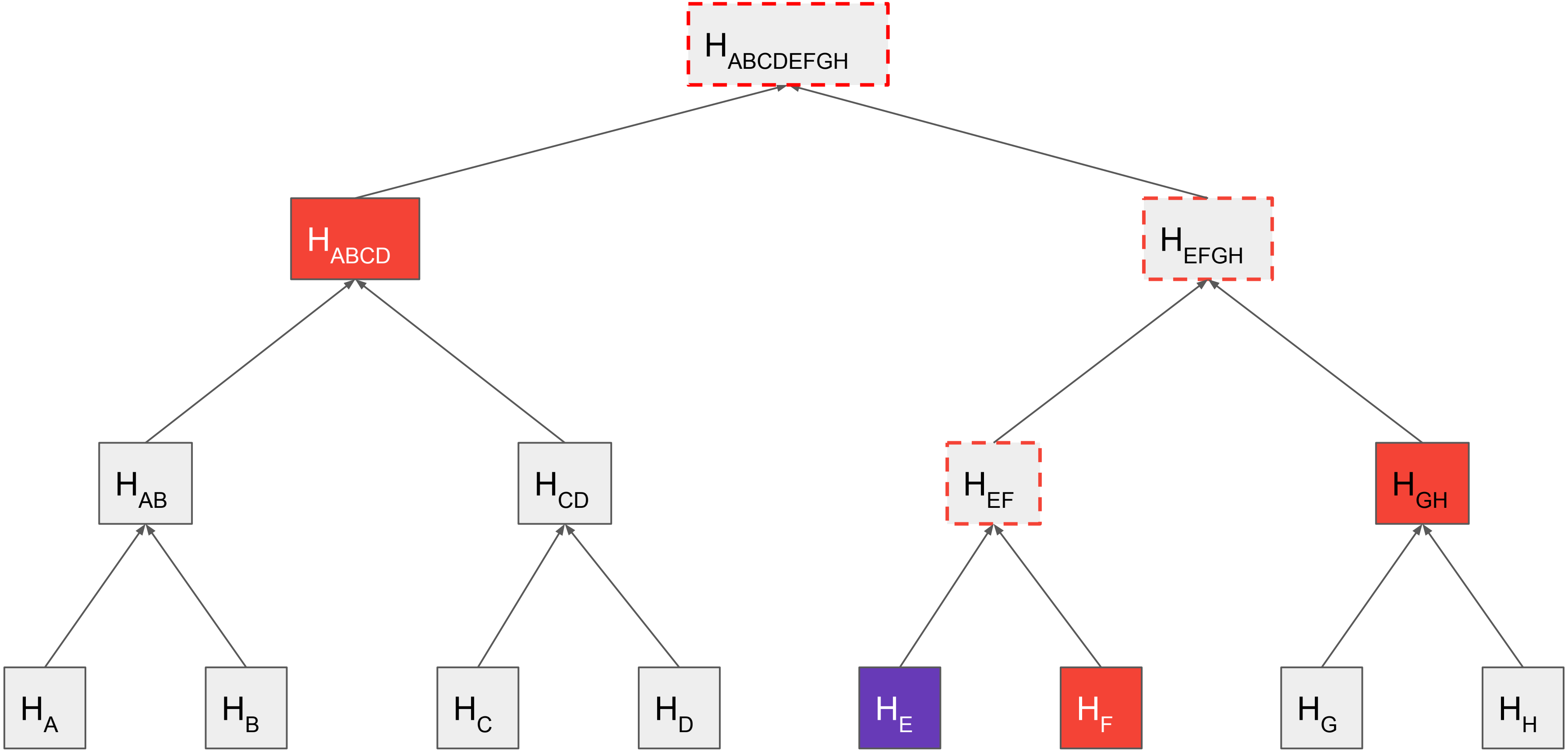
Merkle tree: proof of inclusion



Merkle tree: proof of inclusion



Merkle tree: proof of inclusion



Merkle Tree proof-of-inclusion

- Prover sends chunk
- Prover sends **siblings** along path connecting leaf to MTR
- Verifier computes hashes along the path connecting leaf to MTR
- Verifier checks that computed root = MTR
- How big is proof-of-inclusion?

Proof-of-inclusion succinctness

$$|\pi| \in \Theta(\lg|D|)$$

Notation :
lg = log base 2

Merkle Tree proof-of-inclusion security

- If adversary can present proof-of-inclusion for incorrect leaf, then we can break the hash function

Merkle tree applications

- Bitcoin uses Merkle trees to store transactions
- BitTorrent uses Merkle Tree to exchange files
- Ethereum uses Merkle–Patricia tries for storage and transactions

