How I Used Formal Methods for Blockchain Smart Contract Security

Daejun Park

March 1, 2022

Background

Developing and applying practical formal methods for improving quality, reliability, and security of production systems software

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- Master's thesis: scalable, context-/path-sensitive program analysis
- 

(2008–2011): static analysis for detecting memory safety bugs for embedded systems software
- PhD thesis: language-parametric formal methods
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(2018–Present): formal verification of blockchain consensus protocols and smart contracts

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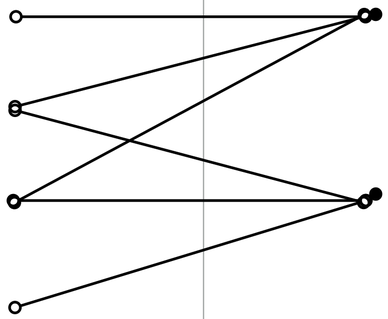
- PhD thesis: language-parametric formal methods
- runtime verification (2018–Present): formal verification of blockchain consensus protocols and smart contracts

Language-parametric Formal Methods

PhD thesis: language-parametric formal methods

Executable Semantics of Production Languages

- JavaScript [PLDI'15]
- Ethereum VM [CSF'16]
- x86 [PLDI'19]
- LLVM [ASPLOS'21]
- …



Language-parametric Formal Methods

Distinguished Paper Award

- Deductive verification [OOPSLA'16, FSE'18, CAV'20]
- Translation validation [ASPLOS'21]
- …

Developed once, and reused for all others

PhD thesis: language-parametric formal methods

- Complete
- Extensively tested
- Found bugs in language implementations

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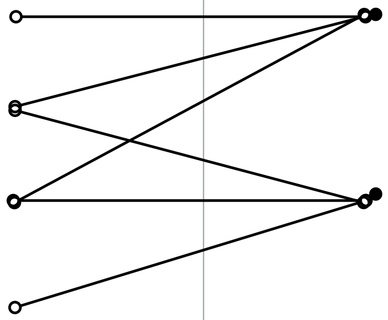

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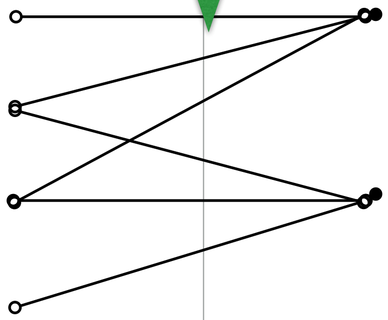

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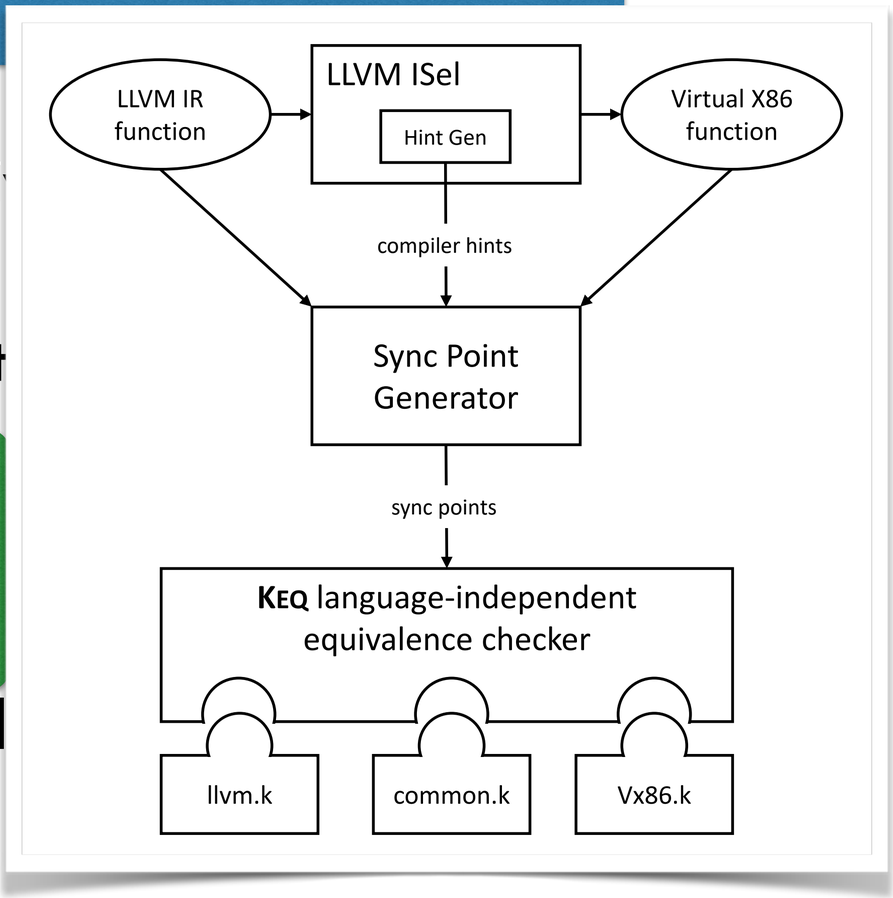

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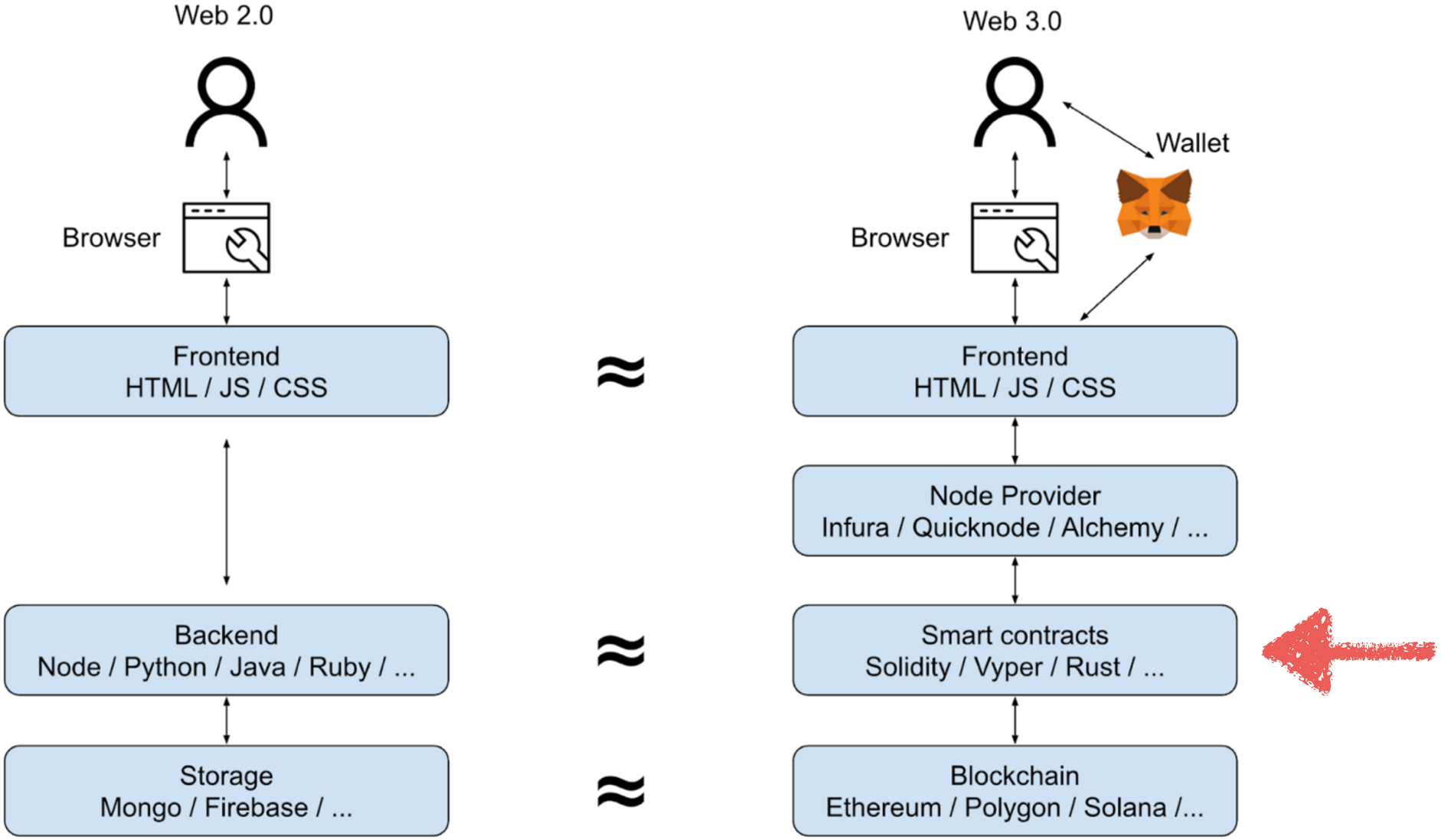
Smart Contract Verification

Smart contracts



* Image by https://towardsdatascience.com/decoding-ethereum-smart-contract-data-eed513a65f76

Smart contract example

```
 1 mapping(address => uint) balance;
 2
 3 function batchTransfer(address from, address[] to, uint amount) {
 4     uint total = amount * to.length;        // compute the total amount
 5
 6     if (balance[from] < total) revert();    // check if balance is enough
 7
 8     balance[from] -= total;                 // deduct the total amount
 9
10     for (int i = 0; i < to.length; i++) {
11         balance[to[i]] += amount;           // credit to each receiver
12     }
13 }
```

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* BatchTransfer Overflow (CVE-2018-10299): https://nvd.nist.gov/vuln/detail/CVE-2018-10299

Smart contract example

```
 1 mapping(address => uint) balance;
 2
 3 function transfer(address from, address to, uint amount) {
 4     uint newBalanceFrom, newBalanceTo;
 5
 6     if (balance[from] >= amount) {
 7         newBalanceFrom = balance[from] - amount; // compute new balance of sender
 8         newBalanceTo   = balance[to]   + amount; // compute new balance of receiver
 9     } else {
10         revert();
11     }
12
13     balance[from] = newBalanceFrom;  // update the sender's balance
14     balance[to]   = newBalanceTo;    // update the receiver's balance
15 }
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Smart contract example

$$\{\texttt{from} \mapsto x \ * \ \texttt{to} \mapsto y \ * \ M\} \ \texttt{transfer}(\texttt{from}, \texttt{to}, v) \ \{\texttt{from} \mapsto (x - v) \ * \ \texttt{to} \mapsto (y + v) \ * \ M\}$$

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what if "from == to"?

$$\texttt{sum}(\texttt{balance}) = \texttt{sum}(\texttt{balance}')$$

How to obtain quality specifications?

- Best-effort approach, e.g.:
  - Identify functional correctness specs (for core business logic)
  - Generalize known security vulnerabilities and turn them into specs
  - Clarify reasonable assumptions on external environment
- Peer review
- Client communication

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Can we get clients involved in verification process?

From property-based testing to verification

```
mapping(address => uint) balance;

function transfer(address from, address to, uint amount) { ... }


// test total balance preservation: sum(old(balances)) == sum(balances)
function testTransfer(address from, address to, address other, uint amount) {
    // snapshot old balances
    uint oldBalFrom  = balance[from];
    uint oldBalTo    = balance[to];
    uint oldBalOther = balance[other];
    require(other != from && other != to); // ensure `other` represents the rest

    // run the target function (concretely or symbolically)
    transfer(from, to, amount);

    // check total balance preserved
    assert(Math.add(oldBalFrom, oldBalTo) == Math.add(balance[from], balance[to]));
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{P} {C} {Q}

From property-based testing to verification

- This can be written and maintained by developers.
- This can be run on CI.
- This can be (easily translated to) specification.

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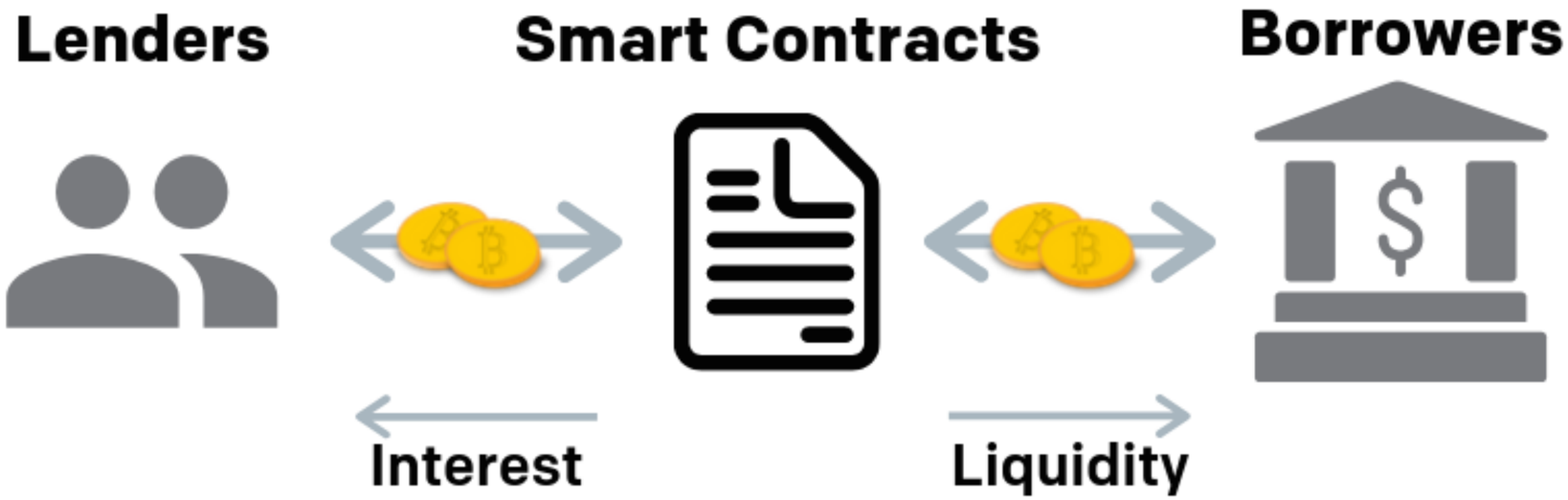
Refinement-based Verification

Example: simple lending protocol



* Image by https://medium.com/@goldfarbas/everything-you-need-to-know-about-defi-lending-protocols-6a5e8404f2b0

Example: simple lending protocol

Reference Model

```
mapping(address => num) principal;
mapping(address => num) interest;



function deposit(address user, num amount) {

    principal[user] += amount;
}

function reward(num amount) {
    num rate = amount / sum(principal);
    for (address user : keys(principal)) {
        interest[user] += principal[user] * rate;
    }
}
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```

Optimized Code