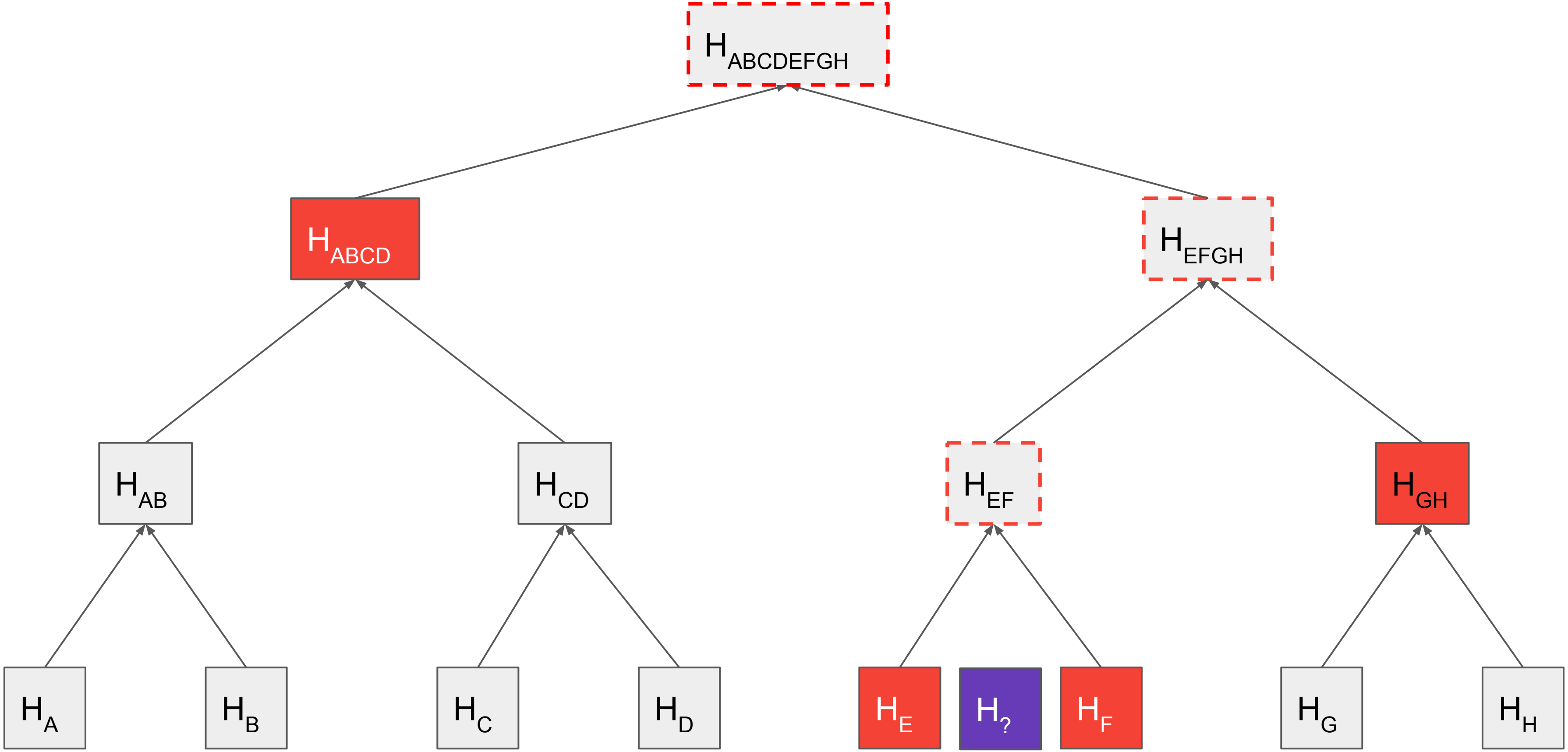
Storing *sets* instead of lists

- Merkle Trees can be used to store sets of keys instead of lists
- Verifier asks prover to store a set of keys
- Verifier deletes set
- Verifier later asks prover if key belongs to set
- Prover provides proof-of-inclusion or proof-of-non-inclusion
- Prover can be adversarial

Merkle trees for set storage

- Verifier sorts set elements
- Creates MTR on sorted set
- Proof-of-inclusion as before
- Proof-of-non-inclusion for x
  Show proof-of-inclusion for previous $H_<$ and next $H_>$ element in set
- Verifier checks that $H_<$, $H_>$ proofs-of-inclusion are correct
- Verifier checks that $H_<$, $H_>$ are adjacent in tree
- Verifier checks that $H_< < x$ and $H_> > x$
- The two proofs-of-inclusion can be compressed into one

Merkle tree: proof of inclusion / non-inclusion

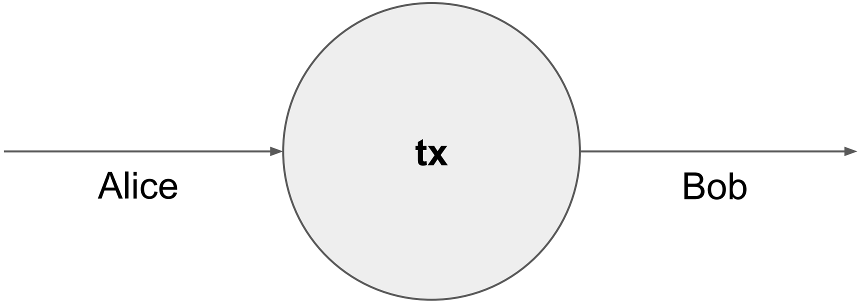


Transactions

A simple transaction for financial data

- Input: contains a signature and a public-key
- Output: contains a verification procedure and a value

UTXO = “unspent transaction output”



Example from Bitcoin

Input:
Previous tx: f5d8ee39a430901c91a5917b9f2dc19d6d1a0e9cea205b009ca73dd04470b9a6
Index: 0
scriptSig: 304502206e21798a42fae0e854281abd38bacd1aeed3ee3738d9e1446618c4571d10
90db022100e2ac980643b0b82c0e88ffdfec6b64e3e6ba35e7ba5fdd7d5d6cc8d25c6b241501

Output:
Value: 5000000000
scriptPubKey: OP_DUP OP_HASH160 404371705fa9bd789a2fcd52d2c580b65d35549d
OP_EQUALVERIFY OP_CHECKSIG

The input imports 50 BTC from output #0 of tx f5d..
and sends them to a Bitcoin address 404…

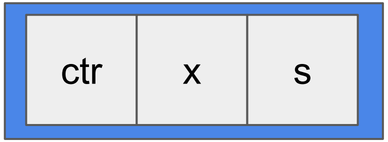
Transaction Verification

scriptPubKey: OP_DUP OP_HASH160 <pubKeyHash> OP_EQUALVERIFY OP_CHECKSIG

scriptSig: <sig> <pubKey>

Bitcoin
Script
That verifies
The
spending of
the UTXO

Blocks



- Data structure with three parts:
    - nonce (ctr), data (**x**), reference (s)
    - Typically called the **block header**
- data (**x**) is application-dependent
    - In Bitcoin it stores financial data ("UTXO"-based)
    - In Ethereum it stores contract data (account-based)
    - In Namecoin it stores name data
    - We leave this undefined for now -- we will come back to this in future lectures
- Block validity:
    - Data must be valid (application-defined validity)

Proof-of-work in blocks

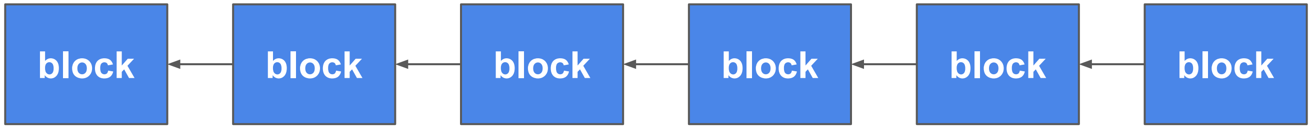
- Blocks must satisfy proof-of-work equation

$$H(ctr \,||\, \mathbf{x} \,||\, s) \le T$$

- for some constant T
- ctr is the nonce used to solve proof-of-work
- The value H(ctr || x || s) is known as the **blockid**

Blockchain

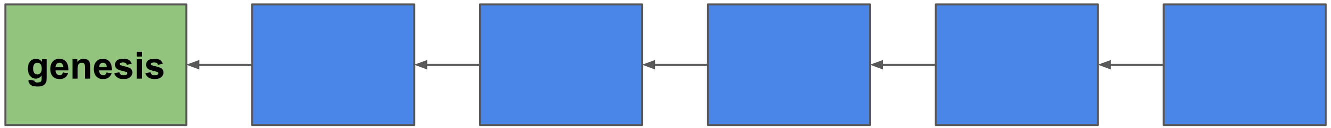
- Each block references a **previous** block
- This reference is by **hash** to its **previous** block, similar to Merkle Trees
- This linked list is called the **blockchain**
- Convention: Arrows show authenticated inclusion



- Blocks use the *s* value to point to the previous block by hash

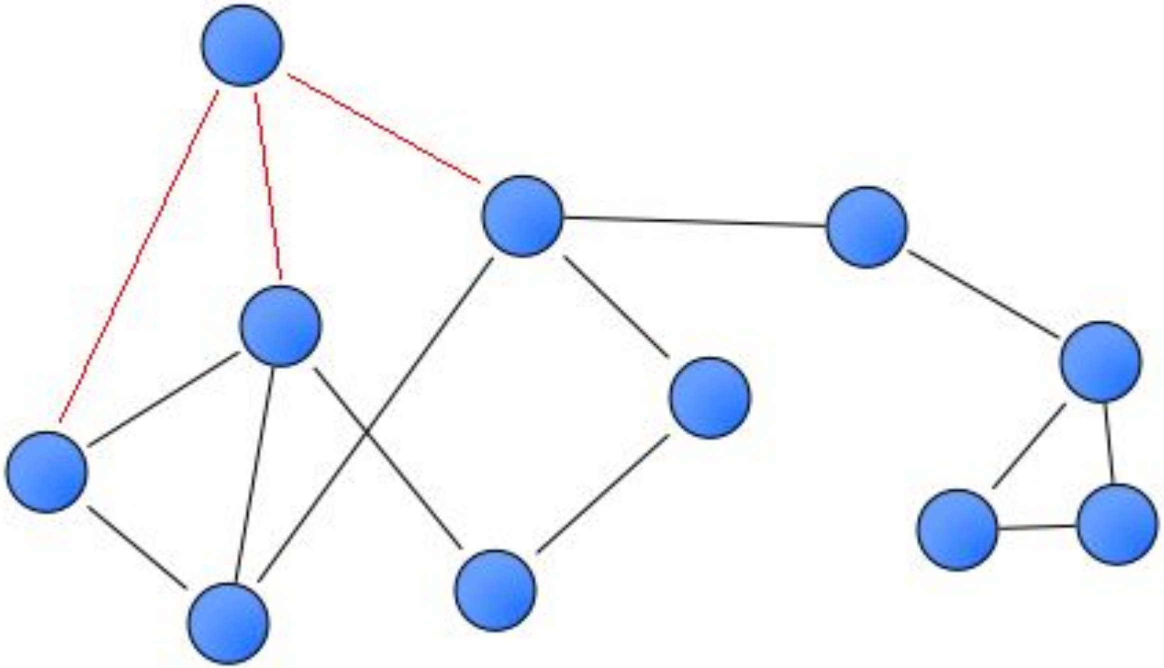
Blockchain

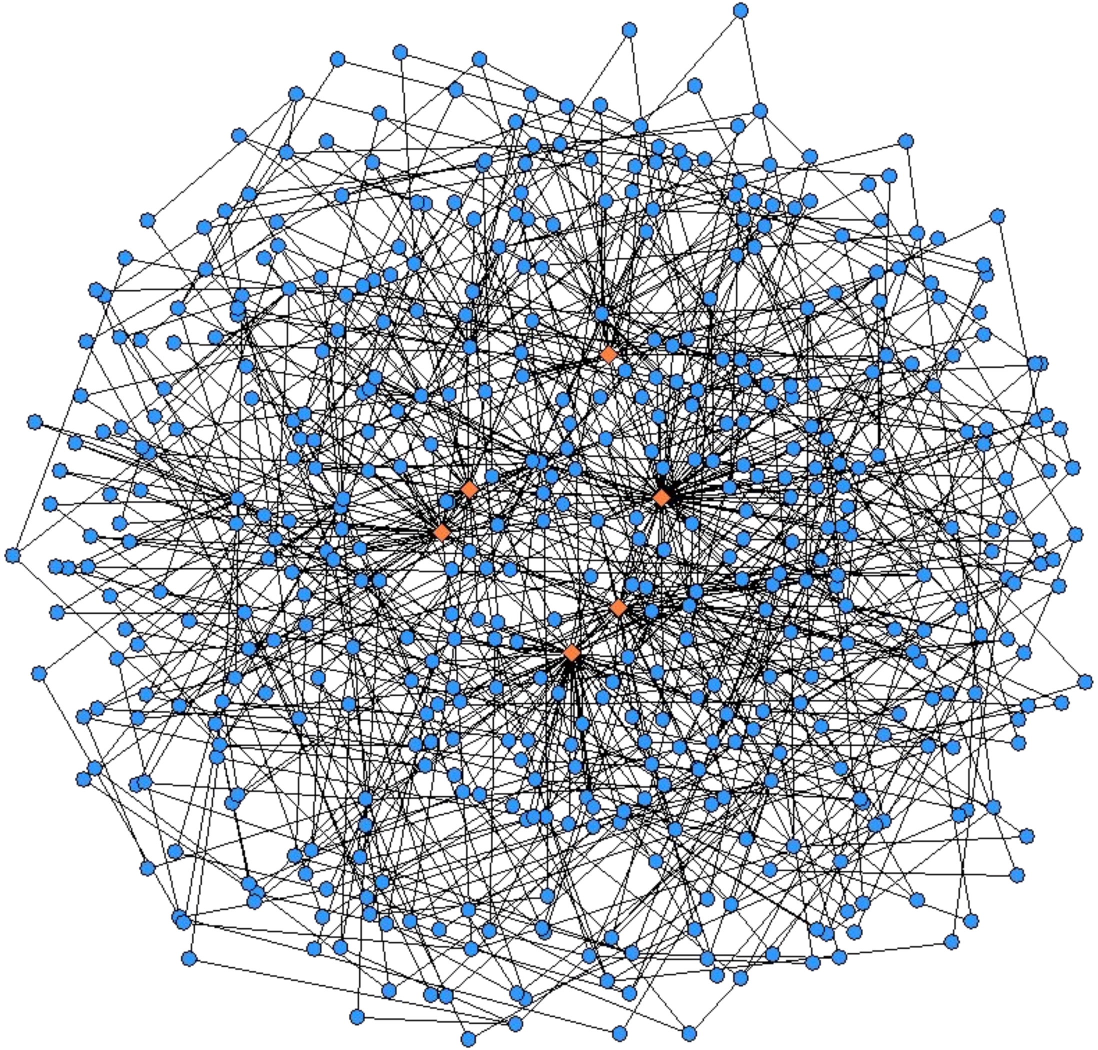
- The **first** block of a blockchain is called the Genesis Block