```
mapping(address => num) principal;
mapping(address => num) interest;
mapping(address => num) lastRateSum;
num currRateSum;

function deposit(address user, num amount) {
    update(user);
    principal[user] += amount;
}

function reward(num amount) {
    num rate = amount / sum(principal);
    currRateSum += rate;
}

function update(address user) {
    num rate = currRateSum - lastRateSum[user];
    interest[user] += principal[user] * rate;
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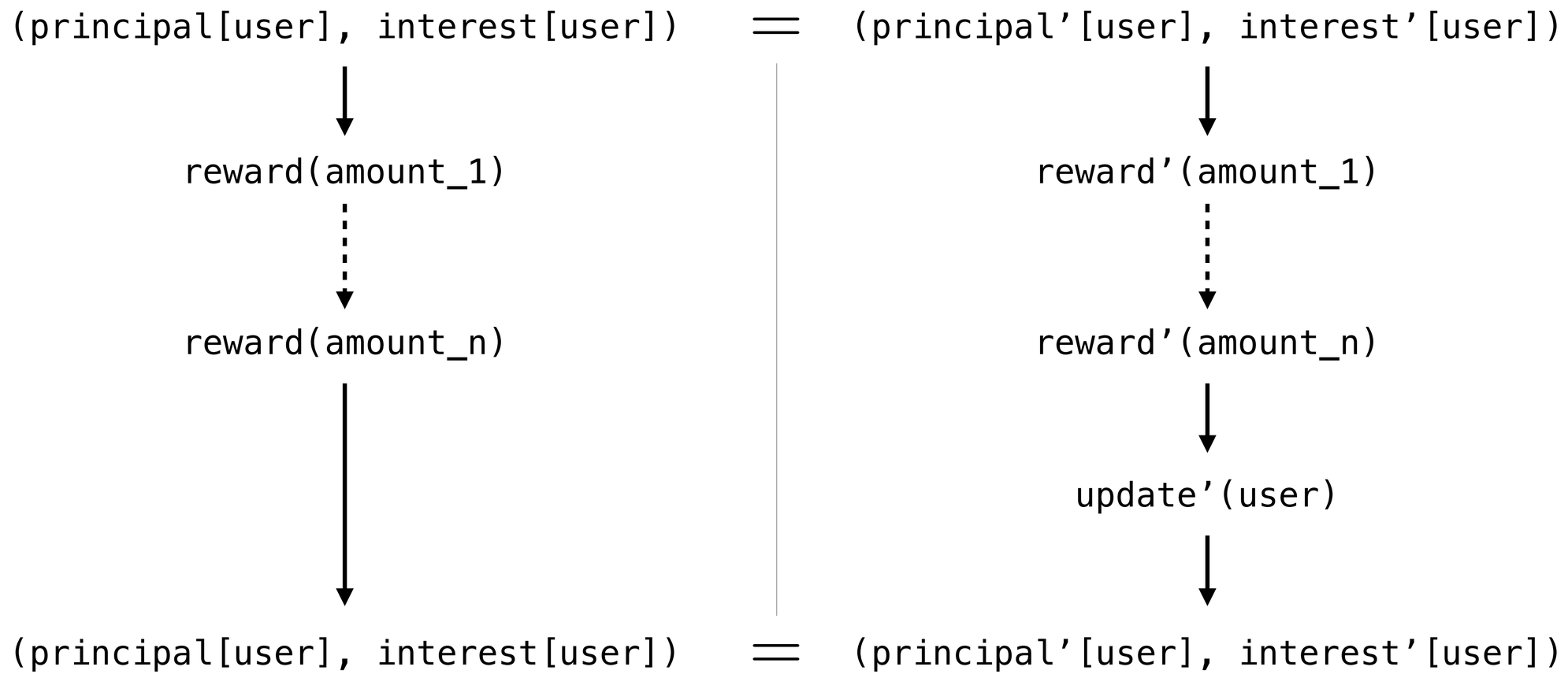
Refinement proof



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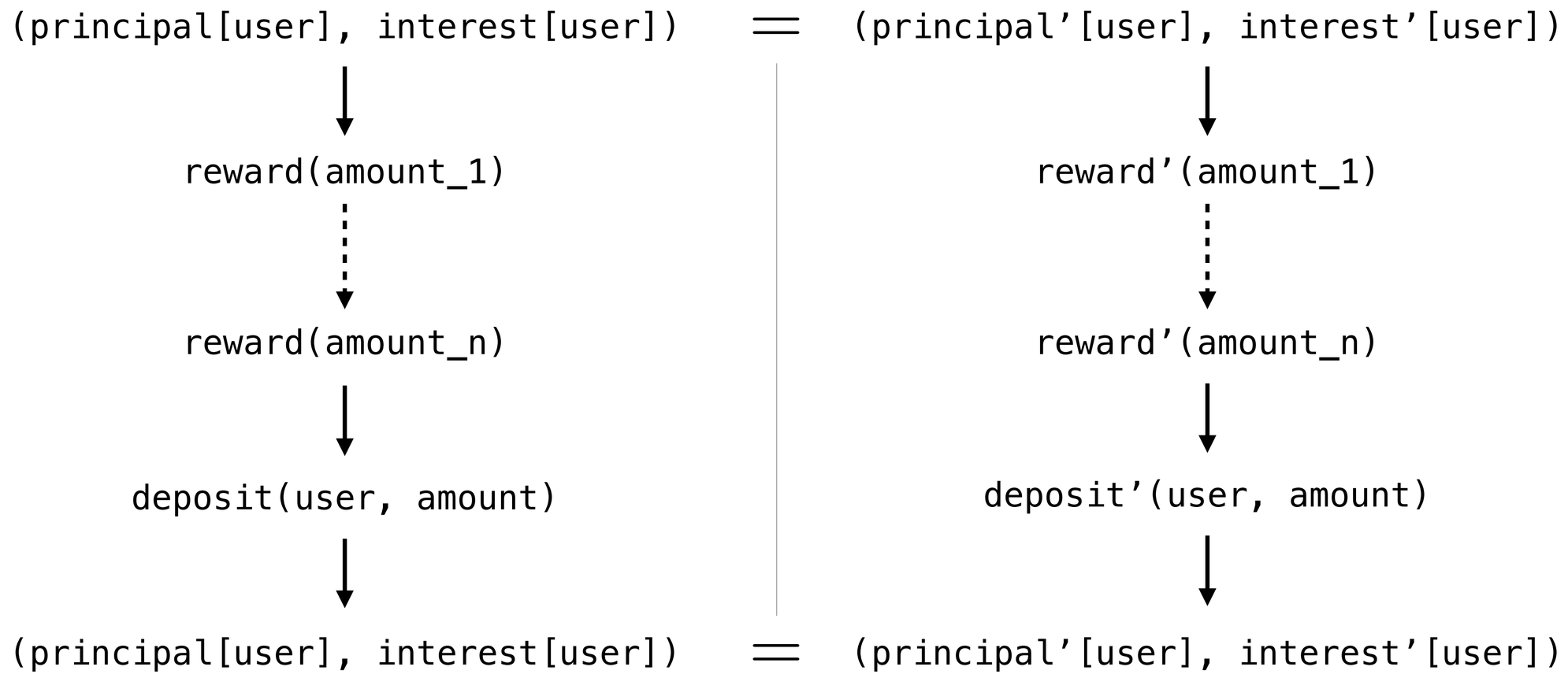
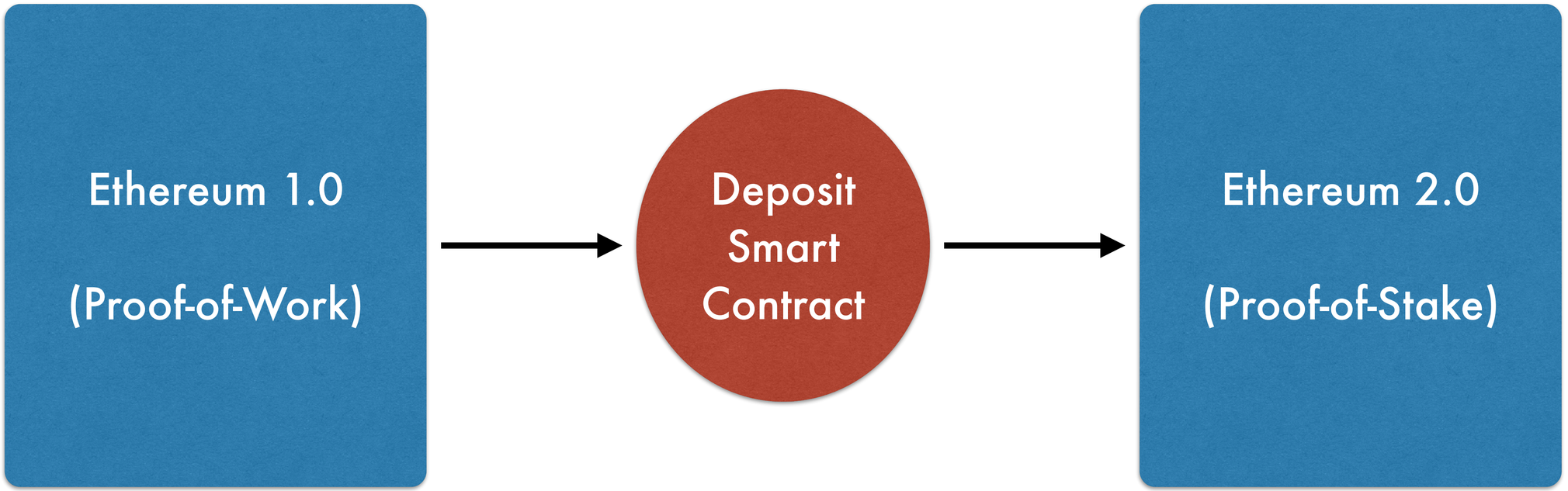