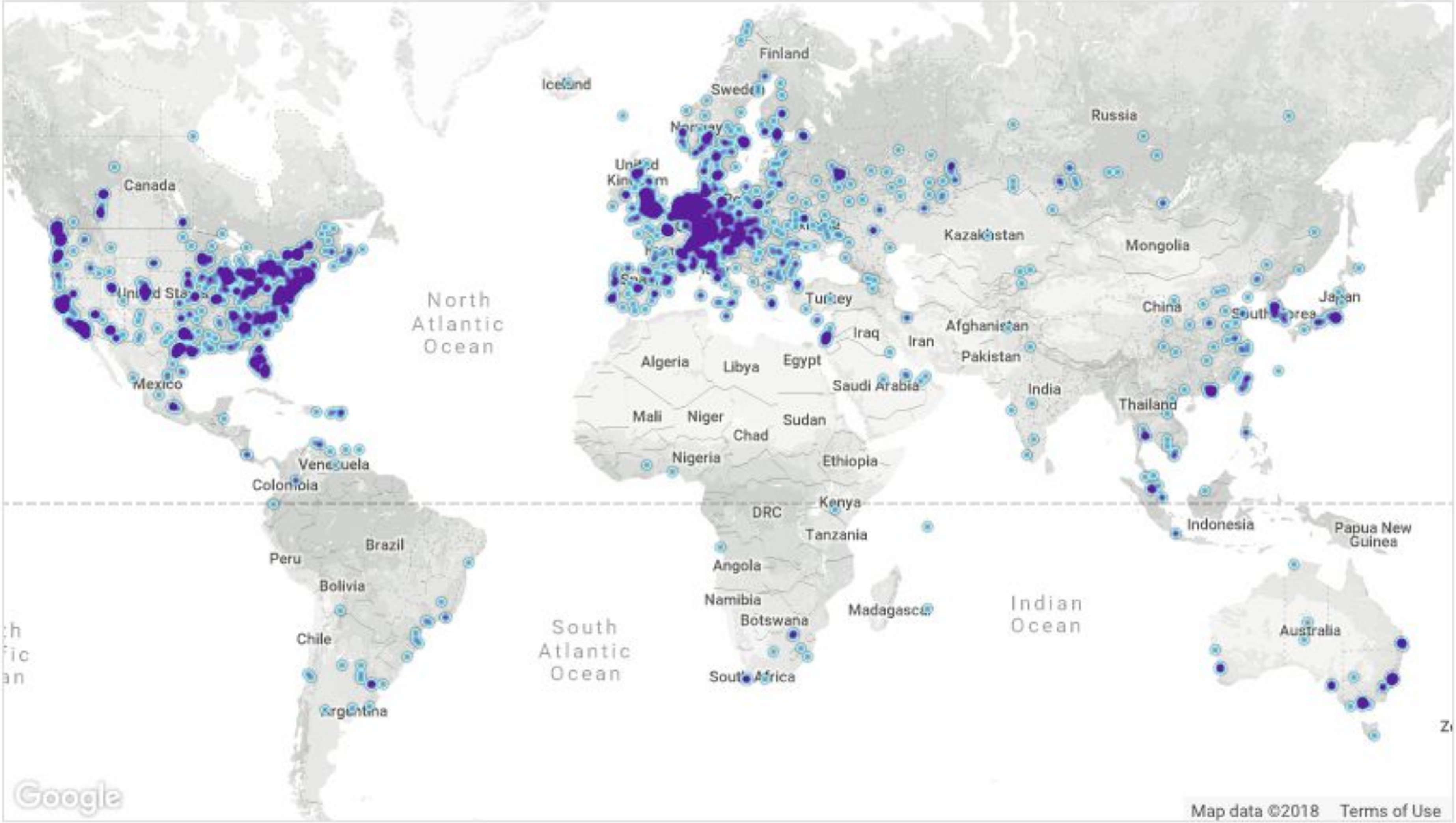


The bitcoin network

- All bitcoin nodes connect to a common p2p network
- Each node runs the code of bitcoin
- A node can run on a phone, computer, etc.
- Open source code
- Each node connects to its neighbours
- They continuously exchange financial data
- Each node can **freely** enter the network -- no permission needed! A "permissionless network".
- **The adversarial assumption:**
  There is no trust on the network! Each neighbour can lie.






Finland
Russia
Canada
Kazakhstan
Mongolia
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North Atlantic Ocean
Turkey
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Afghanistan
Pakistan
Algeria
Libya
Egypt
Saudi Arabia
India
Mexico
Thailand
Mali
Niger
Sudan
Chad
Nigeria
Ethiopia
Colombia
Kenya
DRC
Tanzania
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Angola
Bolivia
Namibia
Botswana
Indian Ocean
South Atlantic Ocean
Chile
Australia
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Peer discovery

- Each node stores a list of peers (by IP address)
- When Alice connects to Bob, Bob sends Alice his own known peers
- That way, Alice can learn about new peers

Bootstrapping the p2p network

- Peer-to-peer nodes come “preinstalled” with some peers by IP / host
- When running a node, you can specify extra “known peers”

The *gossip* protocol

- When a node **Alice** generates some new data...
- Alice **broadcasts** data to its peers
- Each peer broadcasts this data to *its* peers
- If a peer has seen this data before, it ignores it
- If this data is new, it broadcasts it to its peers
- That way, the data spreads like an epidemic, until the whole network learns it
- This process is called **diffuse**

Financial data and Transactions

- Financial data is encoded in the form of *transactions*
- Every transaction is broadcast on the network to everyone using the gossip protocol