End-to-End Formal Verification of Ethereum 2.0 Deposit Smart Contract

Ethereum 2.0 deposit contract



Top Accounts by ETH Balance

A total of > 1,999,999 accounts found (118,148,868.055 Ether)

(Showing the last 10,000 top accounts only)

First < Page 1 of 400 > Last

Rank	Address	Name Tag	Balance	Percentage
1	0x00000000219ab540356cbb839cbe05303d7705fa	Eth2 Deposit Contract	9,366,114.000069 Ether	7.92738361%
2	0xc02aaa39b223fe8d0a0e5c4f27ead9083c756cc2	Wrapped Ether	7,711,580.31105652 Ether	6.52700313%
3	0xda9dfa130df4de4673b89022ee50ff26f6ea73cf	Kraken 13	2,113,030.001 Ether	1.78844710%
4	0x73bceb1cd57c711feac4224d062b0f6ff338501e		2,003,504.57090949 Ether	1.69574589%
5	0xbe0eb53f46cd790cd13851d5eff43d12404d33e8	Binance 7	1,996,008.34195866 Ether	1.68940116%
6	0x9bf4001d307dfd62b26a2f1307ee0c0307632d59		1,490,000.0180927 Ether	1.26112086%
7	0x4ddc2d193948926d02f9b1fe9e1daa0718270ed5	Compound: cETH Token	976,993.92778433 Ether	0.82691772%
8	0x61edcdf5bb737adffe5043706e7c5bb1f1a56eea	Gemini 3	929,498.95358134 Ether	0.78671846%
9	0xdc24316b9ae028f1497c275eb9192a3ea0f67022	Lido: Curve Liquidity Farming Pool Contract	603,436.15441902 Ether	0.51074222%

Etherscan

Eth: $3,227.56 (+3.97%) | 82 Gwei

Contract Overview

Eth2 Deposit Contract

Balance: 9,366,114.000069000000000069 Ether

Value: $30,220,047,804.64 (@ $3,226.53/ETH)

Token: >$592,202.12 >107

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3	0xda9dfa130df4de4673b89022ee50ff26f6ea73cf	Kraken 13	2,113,030.001 Ether	1.78844710%
4	0x73bceb1cd57c711feac4224d062b0f6ff338501e		2,003,504.57090949 Ether	1.69574589%
5	0xbe0eb53f46cd790cd13851d5eff43d12404d33e8	Binance 7	1,996,008.34195866 Ether	1.68940116%
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Ethereum 2.0 deposit contract

deposit ledger

Name	Amount
Alice	10 ETH
Bob	20 ETH
-	-
-	-

Ethereum 2.0 deposit contract

deposit ledger

2^{32}

~4 billion

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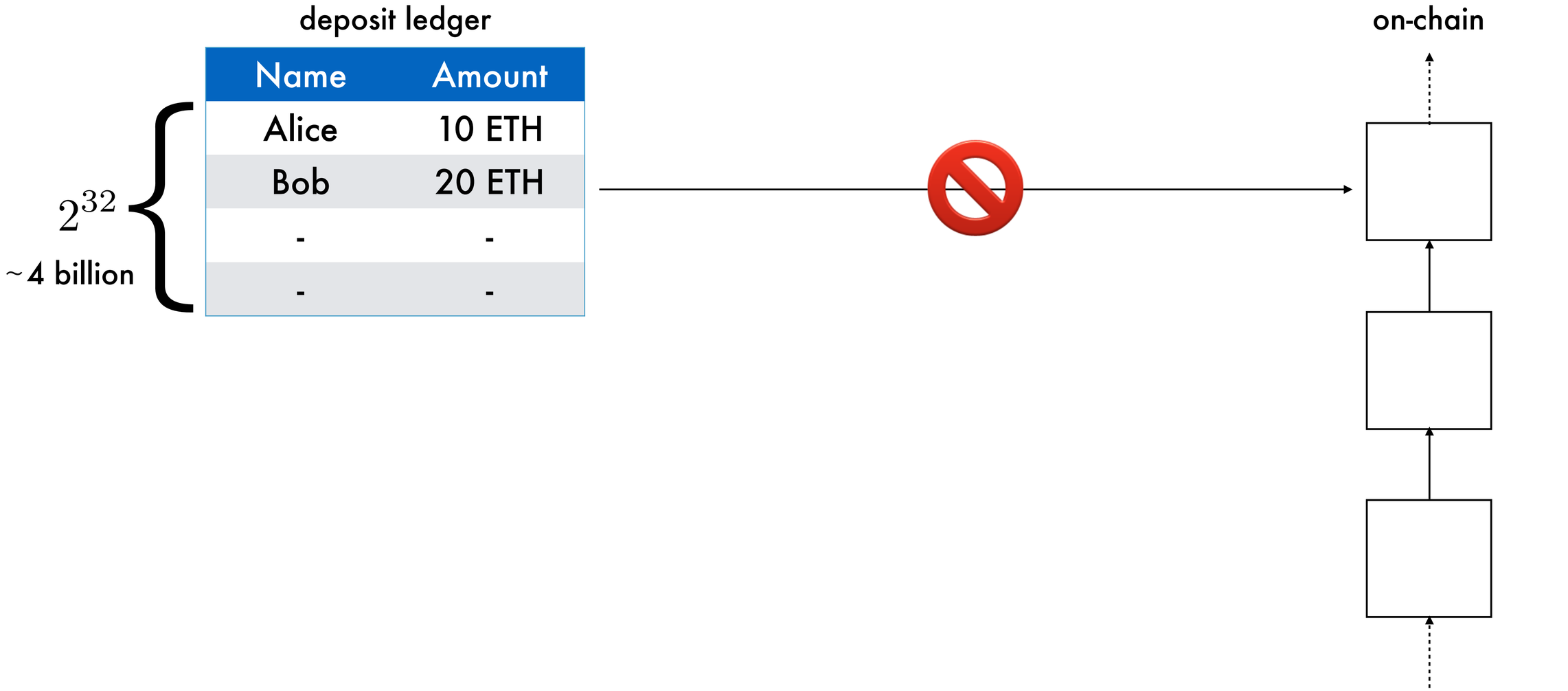