Transactions on blockchain.info

Tries

- Called also radix tree or prefix tree
- Search tree: ordered tree data structure
- Used to store a set or an associative array (key/value store)
- Keys usually are strings

Tries

- Supports two operations: **add** and **query**
- **add** adds a string to the set
- **query** checks if a string is in the set (true/false)
- **Initialize**: Start with empty root

Tries: add(string)

- Start at root
- Split string into characters
- For every character, follow an edge labelled by that character
- If edge does not exist, create it
- Mark the node you arrive at

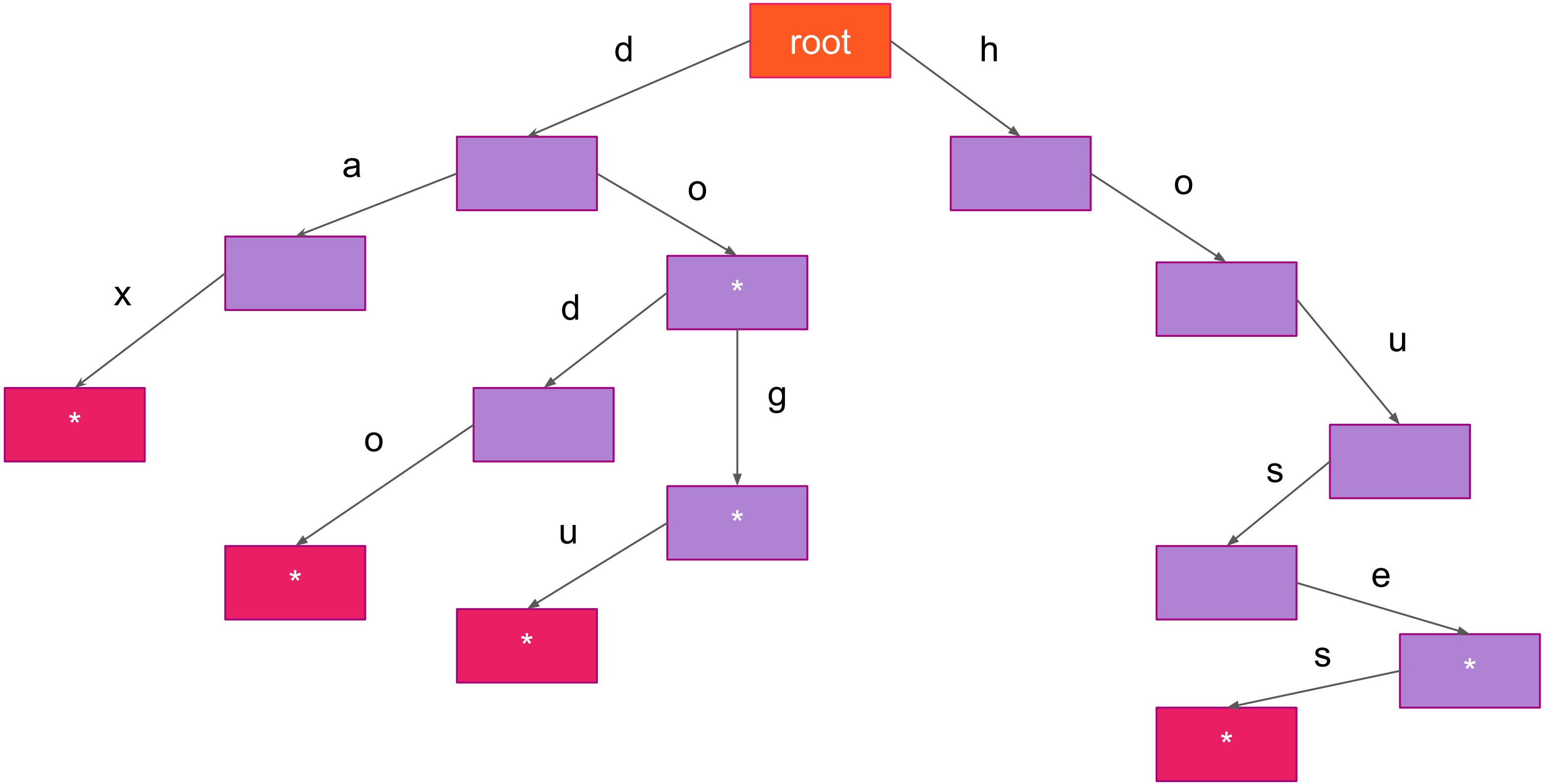
Tries: query(string)

- Start at root
- Split string into characters
- For every character, follow an edge labelled by that character
- If edge does not exist, return false
- When you arrive at a node and your string is consumed, check if node is marked
- If it is marked, return **yes**
- Otherwise, return **no**

Tries: example

{ **do**: 0, **dog**: 1, **dax**: 2, **dogu**: 3, **dodo**: 4, **house**: 5, **houses**: 6 }

Tries



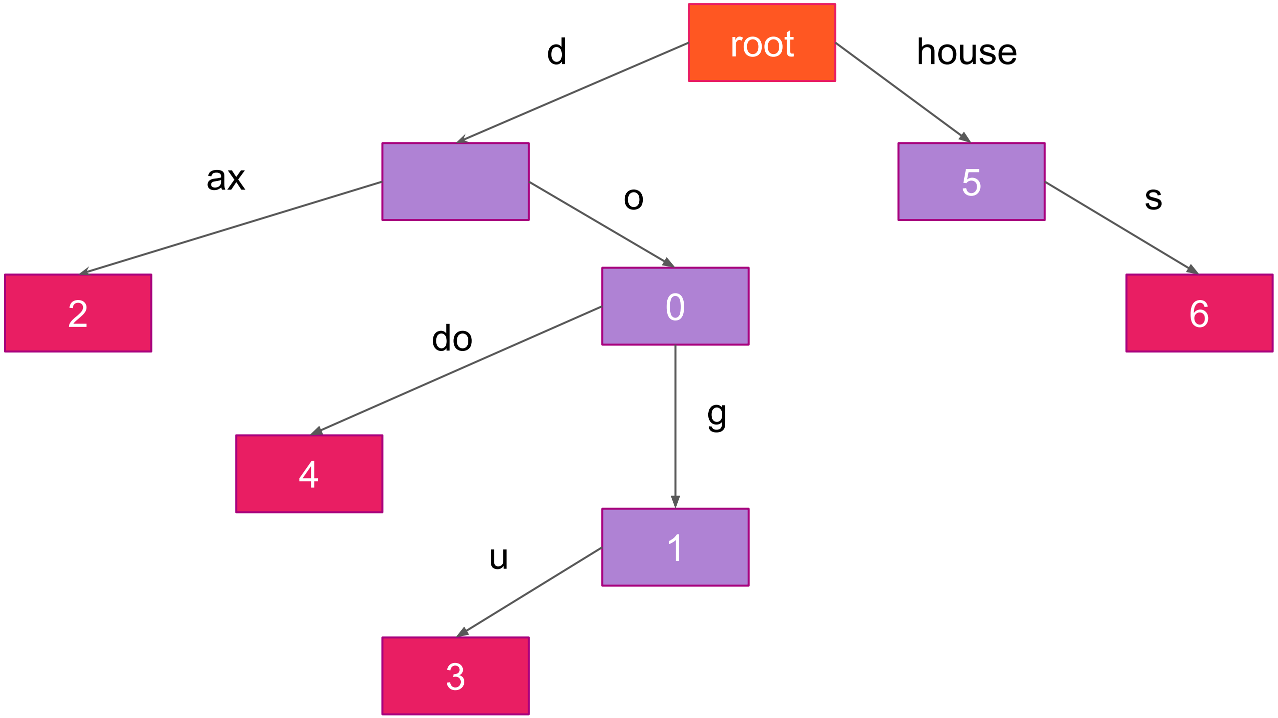
Patricia (or radix) trie

- Space-optimized trie
- An isolated path (with nodes which are only children) with unmarked nodes is *merged* into one edge
- The label of the merged edge is the concatenation of the merged symbols

Tries / Patricia tries as key/value store

- Marking can contain arbitrary value
- This allows us to map keys to values
- **add(key, value)**
- **query(key) → value**

Patricia trie



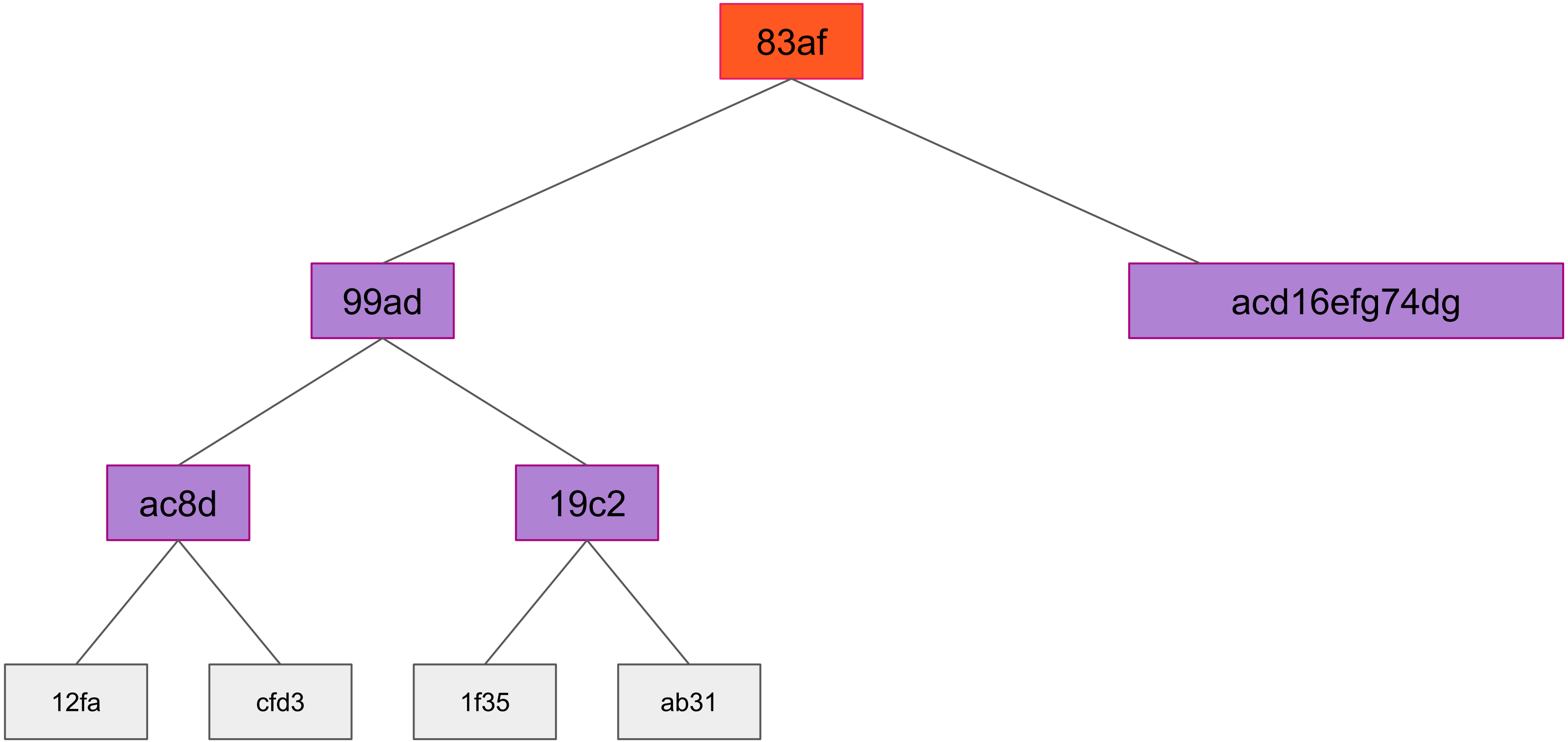
Merkle Patricia trie

- An authenticated Patricia Trie
- First implemented in Ethereum
- Allows proof-of-inclusion (of key, with particular value)
- Allows proof-of-non-inclusion (by showing key does not exist in trie)

Merkle Patricia Trie

- Split nodes into three types:
  - **Leaf**: Stores edge string leading to it, and **value**
  - **Extension**: Stores **string** of a single edge, **pointer** to next node, and **value** if node marked
  - **Branch**: Stores one pointer to another node per alphabet symbol, and **value** if node marked
- We encode keys as hex, so alphabet size is 16
- We encode all child edges in every node with some encoding (e.g. JSON)
- Pointers are by hash application
- Arguments for correctness and security are same as for Merkle Trees