Ethereum 2.0 deposit contract

deposit ledger

2^{32} ~4 billion

Name	Amount
Alice	10 ETH
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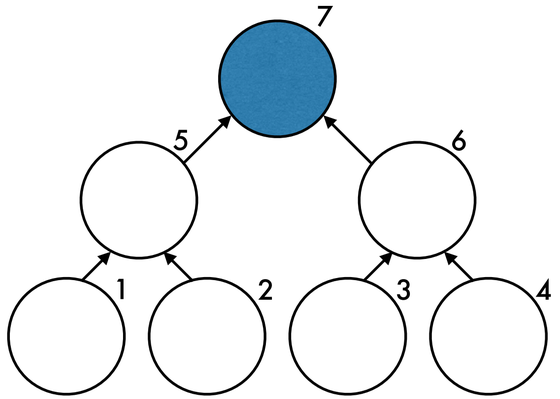
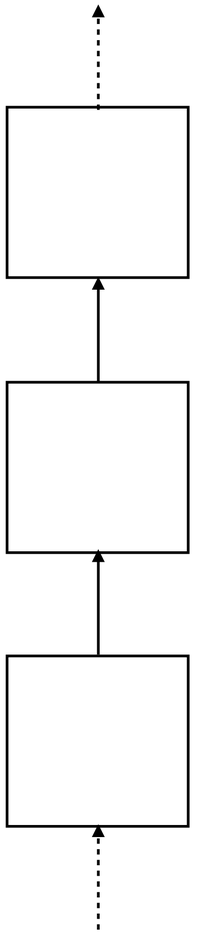
-	-
-	-

Merkle tree



on-chain



Ethereum 2.0 deposit contract

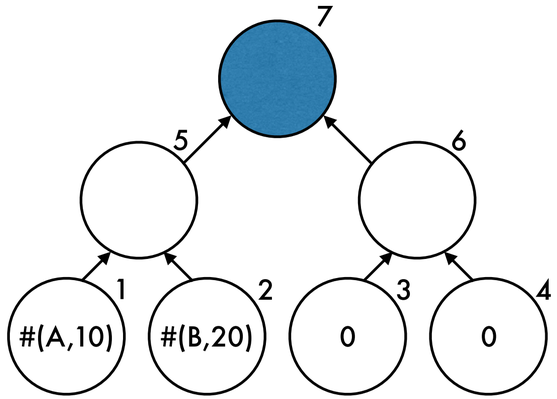
deposit ledger

2^{32}

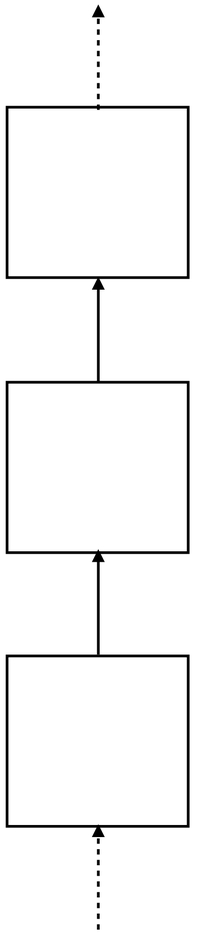
~4 billion

Name	Amount
Alice	10 ETH
Bob	20 ETH
-	-
-	-

Merkle tree



on-chain



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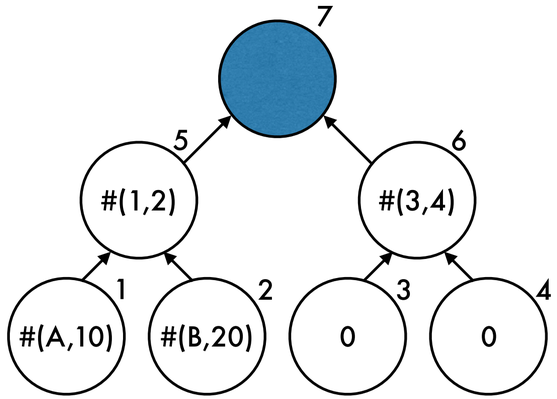
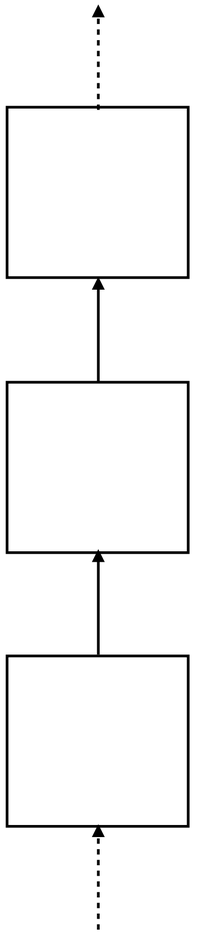