Merkle Patricia trie

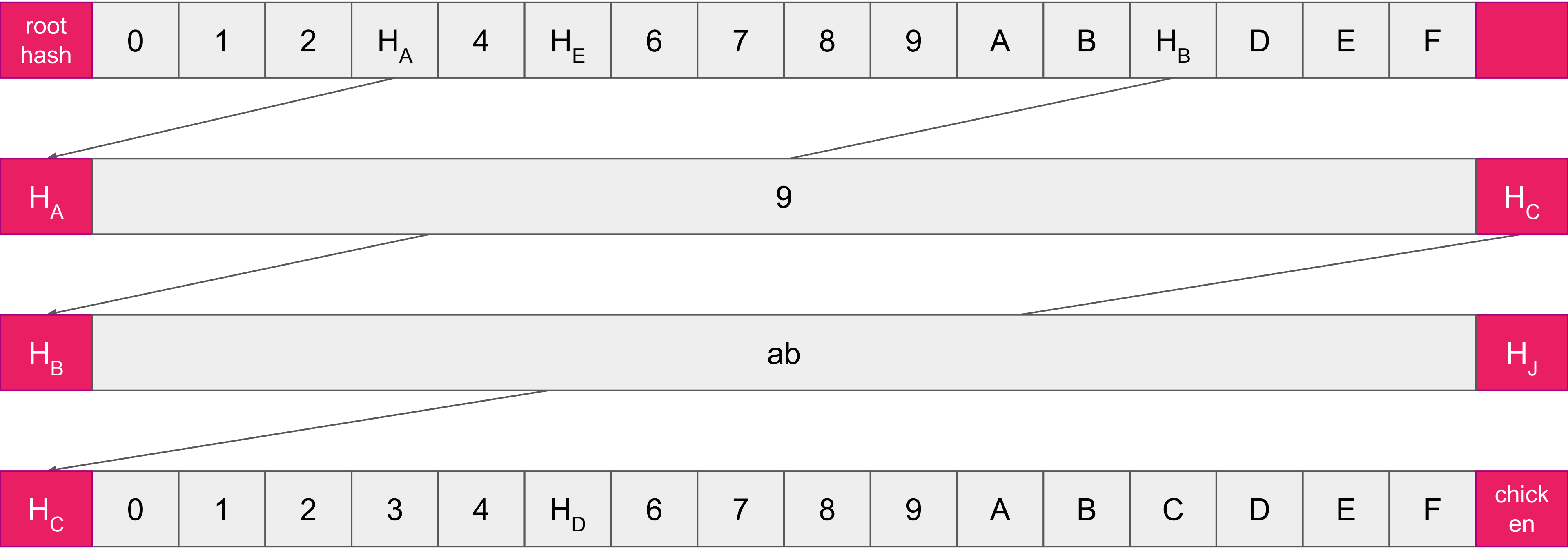


Merkle patricia trie: node

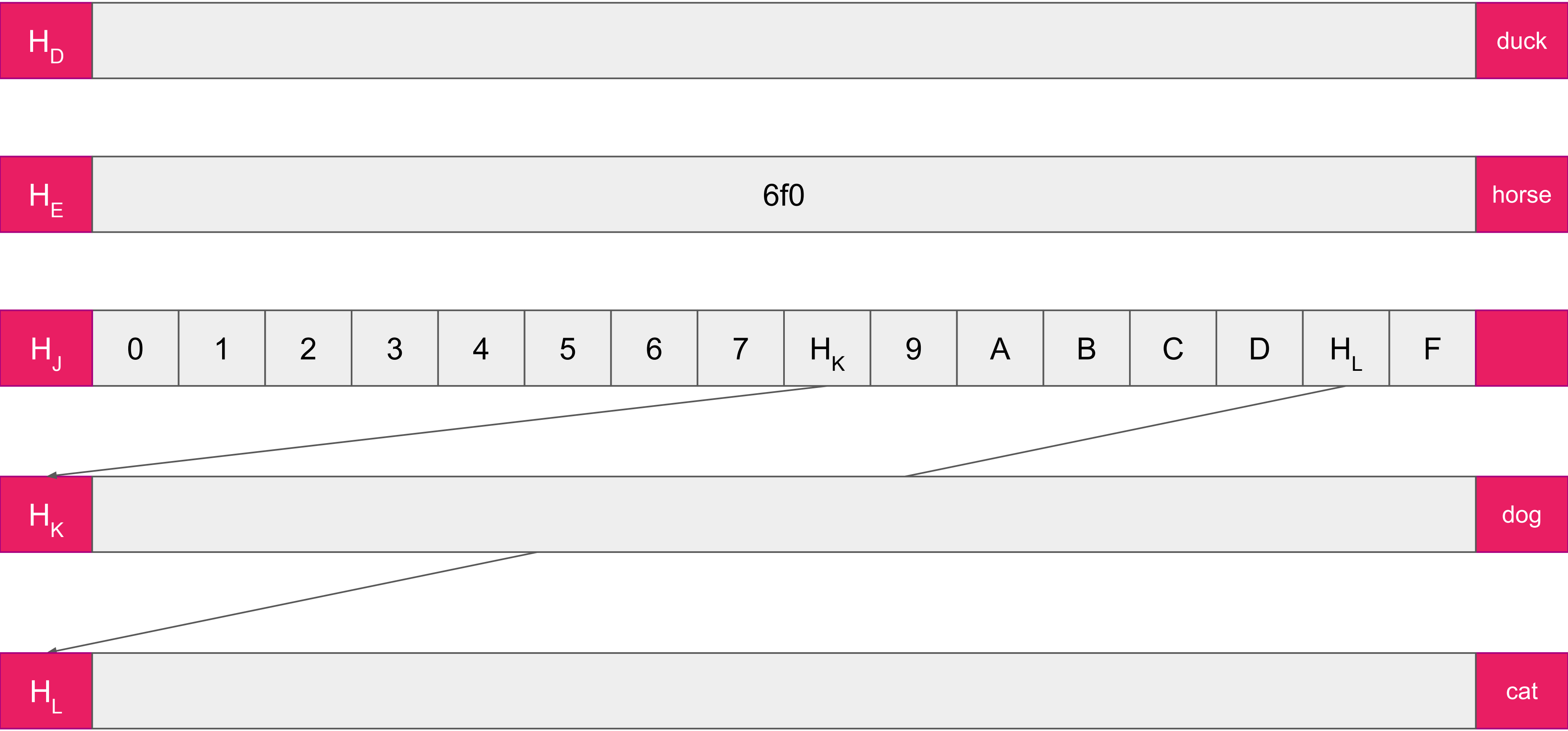
key	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F	value