on-chain



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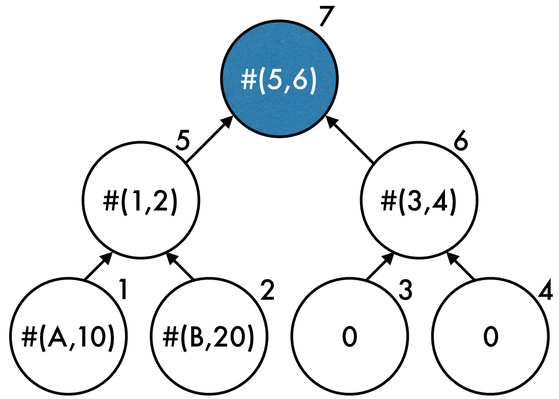
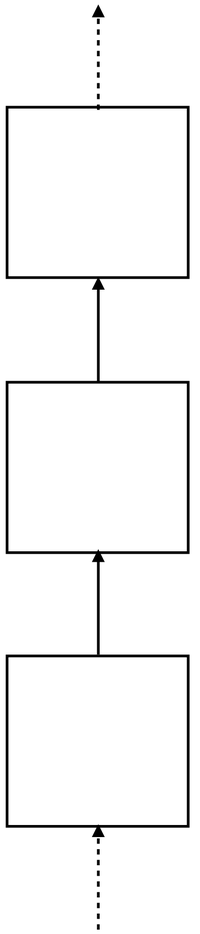
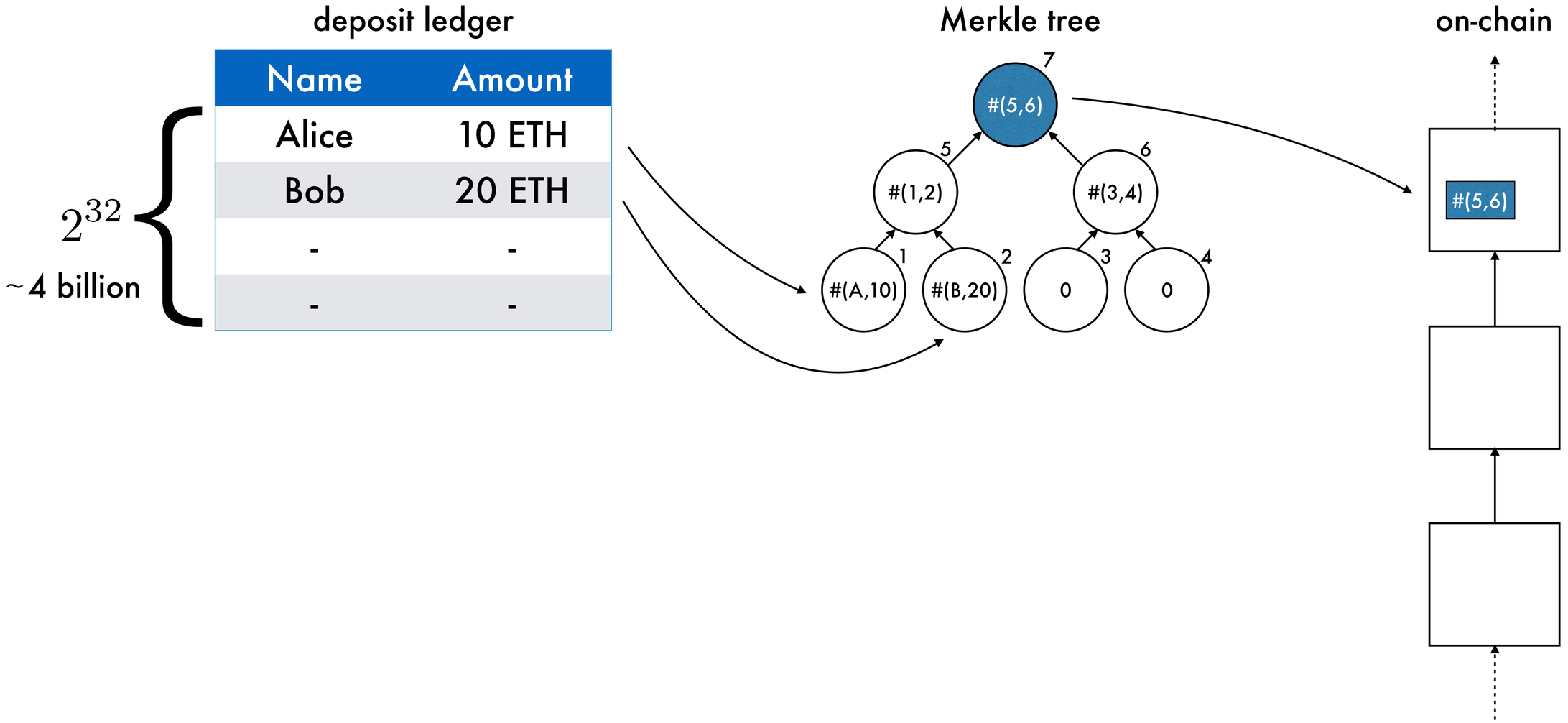