Merkle patricia trie: example

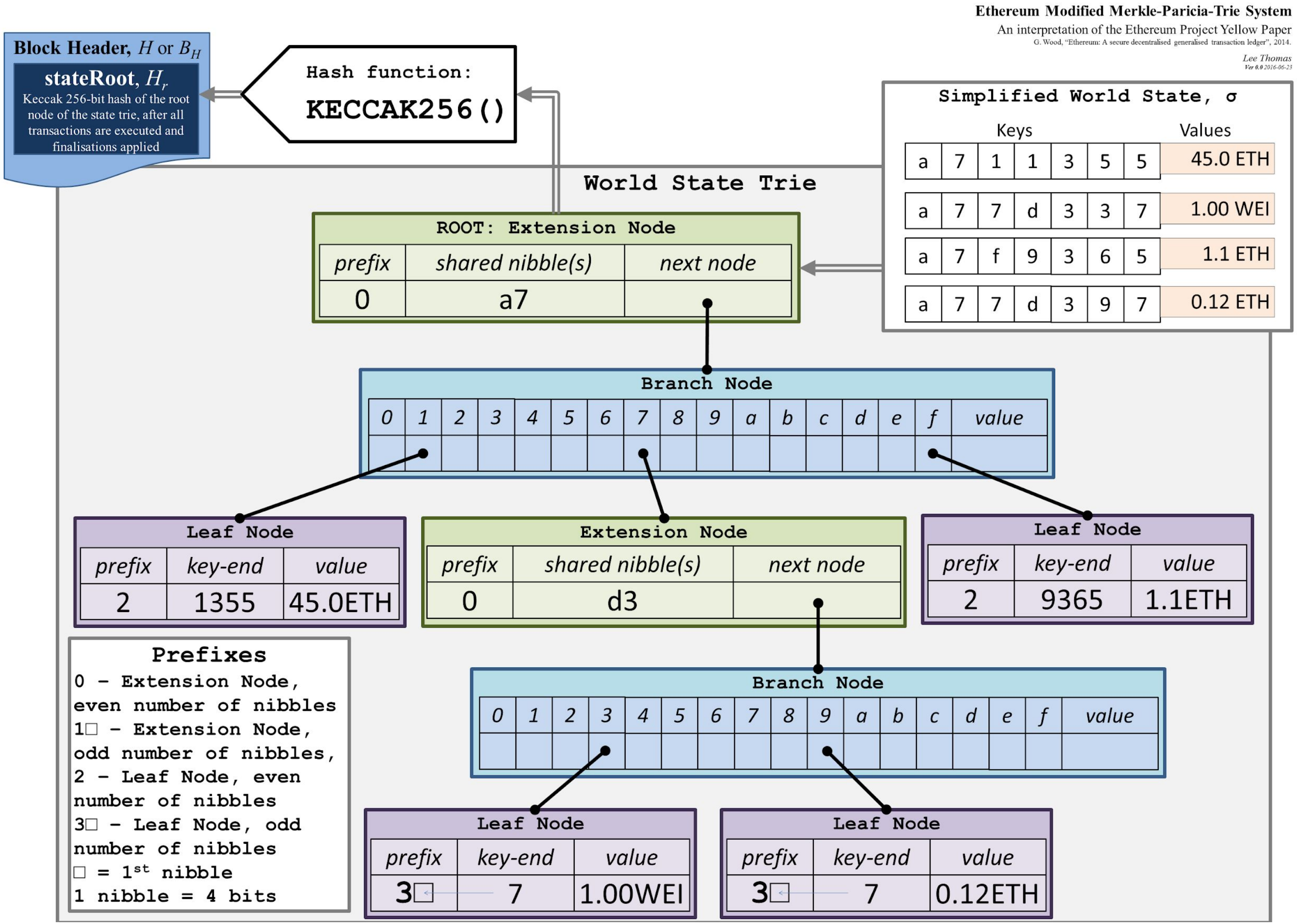
{ **'cab8'**: 'dog', **'cabe'**: 'cat', **'39'**: 'chicken', **'395'**: 'duck', **'56f0'**: 'horse' }



root hash
0
1
2
H_A
4
H_E
6
7
8
9
A
B
H_B
D
E
F
H_A
9
H_C
H_B
ab
H_J
H_C
0
1
2
3
4
H_D
6
7
8
9
A
B
C
D
E
F
chick en



H_D
duck
H_E
6f0
horse
H_J
0
1
2
3
4
5
6
7
H_K
9
A
B
C
D
H_L
F
H_K
dog
H_L
cat



Ethereum Modified Merkle-Paricia-Trie System
An interpretation of the Ethereum Project Yellow Paper
G. Wood, "Ethereum: A secure decentralised generalised transaction ledger", 2014.
Lee Thomas
Block Header, H or B_H
stateRoot, H_r
Keccak 256-bit hash of the root node of the state trie, after all transactions are executed and finalisations applied
Hash function:
KECCAK256()
Simplified World State, σ
Keys
Values
a 7 1 1 3 5 5
45.0 ETH
a 7 7 d 3 3 7
1.00 WEI
a 7 f 9 3 6 5
1.1 ETH
a 7 7 d 3 9 7
0.12 ETH
World State Trie
ROOT: Extension Node
prefix
shared nibble(s)
next node
0
a7
Branch Node
0 1 2 3 4 5 6 7 8 9 a b c d e f
value
Leaf Node
prefix
key-end
value
2
1355
45.0ETH
Extension Node
prefix
shared nibble(s)
next node
0
d3
Leaf Node
prefix
key-end
value
2
9365
1.1ETH
Prefixes
0 – Extension Node, even number of nibbles
1□ – Extension Node, odd number of nibbles,
2 – Leaf Node, even number of nibbles
3□ – Leaf Node, odd number of nibbles
□ = 1st nibble
1 nibble = 4 bits
Branch Node
0 1 2 3 4 5 6 7 8 9 a b c d e f
value
Leaf Node
prefix
key-end
value
3□
7
1.00WEI
Leaf Node
prefix
key-end
value
3□
7
0.12ETH

Eclipse attacks

- Isolate the some honest nodes in the network effectively causing a “net split” in two partitions A and B
- If peers in A and peers in B are disjoint and don’t know about each other, the networks will remain isolated
    - More recent attack: Erebus

- The connectivity assumption:
  There is a path between two nodes on the network
  If a node broadcasts a message, every other node *will* learn it