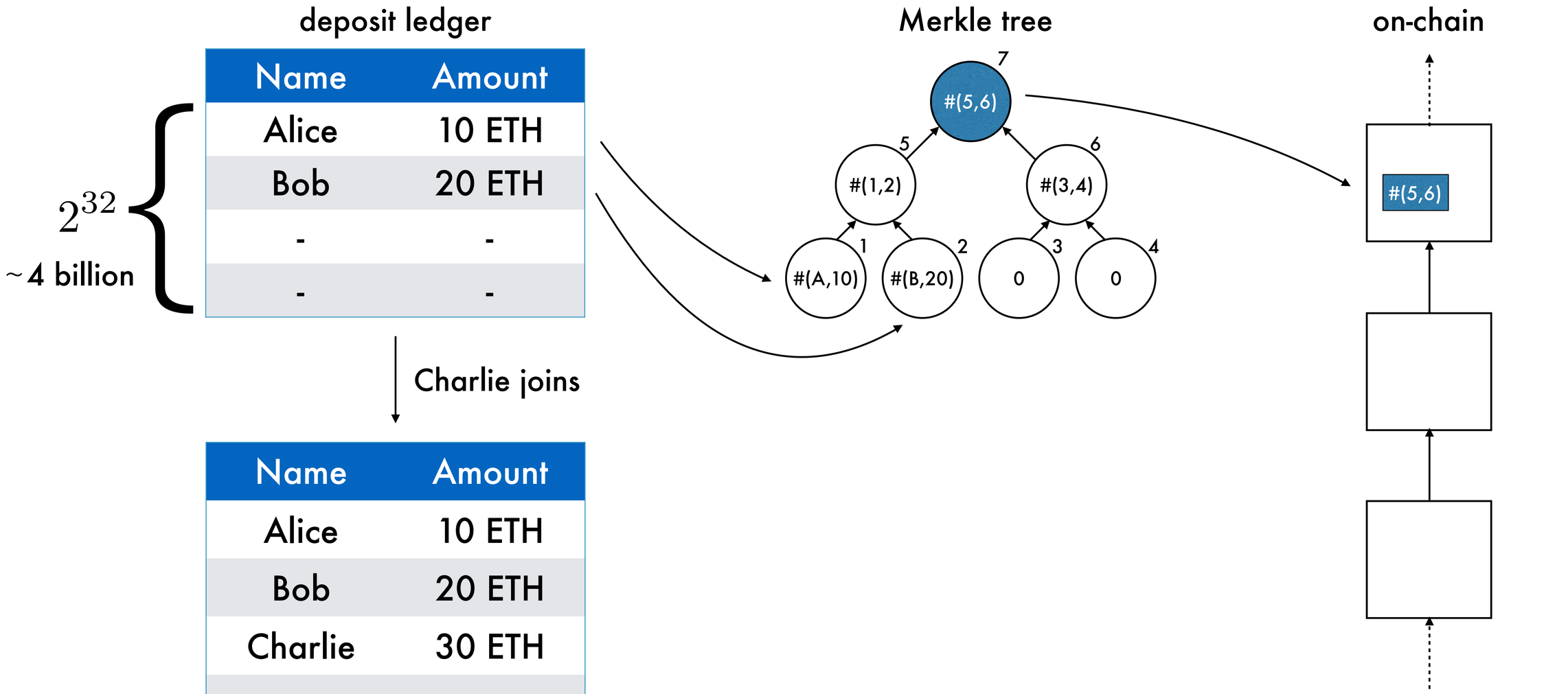
on-chain



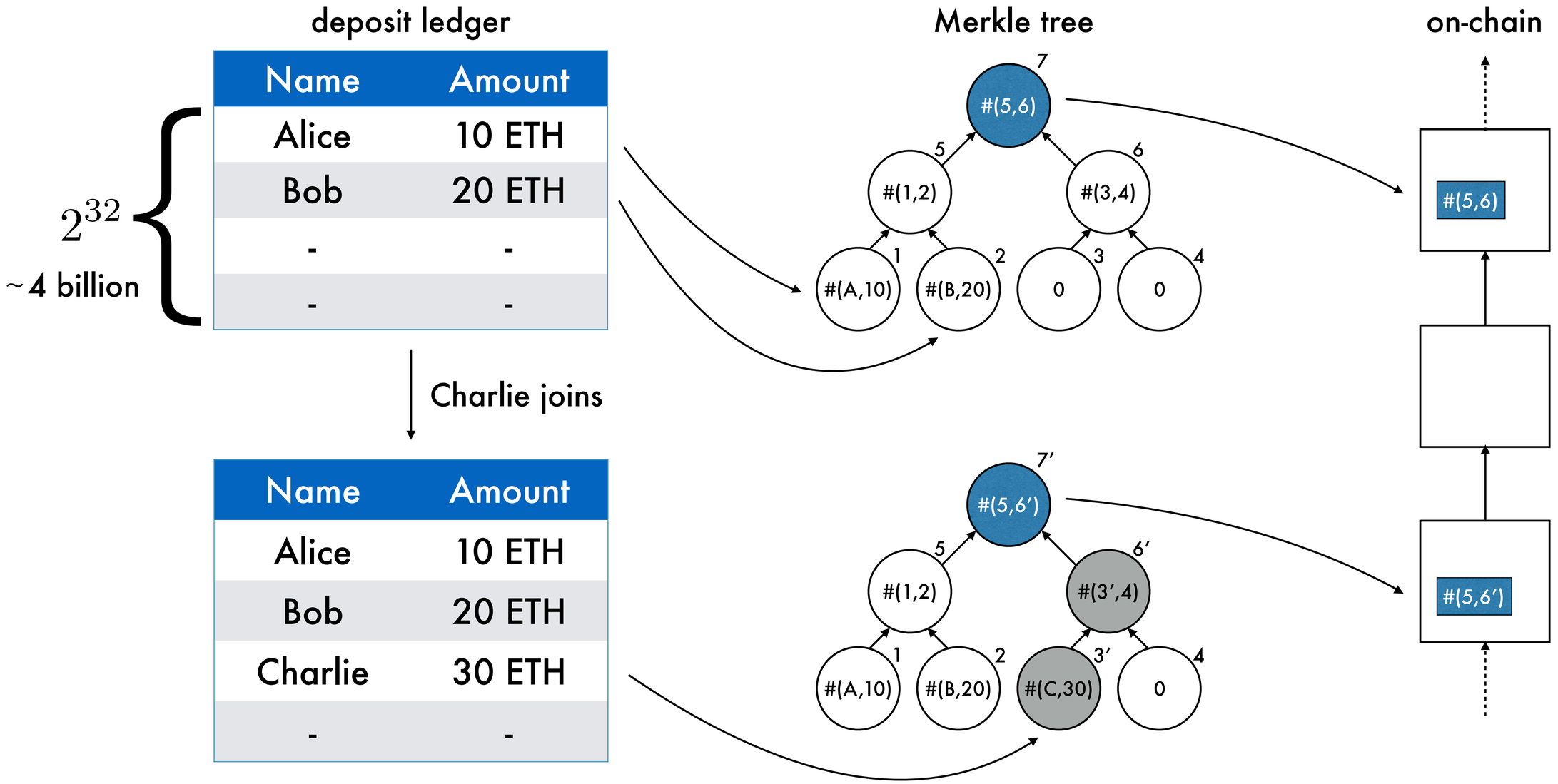
Ethereum 2.0 deposit contract



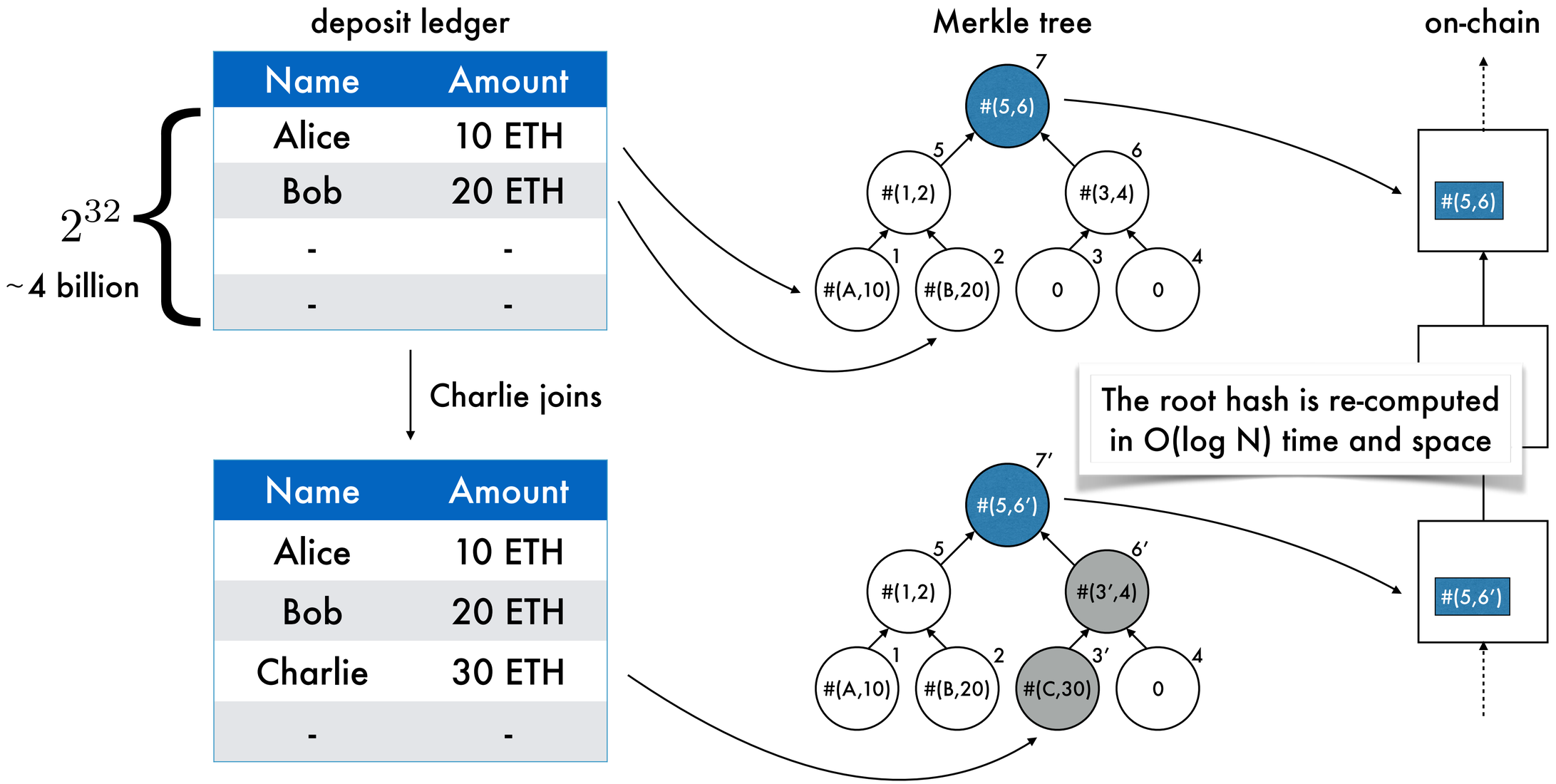
Ethereum 2.0 deposit contract



Ethereum 2.0 deposit contract



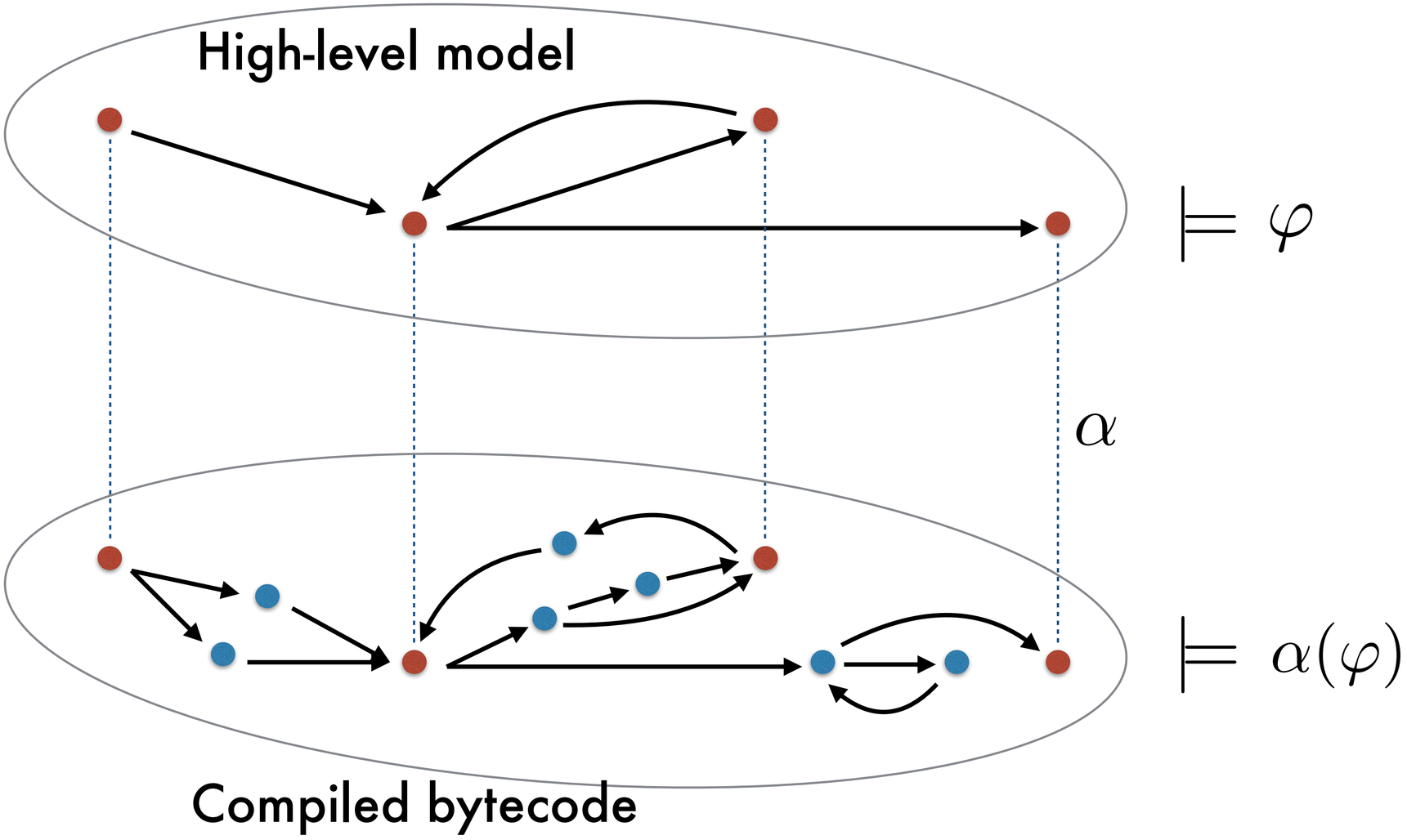
Ethereum 2.0 deposit contract



Formal verification of deposit contract

- *End-to-end* verification via *refinement-based* approach
  - Formalize and verify the incremental Merkle tree algorithm
  - Verify the contract *bytecode* faithfully implements the algorithm
    - No need to trust compiler
- This separation of concerns helped to reduce verification effort

Refinement-based verification



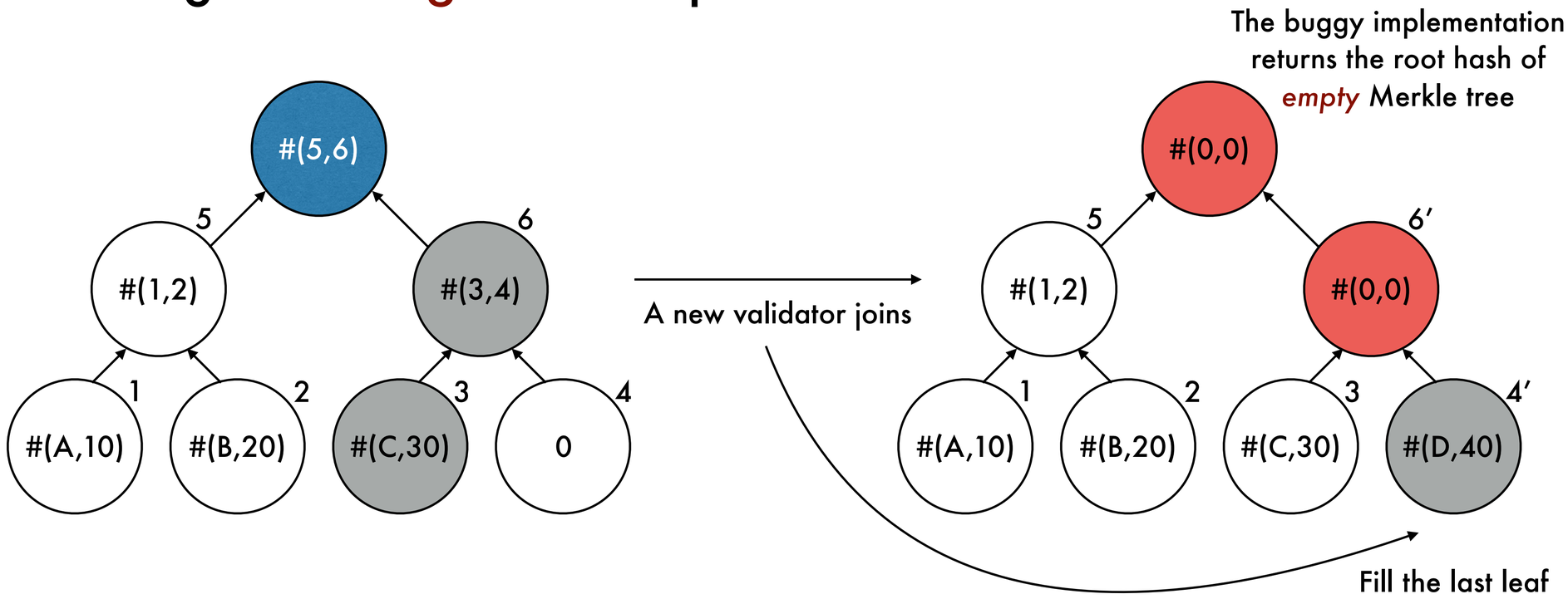
Verification effort

Correctness proof (over formal model)	2 person-weeks
Refinement proof (over bytecode)	5 person-weeks
Total	7 person-weeks

Source code	~100 LOCs
Bytecode	~3,000 instructions
Mechanized proofs	~1,000 LOCs

Findings

- Critical bug in the *algorithm* implementation



- Several bugs in the compiled *bytecode*
  - Mostly due to *compiler bugs*

Thank you!